



SHAPING TOMORROW'S BUILT ENVIRONMENT

CONVERGENCE OF DIGITAL INNOVATION AND SUSTAINABLE STRATEGY

EDITORS

Dr. Sushma S. Kulkarni

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About the Book

The National Level Post Graduate Research Symposium (NLPGRS)-2026, co-hosted by NICMAR Business School and the School of Project Management at NICMAR University, Pune, on March 14, 2026, was a huge success. We were thrilled by the massive turnout: over 500 abstracts poured in, and we accepted 451 full papers across seven exciting tracks. These covered hot topics like Construction & Infrastructure Management, Lean Construction, BIM, Quality Management, IT and Automation, Financial & Supply Chain Management, Green Energy and Risk Management, Circular Economy, Contract Management, Delay Analysis, Green Infrastructure and Sustainability, Project Management, Real Estate & Urban Infrastructure, and Construction Materials.

The tracks spanned Contemporary Issues in Management; Civil Engineering and Construction Management; Real Estate and Facility Management; Architecture, Design and Planning; Energy, Environment, and Sustainability; Engineering and Project Management; and Innovation, Entrepreneurship & Venture Development/Start-up Proposals.

We kicked things off by publishing the symposium abstracts in a book called Digitalization, Sustainability, and Strategic Evolution in Construction. From those 451 papers, we carefully selected 49 top ones after a thorough review process for our new volume, *Shaping Tomorrow's Built Environment: Convergence of Digital Innovation and Sustainable Strategy*. This collection highlights cutting-edge work blending digital tools—like BIM, IT automation, and AI—with sustainable approaches such as green energy, circular economy practices, green infrastructure, and risk-resilient building. These fresh insights from up-and-coming scholars give practical advice for industry pros, policymakers, and fellow academics tackling big issues like urban growth, climate change, and tech shifts in construction. It's all part of NICMAR University's push to connect research with real-world impact, building a tougher, smarter, and greener future for our built environment.

About the Editors

Dr. Sushma S. Kulkarni, Vice Chancellor of NICMAR University-Pune, is a transformative civil engineering leader with over 37 years of pioneering experience. Her ground-breaking role as the first Indian Chair of the Global Engineering Deans Council (GEDC) positions her at the forefront of shaping engineering education worldwide. She has steered institutions to autonomy, secured ₹15+ crore in funding, and published 155+ papers. A recipient of 35+ awards, her influence spans research, leadership, and advocacy for women in STEM fields.



Dr. Anil Agarwal is Professor at NICMAR University, Pune, and also serves as Dean of Academics. He has been associated with NICMAR since 1999 and played a key role in the institute's evolution into NICMAR University. His areas of academic and research interest include project and construction management, quality, and construction materials, and he has contributed actively to professional bodies such as the Bureau of Indian Standards (BIS) Construction Management Sectional Committee CED-29. Recognized for his academic leadership, he continues to guide curriculum development and academic strategy across the university.



Dr. Harish Kumar Singla is Professor and Dean of NICMAR Business School, NICMAR University, Pune. With over 22 years of academic experience, his expertise lies in Accounting and Finance. He has published 30+ research papers in ABDC- and Scopus-indexed journals, focusing on behavioral issues in investing and finance, intellectual capital, and related construction-management themes. He actively mentors' doctoral scholars and contributes to curriculum development, research, and industry-academia engagement at NICMAR University.



Dr. Devang Desai is a Mechanical Engineer from NIT, Surat and has postgraduate and doctorate degree in Marketing Management. He has more than 25 years of experience in corporates and academics. His teaching & research interest includes Marketing Management, Business Development & Project Marketing, Strategic Management, Human Resource Management, and Entrepreneurship & Innovation Management. He is currently dean and Senior Associate professor of School of Project Management.



Preface

Shaping Tomorrow's Built Environment: Convergence of Digital Innovation and Sustainable Strategy emerged from the exciting discussions at the National Level Post Graduate Research Symposium (NLPGRS)-2026. Hosted together by NICMAR Business School and the School of Project Management at NICMAR University, Pune, the event drew over 500 abstracts and 451 full papers across seven dynamic tracks. These spanned everything from Construction & Infrastructure Management and Lean Construction to BIM, Quality Management, IT and Automation, Financial & Supply Chain Management, Green Energy and Risk Management, Circular Economy, Contract Management, Delay Analysis, Green Infrastructure and Sustainability, Project Management, Real Estate & Urban Infrastructure, and Construction Materials. From this wealth of ideas, we selected 49 standout papers after a rigorous review process to feature in this volume.

These contributions highlight a key shift: digital innovation and sustainable strategies aren't silos anymore—they're teaming up to transform our built world. The authors dive into how tools like Building Information Modelling (BIM), data analytics, automation, and smart tech can boost project efficiency, transparency, and long-term performance, all while tackling urgent environmental, social, and economic issues. You'll see recurring themes like circular economy practices in construction, green infrastructure, energy-efficient buildings, and smart risk management, showing a real dedication to building responsibly and resiliently.

This book is for construction pros, infrastructure experts, real estate folks, urban planners, academics, researchers, and students who want practical ways to blend digital tools with sustainability in the real world. The case studies, models, and frameworks here provide both hands-on tips and solid theory for handling tough projects.

We hope *Shaping Tomorrow's Built Environment* doesn't just capture fresh research—it sparks more teamwork, fresh ideas, and real action for a smarter, greener, more sustainable future.

Editors

Dr. Sushma S. Kulkarni
Dr. Anil Agarwal
Dr. Harish Kumar Singla
Dr. Devang Desai

Acknowledgements

The successful launch of *Shaping Tomorrow's Built Environment: Convergence of Digital Innovation and Sustainable Strategy* wouldn't have been possible without the teamwork, guidance, and encouragement from so many people and partners. Thank you all for making this academic adventure come to life.

First off, huge thanks to Shri Rajeev Agrawal, Chief Executive Officer of Shapoorji Pallonji (EPC Division and Water & Utility Infra Division), for kicking off the National Level Post Graduate Research Symposium (NLPGRS)-2026 as our Chief Guest. His presence and inspiring words gave the event real energy and fired up our young researchers about the future of the built environment.

A big shoutout also goes to Mr. Rohit Koul, Managing Director of Green-Ecomes Solutions Pvt. Ltd., who joined us for the valedictory session as Chief Guest. His thoughtful insights and encouragement wrapped things up on a high note, underscoring how vital innovation and sustainability are for our industry.

Special thanks to Dr. Sushma S. Kulkarni, former Vice-Chancellor of NICMAR University, Pune, and Dr. Tapash Kumar Ganguli, Director General (Interim), NICMAR, for their steady support, wise guidance, and constant motivation. They helped turn the symposium—and this book—into a true success.

We're deeply grateful to our faculty, editors, reviewers, organizing committee, and staff for their tireless work in running the event smoothly and picking the best papers for this volume. And to our students and research scholars—your passion, hard work, and brilliant ideas are what make this book truly meaningful and timely.

Finally, heartfelt thanks to every contributor, stakeholder, and supporter who's been part of this journey. You've helped create a platform that pushes forward knowledge in digital innovation, sustainability, and smart strategies for the built environment.

CHAPTER 1

A Comparative Study of Delay Analysis Methods

Simran Rauniyar, Kiran P.** and Smitha Yadav****

ABSTRACT

Delays in construction projects remain one of the most persistent challenges affecting timely completion and cost efficiency. Accurate delay analysis is therefore crucial for identifying the causes and for forming appropriate corrective action plan. This research aims to conduct a comparative evaluation of five principal delay analysis methods—Time Impact Analysis (TIA), Impacted As-Planned Analysis, Time Slice Window Analysis, As-Planned versus As-Built Analysis, and Collapsed As-Built (But-For) Analysis. The study utilizes a real-world case of an industrial shed construction project located in Pune, India, where baseline scheduling and actual progress data are inputted in Microsoft Project (MSP). Each delay analysis method will be systematically applied to the same dataset to assess its suitability, accuracy, and cost implications. Through comparative interpretation, the research seeks to identify the most appropriate delay analysis technique for projects of similar scale and complexity. The findings are expected to contribute toward establishing a structured framework for selecting delay analysis methodologies in the Indian construction industry, thereby improving dispute resolution, project monitoring, and time management practices.

Keywords: Delay analysis, Cost overrun, Cost efficiency.

1.0 Introduction

1.1 General

“Delays,” in the current context, refer to any slowing or postponement in the project timeline that has a significant impact on the project schedule, budget, and, in many cases, the relationships among the stakeholders. This problem is common in the construction industry and has severe economic and managerial implications (Gurpreet Singh, 2024).

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It has been found that a substantial quota of projects in construction industry is prone to delays, which in some cases may be minor but, in other cases, may be critical, thereby posing a threat to the successful completion of projects (Gurpreet Singh, 2024). The rising complexity of projects, especially in infrastructure projects, further increases susceptibility to such problems (Kwame B. O. Amoah, 2024).

In this regard, delay analysis has emerged as an important tool for analyzing delay effects, assigning liability, resolving disputes, and avoiding future delays. It helps in assigning liability and ensuring just compensation by analyzing project schedules systematically (Choosing a Delay Analysis Methodology, 2021). This paper presents a comparative analysis of the most popular delay analysis techniques that are often employed in practice, such as As-Planned vs. As-Built, Impacted As-Planned, Time Impact Analysis, Windows Analysis and Collapsed As-Built.

1.2 Delay analysis methods classification

Delay analysis may be defined as the process of assessing and measuring delays to ascertain their causes and effects. The Society of Construction Law Delay and Disruption Protocol outlines the most commonly applied techniques for delay analysis; these are the ones considered in this section.

1.2.1 Time Impact Analysis (TIA)

Time Impact Analysis (TIA) is a technique that takes into account every single delay event as it happens. The essence of this analysis is in determining the impact of every delay event on the project completion date by comparing the schedule before and after the insertion of the delay event (Construction Delays Analysis Methods, n.d.). TIA, therefore, is a technique that analyses delays one after the other. The information needed for this technique includes the original project schedule, periodic project schedule updates reflecting the project status, and information on every single delay event, including the date of occurrence, duration, and type (Choosing a Delay Analysis Methodology, 2021).

1.2.2 Impacted As-Planned Analysis

The Impacted As-Planned approach requires the incorporation of delay events into the original project schedule, to theoretically assess the effect of the delay events on the project completion date (Construction Delays Analysis Methods, n.d.). The approach is founded on a theoretical representation of how the project would have happened (Choosing a Delay Analysis Methodology, 2021). The data needed for this approach includes a logically related project schedule and data about the delay events.

1.2.3 Time slice window analysis (windows analysis)

Time Slice Window Analysis, also known as Windows Analysis, divides the project timeline into smaller units called windows. For each window, the analyst determines the amount of delay that happened to the critical path during the window. This method provides a detailed insight into the delays that happen throughout the life cycle of the project (Choosing a Delay Analysis Methodology, 2021). To implement this method, you require an as-built schedule, the original baseline schedule, and updates for each window (Choosing a Delay Analysis Methodology, 2021).

1.2.4 As-Planned vs. As-Built Analysis

The As-Planned vs. As-Built Analysis is a simple technique that compares the original as-planned schedule with the actual as-built schedule to determine activities that began or completed later than scheduled (Construction Delays Analysis Methods, n.d.) (Choosing a Delay Analysis Methodology, 2021). It is a simple observational comparison between planned and actual performance (Types of Delay Analysis in Construction, 2021). The only information needed is as-planned and as-built schedule (Construction Delays Analysis Methods, n.d.). It is very flexible and has been widely used for retroactive analysis (Michaud, 2022). Nevertheless, it is less reliable for large projects, does not treat concurrent delays effectively, and is very sensitive to errors in the schedule (Choosing a Delay Analysis Methodology, 2021) (Lenahan, 2023).

1.2.5 Collapsed As-Built method

The Collapsed As-Built method, also referred to as “But-For” Analysis, is a retrospective analysis method that starts with the as-built schedule of the project. This method is founded on the idea of “virtually subtracting” the impact of delay events from the as-built schedule to arrive at the theoretical completion date if the delay events had not occurred (Construction Delays Analysis Methods, n.d.). The main data required for this method include the as-built schedule and data about the delay events to be eliminated.

1.3 AIM

To critically compare and evaluate the suitability, cost implications, and effectiveness of various delay analysis methods in the construction industry, with the goal of identifying best practices that optimize cost and time management.

1.4 Research objectives

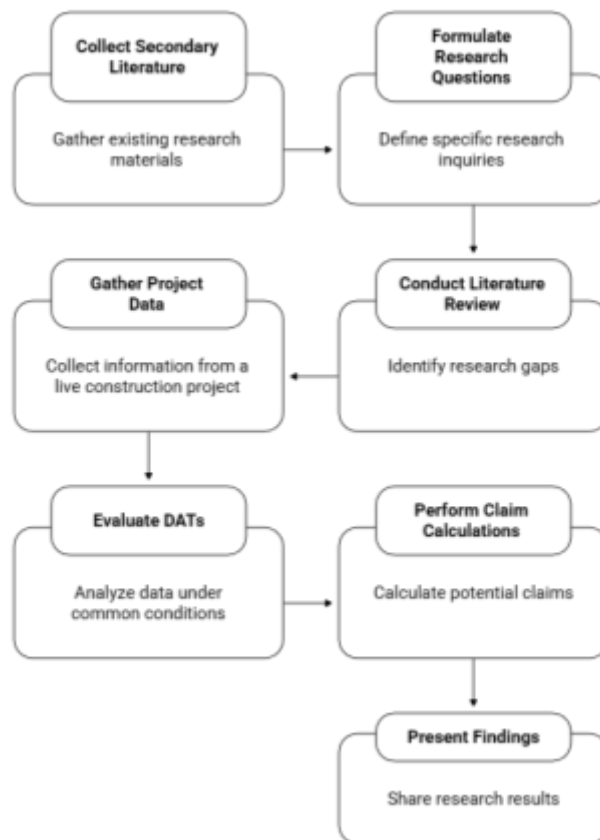
- To understand and perform a comprehensive study on various types of Delay Analysis Methods.

- Identifying commonly used delay analysis techniques in the Indian construction industry.
- To Identify best practices and offer practical recommendations for industry professionals.

2.0 Literature Review

Construction project delays remain an issue globally. Various studies have investigated the factors, impacts, and approaches for analyzing and solving construction project delays.

Figure 1: Flow Chart for Research Approach



Source: Created by authors

In India, (Hemanta Doloi, 2012) concluded that insufficient commitment, bad site management, substandard coordination, unclear scope, and poor communication were major factors, and regression analysis indicated that poor owner decisions, poor labor productivity, poor supervision, and rework were important contributors to delays (Hemanta Doloi, 2012).

In Denmark, the absence of project funding was the most important factor influencing time performance, and consultant errors caused cost overruns (Larsen, Shen, Lindhard, & Brunoe, 2016). In Saudi Arabia and Malaysia, poor communication was an important factor that significantly impacted productivity and quality (Abdallah, Shaawat, & Almohassen, 2024) (Olanrewaju, Tan, & Kwan, 2017).

In developing countries, the issues of subcontractor performance, planning failure, and institutional issues are intricately linked. In Chile, case studies revealed that while issues with subcontractors were prevalent, planning failure had the most detrimental effects on critical activities (González, 2013) (Pablo González, 2014). This was also found to be true in Nepal and South Africa, where delays resulted in cost overruns, arbitration, and distress to the client (Koirala & Shahi, 2024) (Mukuka, Aigbavboa, & Thwala, 2015). In India, the treatment of concurrent delays is inconsistent, which is an indication that there are no standardized legal and analytical processes (Munvar, 2019). Comparisons have also been made between delay analysis methods. Cunningham (1998) showed that different methods can give very different results for the same project (Ndekugri, 2009; Ndekugri, 2009).

4.0 Project Data and Analysis

The project which is chosen is a single Pre-Engineered Building (PEB) structure, which is part of a larger industrial project located in Chakan MIDC. The infrastructure project comprises of many work packages, each awarded to a different contractor. The project which we have chosen is a PEB structure with a mezzanine floor. All the data collected regarding the activities, duration, relationships between activities, delays and who can the delay be attributed to is provided by the contractor firm responsible for that package.

Figure 2: External View of the PEB Structure



Source: Created by authors

We have used Microsoft Project software to carry out our delay analysis activity as it is now becoming popular due to easier interface when compared to its predecessor, Primavera P6. Also, many small and medium firms use MSP and some of the bigger firms are also now adopting this software.

4.1 Activity schedule data

The activities along with their duration and predecessors are given below. These are provided by the contractor firm responsible for the construction of the PEB structure.

Table 1: Project Data

S. No.	Activity	Planned Duration	Duration after delay	Predecessors
	Foundation Works			
1	Excavation	70	76	-
2	PCC	65	65	1SS+13d
3	Footing	65	65	2SS+22d
4	Plinth	40	40	3
5	Pedestal	52	52	4
	PEB			
6	Supply of anchor bolt	3	3	3
7	Procurement & Fabrication	30	40	5,6
8	Supply - Primary & Secondary	21	21	7FS-14d
9	Supply of Liner Sheets, Roof Coil & Profile Machine	3	5	8
10	Supply of Cladding Sheet & Puff Panels	3	4	8
11	Supply of Misc. Work (Gutter, flashing, Down take & Etc)	7	12	8
12	Erection of Primary & Secondary	41	44	8SS+3d, 5
13	Roofing with Liner	14	14	12, 9
14	Cladding with Puff Panel	45	45	12SS+24d, 10
15	Misc. Work (Gutter, flashing, Down take & Etc)	14	14	11,13,14
	Superstructure			
16	Plinth Filling & Compaction	20	33	15
17	GSB with Compaction	18	18	16
18	Flooring	18	26	17FS-13d
19	Densification	19	21	18
20	Supply of Fire Door & Rolling Shutter	6	7	17SS+18d
21	Fixing of Fire Door & Rolling Shutter	7	7	19,20
22	Supply of Façade Materials	7	7	16
23	Fixing of Façade Frames	39	45	22
24	Fixing of Glass, Doors & Sealant	40	53	23SS+7d
25	Painting Work	9	12	24FS-10d,21

Source: Created by authors

4.2 Delay attribution matrix

Table 2: Table Indicating Delay Reason and Responsible Party

S. No.	Activity	Delay Event		Delay (days)	Attribution	Delay Percentage		Reason
		Client	Contractor			Client	Contractor	
Foundation Works								
1	Excavation		D1	6	Contractor Responsible	0%	100%	Site mobilization done late.
2	PCC			0	—	—	—	No delay.
3	Footing			0	—	—	—	No delay.
4	Plinth			0	—	—	—	No delay.
5	Pedestal			0	—	—	—	No delay.
	PEB							
6	Supply of anchor bolt			0	—	—	—	No delay.
7	Procurement & Fabrication	D2	D3	10	Shared Delay	80%	20%	Procurement delay as client-approved vendor delayed, contractor also delayed
8	Supply - Primary & Secondary			0	—	—	—	No delay.
9	Supply of Liner Sheets, Roof Coil & Profile Machine	D4		2	Client Responsible	100%	0%	Client-appointed vendor delayed.
10	Supply of Cladding Sheet & Puff Panels	D5		1	Client Responsible	100%	0%	Client-appointed vendor delayed.
11	Supply of Misc. Work (Gutter, flashing, Down take & Etc)	D6	D7	5	Shared Delay	15%	85%	Contractor placed late order.
12	Erection of Primary & Secondary		D8	3	Contractor Responsible	0%	100%	Poor site-execution.
13	Roofing with Liner			0	—	—	—	No delay.
14	Cladding with Puff Panel			0	—	—	—	No delay.
15	Misc. Work (Gutter, flashing, Down take & Etc)			0	—	—	—	No delay.
Superstructure								
16	Plinth Filling & Compaction		D9	11	Contractor Responsible	0%	100%	Poor site-execution.

17	GSB with Compaction			0	–	–	–	No delay.
18	Flooring		D10	8	Contractor Responsible	0%	100%	Coordination issues between contractor and sub-contractor.
19	Densification	D11	D12	2	Shared Delay	50%	50%	Activity started late due to flooring delay and client delayed approvals.
20	Supply of Fire Door & Rolling Shutter	D13		1	Client Responsible	100%	0%	Procurement delay as client-appointed vendor delayed.
21	Fixing of Fire Door & Rolling Shutter			0	–	–	–	No delay.
22	Supply of Façade Materials			0	–	–	–	No delay.
23	Fixing of Façade Frames	D14	D15	6	Shared Delay	33%	66%	Delay due to late client approvals & installation inefficiencies
24	Fixing of Glass, Doors & Sealant	D16	D17	13	Shared Delay	30%	70%	Delay due to late client approvals & installation inefficiencies
25	Painting Work		D18	3	Contractor Responsible	0%	100%	Activity started late due delay in fixing of fire doors.

Source: Created by authors

This table lists out all the delays faced in the chosen activities of the WBS and who can these delays be attributed to. All the delays listed here are of Excusable Compensable (client responsible) and Non-Excusable- Non-Compensable (contractor responsible) category.

Total Delay days = 71 days

Client total = $8+2+1+1+1+1+2+4 = 20$ days, i.e. client-attributable delay is approximately 28.16%

Contractor total = $6+2+4+3+11+8+1+4+9+3 = 51$ days, i.e. contractor-attributable delay is approx. 71.83%

4.3 As planned schedule

This is the planned baseline schedule for the construction work. It acts as the blueprint for the contractor as to how the scope of work is to be achieved. As planned schedule is the original schedule. It allows us to compare the progress against itself to identify the discrepancies. Refer appendix A for MSP charts.

Total As-Planned duration=375 days

4.4 As built schedule

This schedule states how the work was carried out by the contractor. It comprises of the real start and finish time of the activities along with the impacted durations of the activities due to delays. Refer appendix B for MSP charts.

Total As-built duration= 409 days

4.5 Analysis of data

4.5.1 As planned VS. As built

This technique compares the actual completion dates of activities with the planned (baseline) completion dates, considering all delaying events such as contractor-caused delays and owner/client-caused delays. The total delay for which extension of time or compensation is requested is the difference between the as-built duration and the as-planned duration.

Total As planned duration= 375 days. (Refer appendix A)

Total As-built duration= 409 days. (Refer appendix B)

Total project delay (As-Planned vs As-Built) = $409 - 375 = 34.0$ days.

As discussed above, we have a total raw delay of 71 days, whereas, on adding all the delays in the as planned schedule, gives us the 34 days of net delay.

Hence, concurrent delays= $71 - 34 = 37$ days

Total Delay days= 71 days

Sum of client caused delays = $8 + 2 + 1 + 1 + 1 + 1 + 2 + 4 = 20$ days

Sum of contractor caused delays = $6 + 2 + 4 + 3 + 11 + 8 + 1 + 4 + 9 + 3 = 51$ days

According to the min. Rule method, simultaneous delays caused by both entities is the value of the shorter delay duration, i.e., 20 days.

Hence, total project delay for whom the contractor is responsible= $51 - 20 = 31$ days
Balance is client liability, $34 - 31 = 3$ days

4.5.2 Collapsed as-built schedule

The Collapsed As-Built (CAB) Delay Analysis, also known as the *but-for method*, evaluates responsibility by starting with the actual as-built schedule and then removing the delays attributable to one party—either the owner or the contractor. By subtracting that party's delay events and recalculating the schedule, a hypothetical "but-for" completion date is produced: the date on which the project would have finished if that party had not caused any delay. The difference between the actual as-built completion date and the reconstructed but-for completion date represents the specific delay caused by the selected party. This makes the CAB method highly effective in disputes, as it clearly isolates each party's impact on the final project duration.

We will conduct the collapsed as-built analysis in two parts

- Contractor's point of view

In this method, we will first adjust for the delays caused by client by not considering any delay caused by the client and only considering those delays which are due to the contractor. *The new duration comes out to be 401 days* (Refer appendix C) as compared to 409 days in the as-built schedule. This means the *client's liability is of $409 - 401 = 8$ days*. When the adjusted schedule is compared to the original as-built schedule, it is found that *contractor is responsible for, $34 - 8 = 26$ days* of delay causation.

- Client's point of view

Now, we will adjust to the delays caused by the contractor by not considering any delay caused by the contractor and only considering those delays which are due to the client. *The new duration came out to be 386 days* (Refer appendix C) as compared to 409 days in the as-built schedule. This means the *contractor's liability is of $409 - 386 = 23$ days*. When the adjusted schedule is compared to the original as-built schedule, it is found that *client is responsible for, $34 - 23 = 11$ days* of delay causation.

4.5.3 Impacted as-planned analysis OR time impact analysis

The Impacted As-Planned analysis is used to evaluate how delay events affect the contractor's original CPM schedule. In this method, each delay is modelled as a separate activity and inserted into the baseline programme in chronological order. This helps illustrate how each delay event influences the critical path and the overall project timeline.

Table 3: Impact as Planned Table

Delay Event	Delay	Delay Duration	Delay Days		Delay Impact
			Client	Contractor	
D1	6	375	0.00	6.00	0
D2+D3	10	385	8.00	2.00	10
D4	2	385	2.00	0.00	0
D5	1	385	1.00	0.00	0
D6+D7	4	385	0.60	3.40	0
D8	3	385	0.00	3.00	0
D9	11	396	0.00	11.00	11
D10	8	404	0.00	8.00	8
D11+D12	2	406	1.00	1.00	2
D13	1	406	1.00	0.00	0
D14+D15	6	406	2.40	3.60	0
D16+D17	12	406	3.60	8.40	0
D18	3	409	0.00	3.00	3
Total Impact=			9.00	25.00	34

Source: Created by authors

The resulting delay is determined by comparing the original planned completion date with the updated schedule that includes the inserted delay activities. This approach provides a clearer and more comprehensive understanding of how individual delays altered the baseline schedule and contributed to the project overrun. Refer appendix D for MSP charts.

On conducting this analysis on our activities, it is established that delay events 2,3 and 9 cause the most delay, and some events cause no impact on the schedule.

Hence, the *client is liable for 9 days* of delay for this project, and the *contractor is liable for 25 days of delay*.

4.5.4 Window analysis

For this project, the Window Analysis technique was used to evaluate how delays affected the work sequence over time. The total construction period was divided into smaller, sequential time windows, each representing a distinct phase of progress. Within each window, the schedule was updated to reflect the actual durations, actual start/finish dates, and delay events that occurred during that period, while the remaining future activities retained their as-planned logic. By examining the critical path movement and the revised completion date within each window, the specific delay impact of that time slice was determined. This was done by comparing the new completion date at the end of the window with the planned completion date immediately prior to the analysis. The schedule was divided into eight windows based on key activity groupings such as earthwork, flooring, densification, façade works, and finishing. The analysis was then performed successively for each window to identify how delays accumulated and shifted the critical path throughout the project duration. Refer appendix E for MSP data.

Table 4: Window Analysis Table

Window No.	Window Range	Project Duration	Delay in window slice	
			Client	Contractor
1	17 May, 24 - 1 Aug, 24	375	0	0
2	2 Aug, 24 - 15 Oct, 24	375	0	0
3	16 Oct, 24 - 31 Dec, 24	375	0	0
4	1 Jan, 25 - 15 Mar, 25	375	0	0
5	16 Mar, 25 - 31 May, 25	385	8	2
6	1 Jun, 25 - 15 Aug, 25	385	0	0
7	16 Aug, 25 - 31 Oct, 25	404	0	19
8	1 Nov, 25 - 10 Dec, 25	409	1	4
		Total Delay =	9	25

Source: Created by authors

From window slice analysis, we conclude that the *client is responsible for 9 days* of delay and *contractor is responsible for 25days* of delay.

5.0 Result and Discussion

The results of all applied delay analysis techniques show that contractor is responsible for majority of the delay, with values ranging between 3 to 31 days, while the owner’s contribution remains comparatively lower across all methods. Techniques that incorporate actual progress and critical path evolution—like Window Analysis and Time Impact Analysis—produce the most reliable and consistent results, both identifying the owner’s liability at 9 days and the contractors at 25 days.

Table 5: Results Obtained in all Analysis Methods

Delay Analysis Techniques	Delay (in days)	
	Client	Contractor
As-Planned vs. As-Built Analysis	3	31
Impacted As-Planned / Time Impact Analysis	9	25
Collapsed As-Built – Contractor’s point of view	8	26
Collapsed As-Built – Owner’s point of view	11	23
Window Analysis (approx. 60-day windows)	9	25

Source: Created by authors

6.0 Conclusion

Based on industry best practices and international standards (AACE, SCL Protocol), both Time Impact and Window Analysis are considered the most accurate and defensible methods, as they reflect contemporaneous updates, actual delays, and real critical path shifts throughout the project lifecycle. These methods provide the strongest basis for determining responsibility and supporting delay claims.

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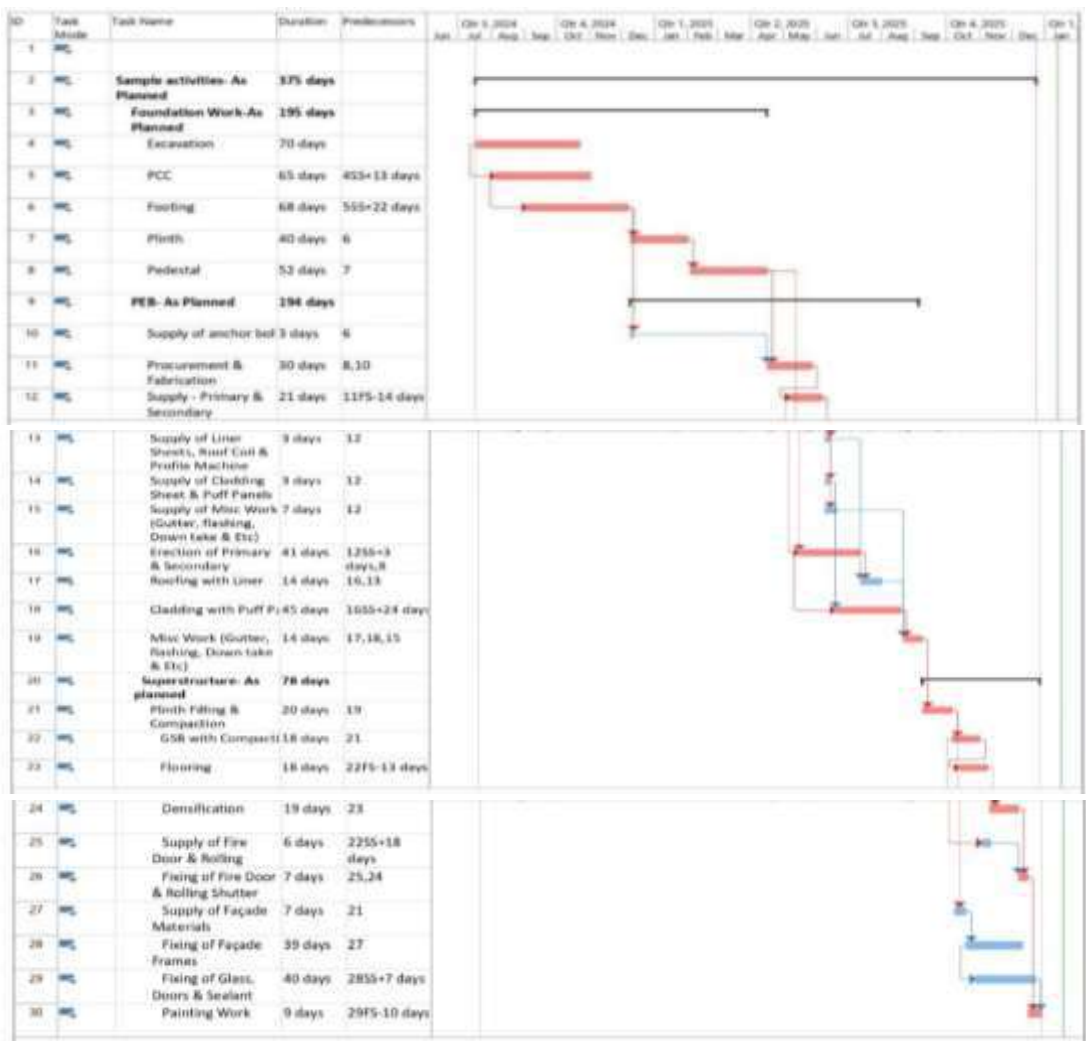
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APPENDICES

9.1 APPENDIX A: As planned schedule (MSP data chart)

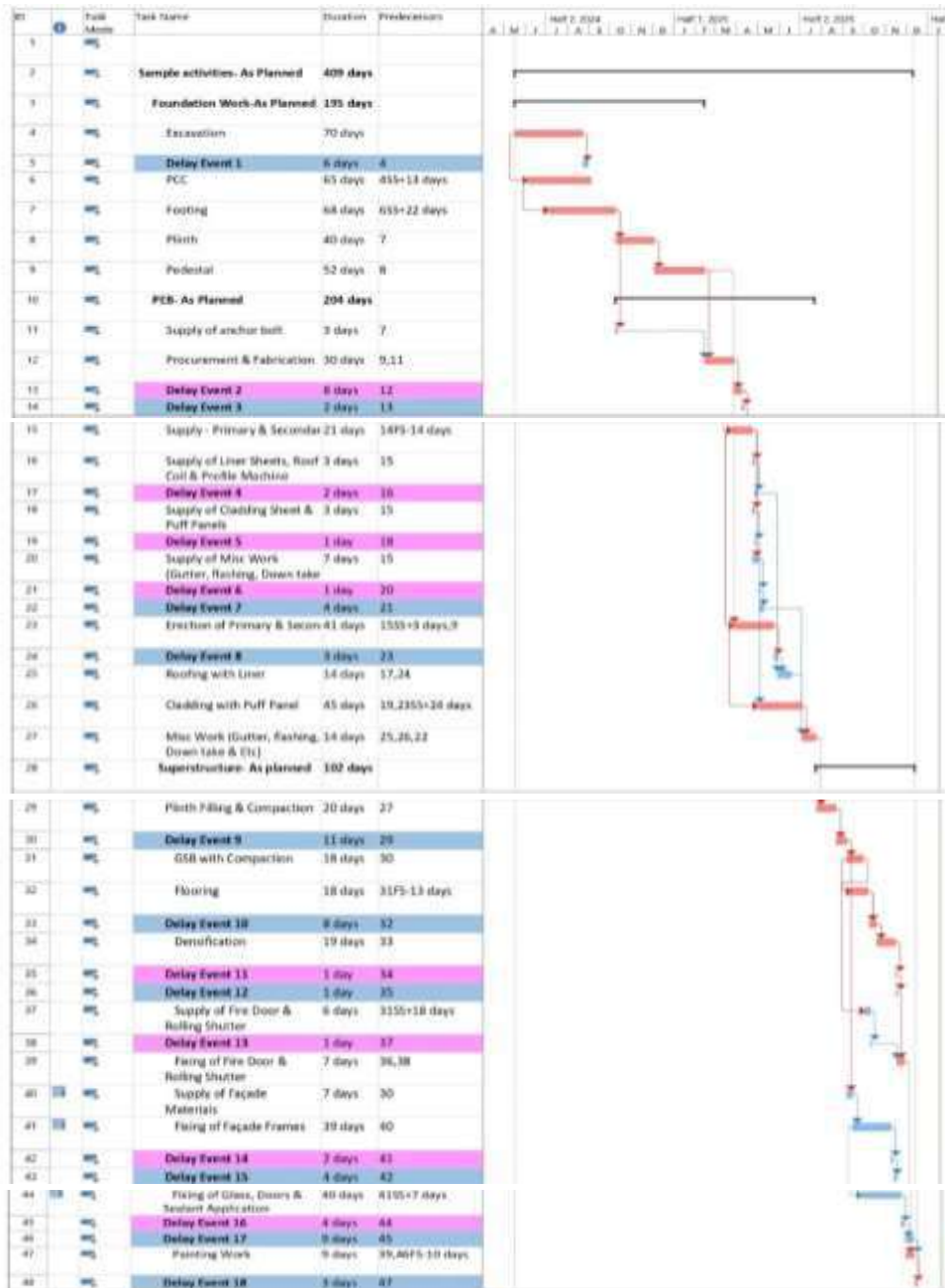
Figure 3: As Planned Schedule MSP Chart



Source: Created by authors

Appendix B: As built schedule (MSP Data Chart)

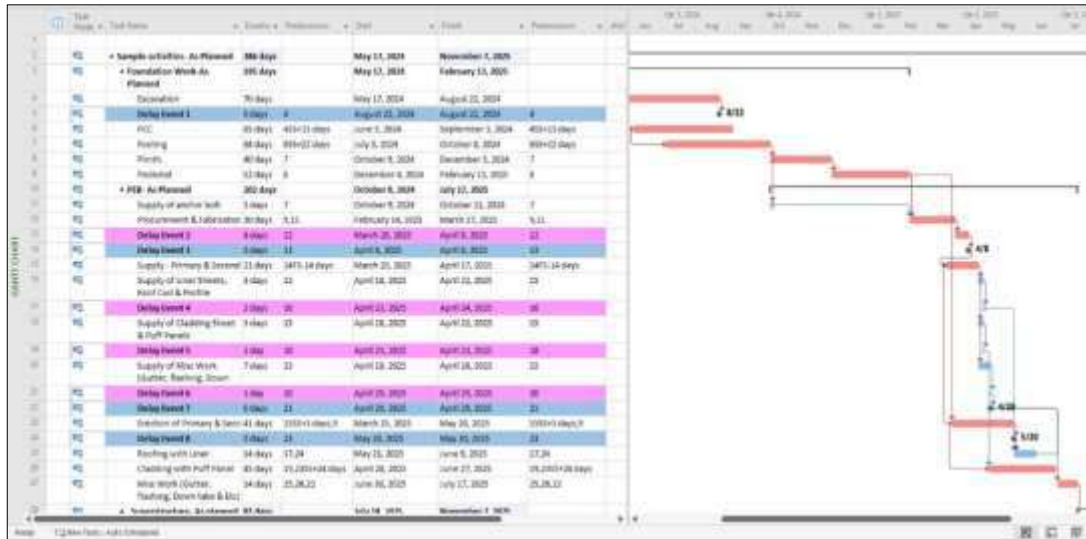
Figure 4: As Built Schedule MSP Chart



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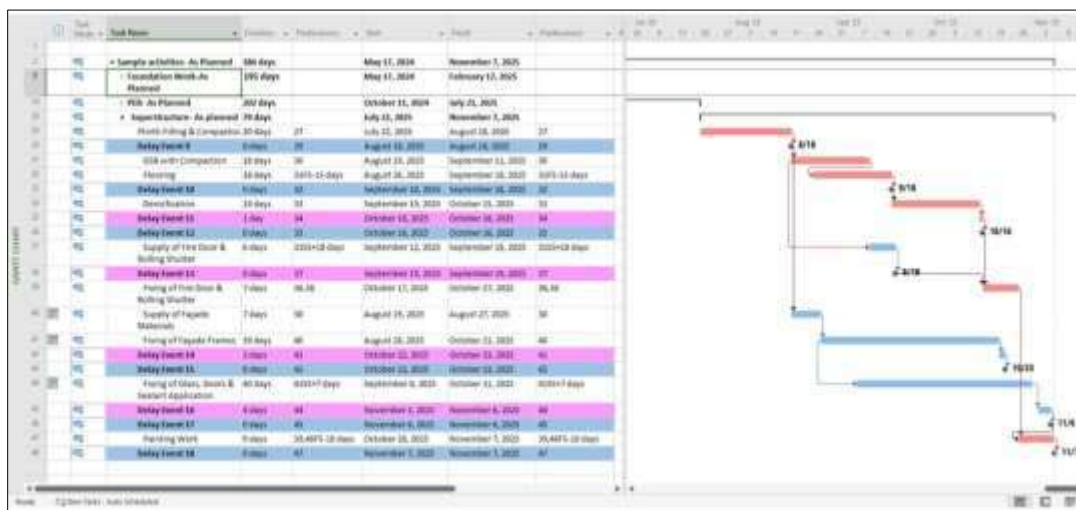
9.3.2 Client's POV

Figure 7: Collapsed As- Built Analysis where Delay Events by Contractor are Considered '0' in Events 1,3,7 and 8



Source: Created by authors

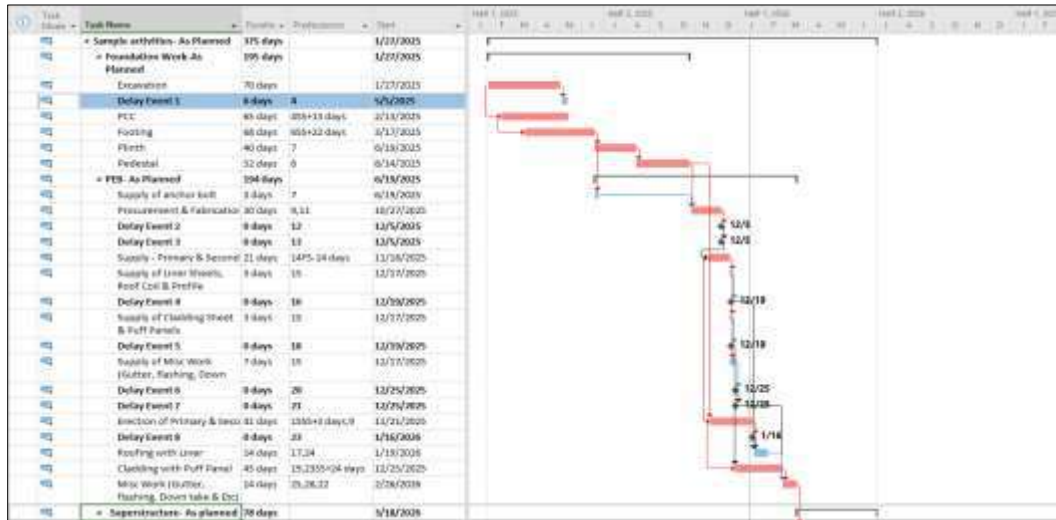
Figure 8: Collapsed As- Built Analysis where Delay Events by Contractor are Considered '0' in Events 9,10,12,15,17 and 18



Source: Created by authors

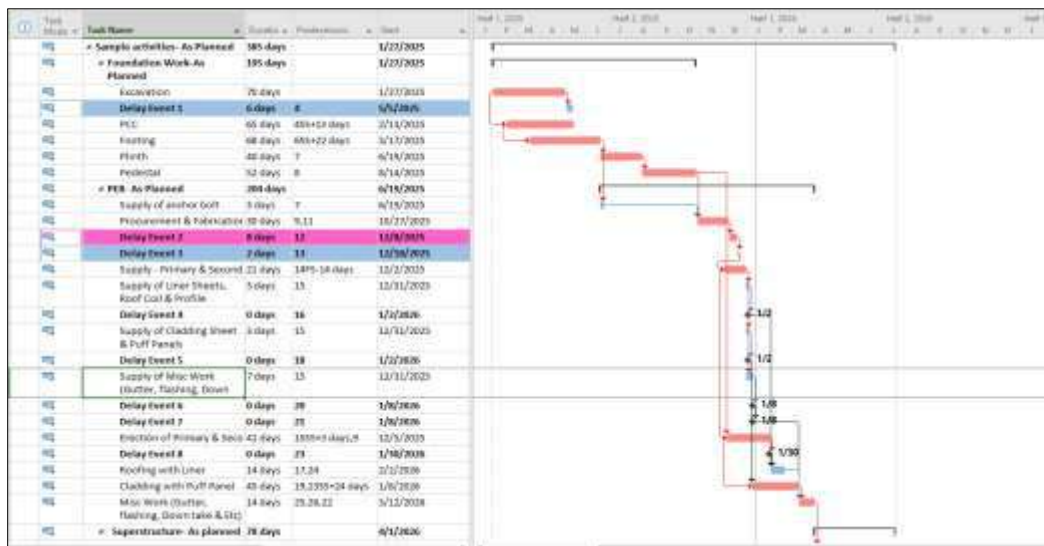
APPENDIX D: Impacted as Planned/ Time Impact Analysis (MSP Data Chart)

Figure 9: Impacted as Planned Analysis, where Delay Event 1 is Inserted and its Impact on as Planned Schedule is Studied. DE 1 has no Impact on Completion Date



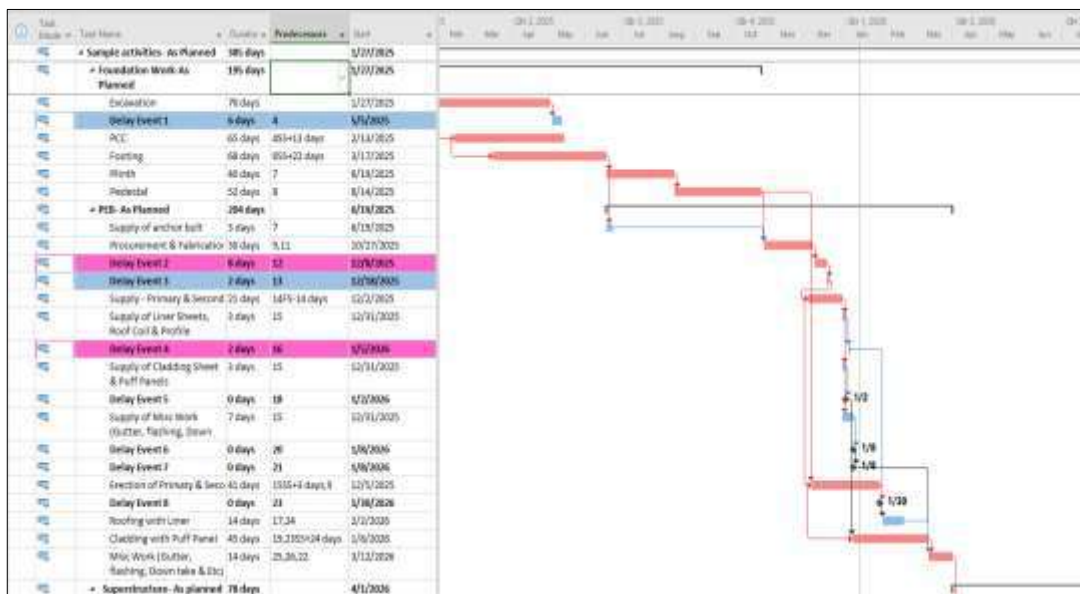
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Figure 10: Inserting Delay Events 2&3 Impacts the Schedule and Delay the Project by 10 Days



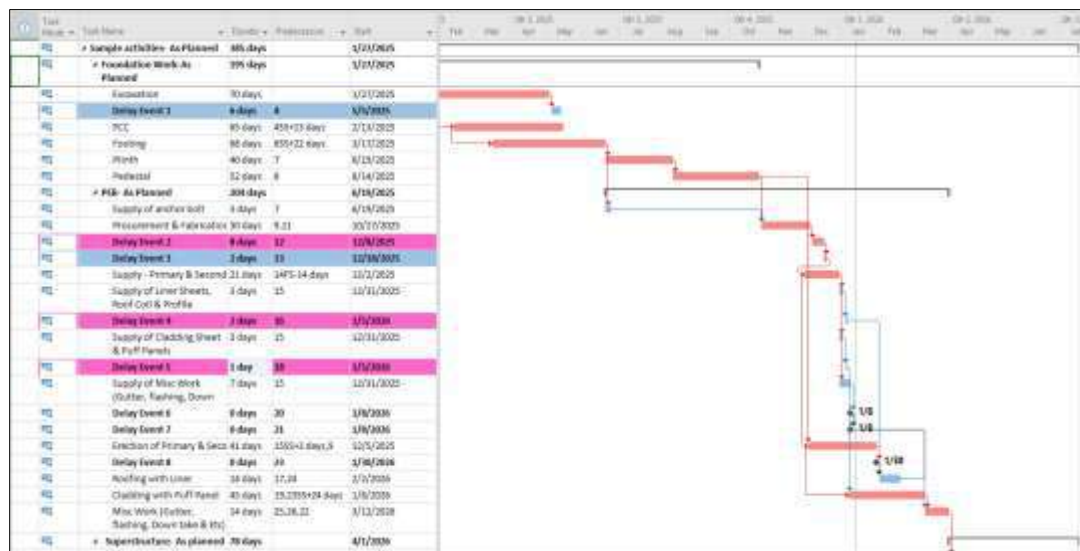
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Figure 11: Delay Event 4 has no Impact on Schedule



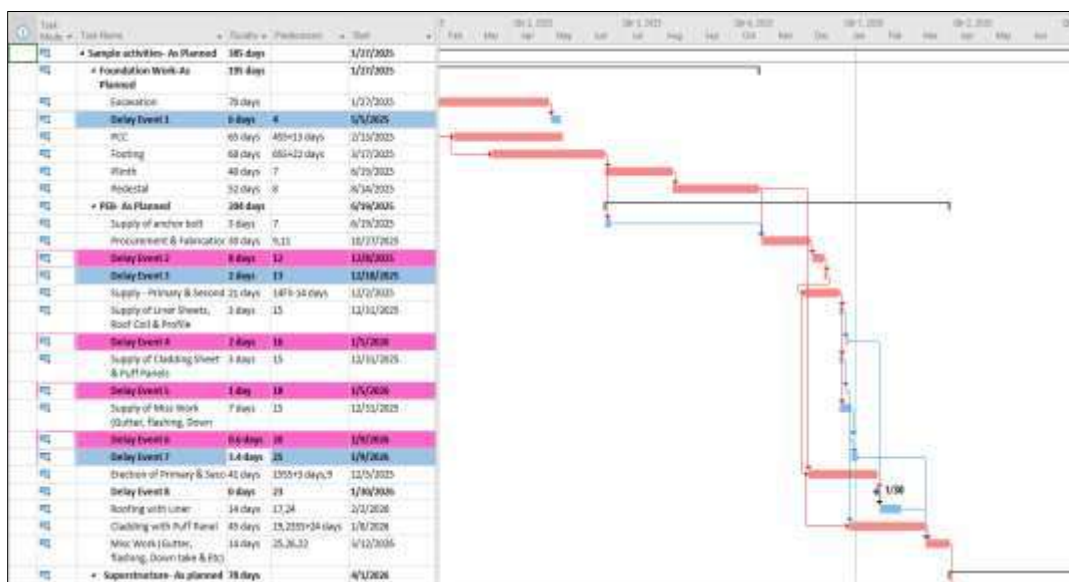
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Figure 12: Delay Event 5 has no Impact on Schedule



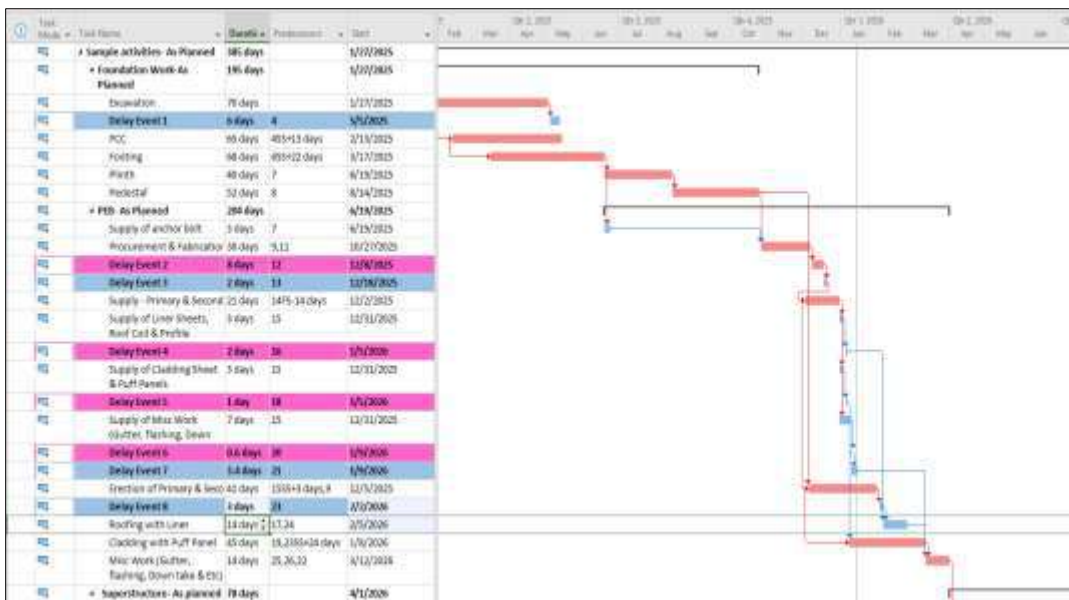
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Figure 13: Delay Event 6&7 have no Impact on Schedule

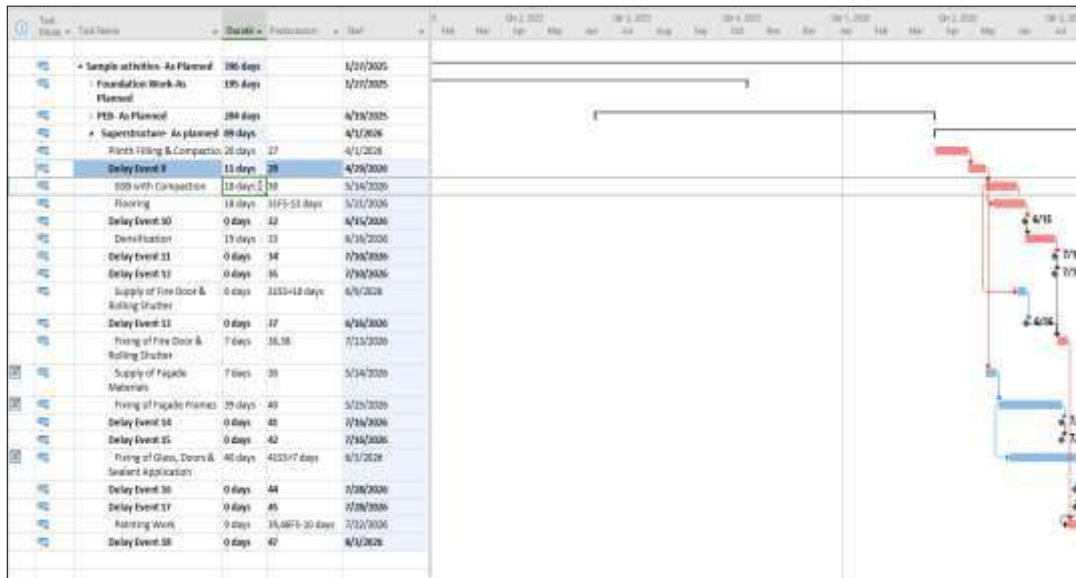


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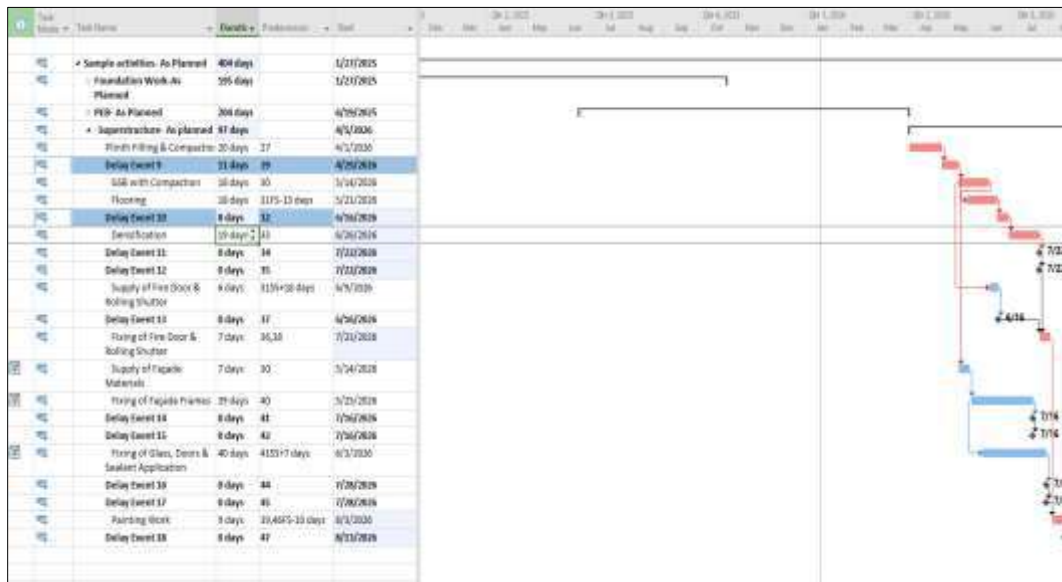
Figure 14: Delay Event 8 has no Impact on Schedule



Source: Created by authors

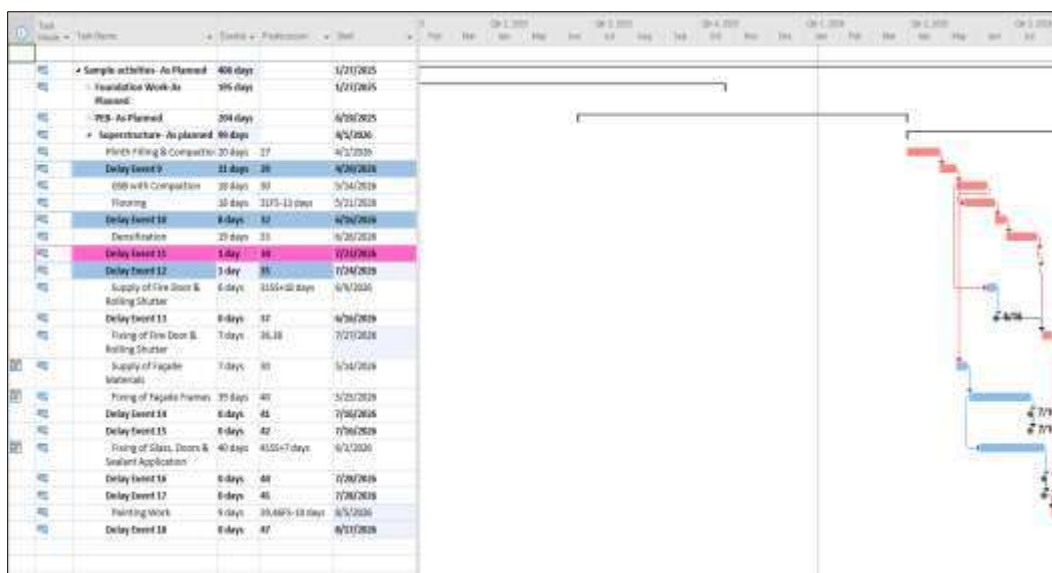
Figure 15: Delay Event 9 Increases the Schedule by 11 Days

Source: Created by authors

Figure 16: Delay Event 10 Increases the Schedule by 8 Days

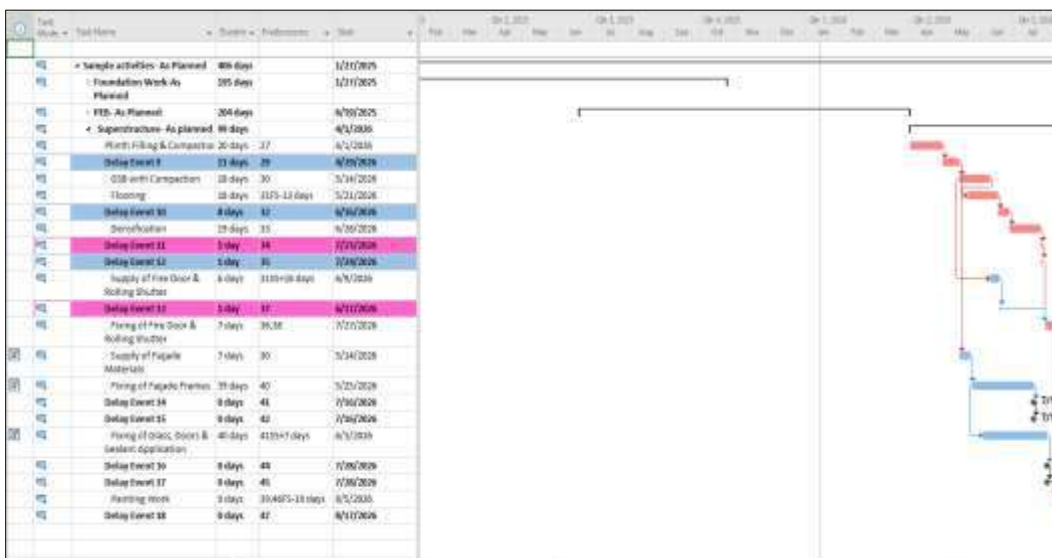
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Figure 17: Delay Event 11&12 Impact the Schedule by 2 Days

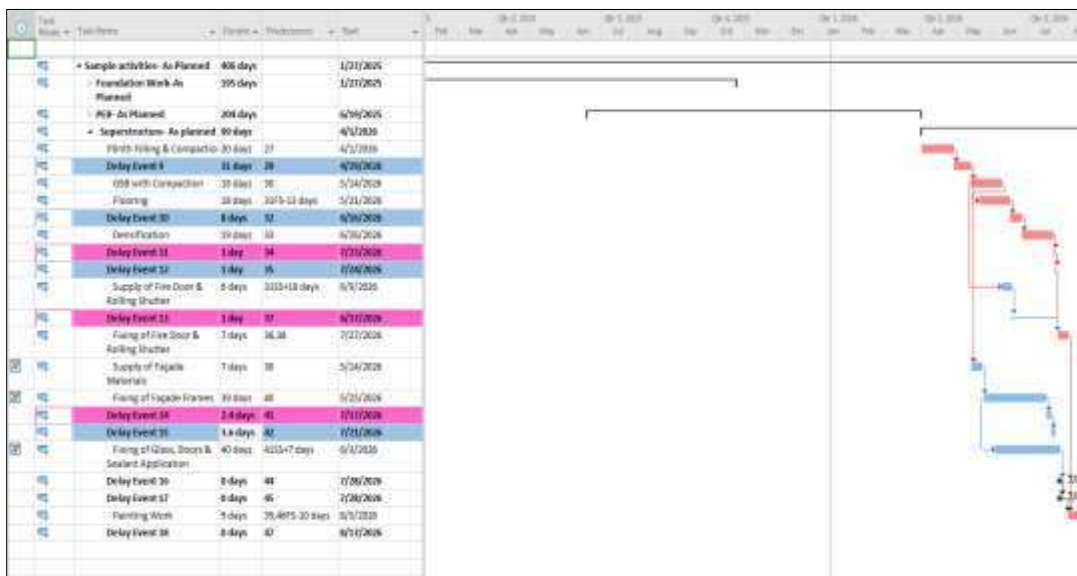


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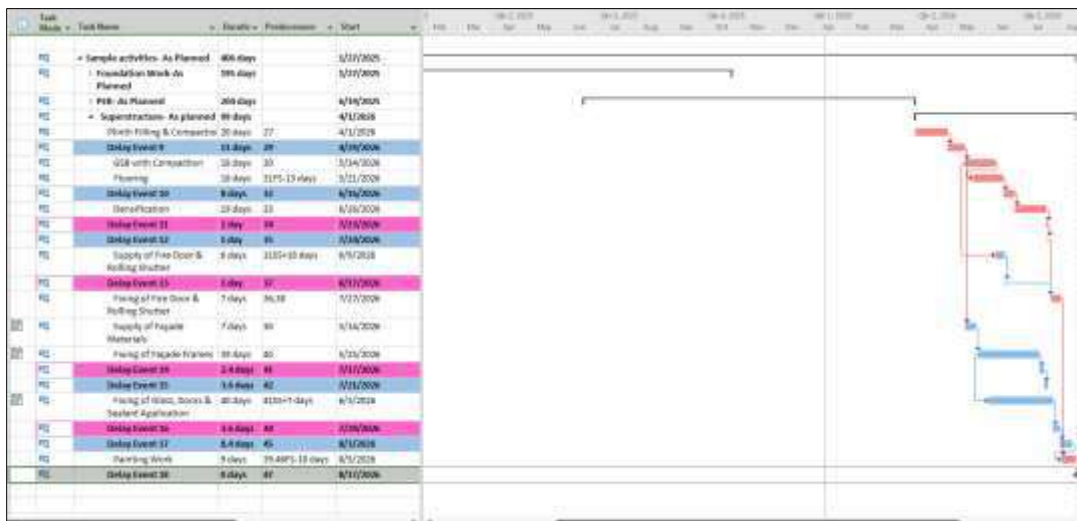
Figure 18: Delay Event 13 has no Impact on the Schedule



Source: Created by authors

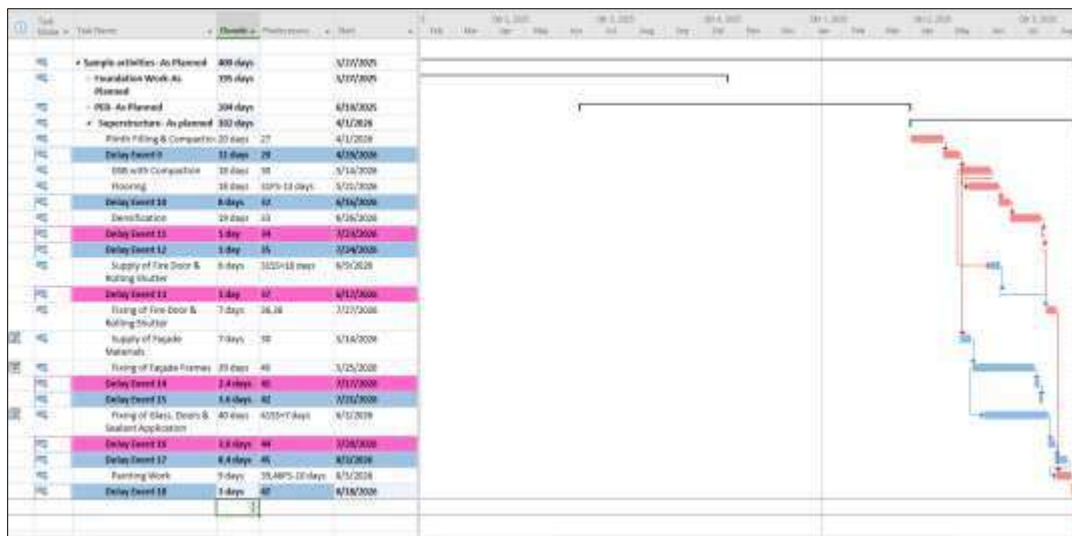
Figure 19: Delay Event 14&15 have no Impact on the Schedule

Source: Created by authors

Figure 20: Delay Event 16&17 have no Impact on the Schedule

Source: Created by authors

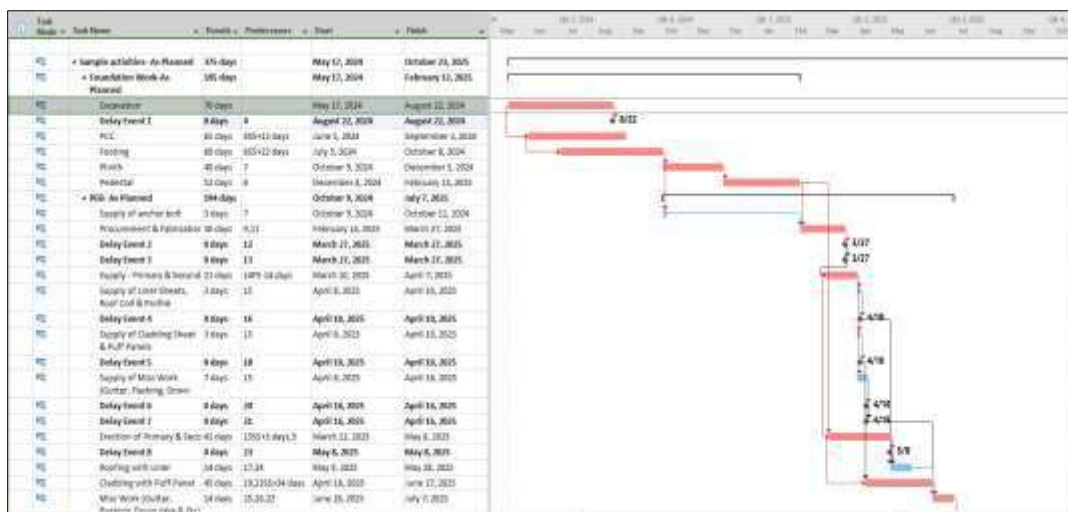
Figure 21: Delay Event 18 Impact the Schedule by 3 Days



Source: Created by authors

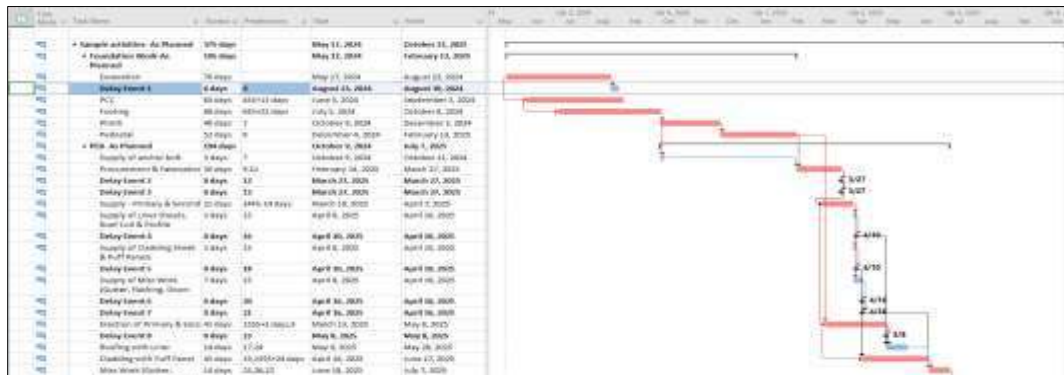
9.5 Appendix E: Window analysis (MSP data chart)

Figure 22: Window 1: 17 May, 24 - 1 Aug, 24
There are no Delay Events in this Window



Source: Created by authors

Figure 23: Window 2: 2 Aug, 24 - 15 Oct, 24 – Delay Event 1 has no Effect on the Completion Date



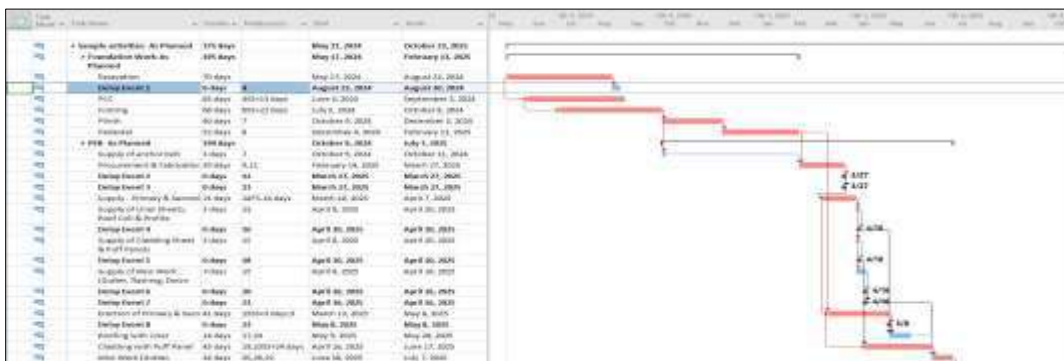
Source: Created by authors

Figure 24: Window 3: 16 Oct, 24-31 Dec, 24-There are no Delay events in this Window



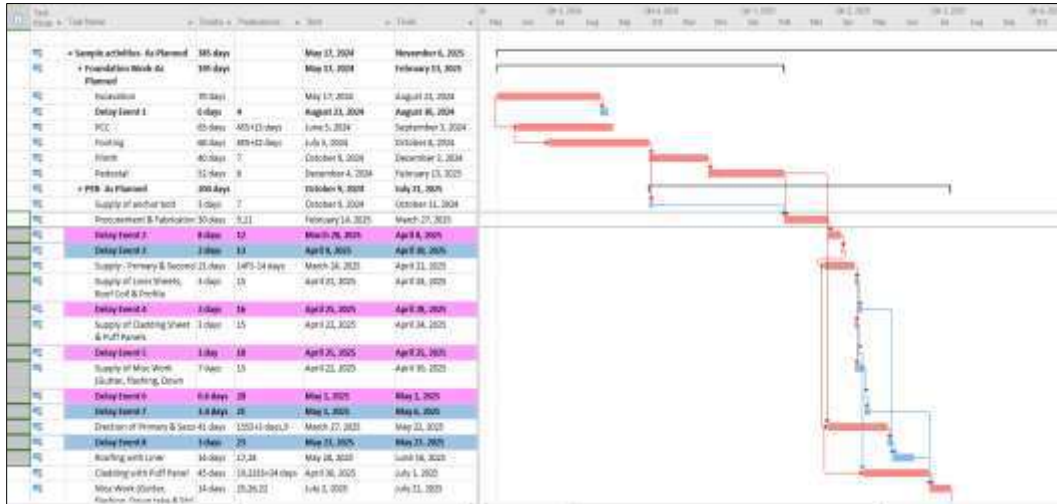
Source: Created by authors

Figure 25: Window 4: 1 Jan, 25-15 Mar, 25-There are no Delay Events in this Window



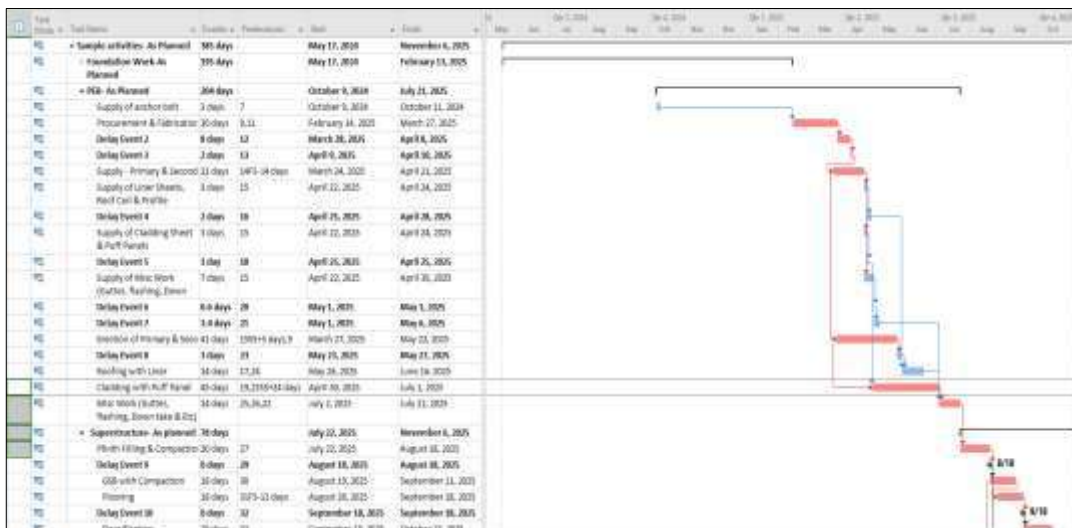
Source: Created by authors

Figure 26: Window 5: 16 Mar, 25-31 May, 25 – Delay Events 2,3,4,5,6,7 and 8 Occur in this Window and the Impact the Project with a Delay of 10 Days



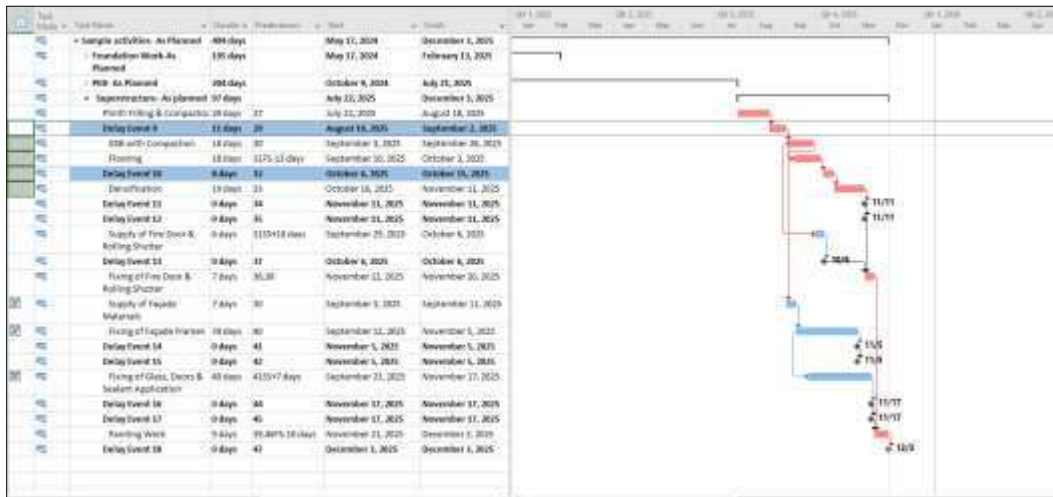
Source: Created by authors

Figure 27: Window 6: 1 Jun, 25-15 Aug, 25 – Zero delay Occurrence in this Window



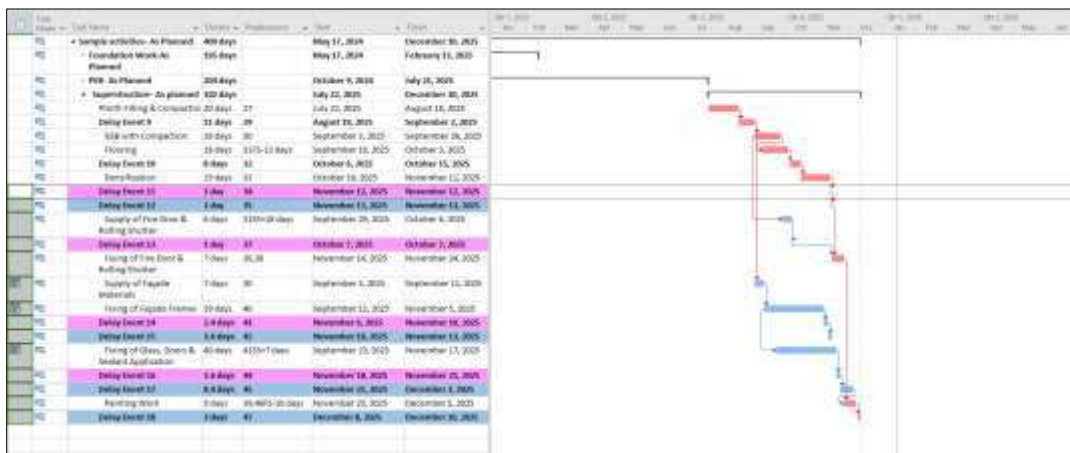
Source: Created by authors

Figure 28: Window 7: 16 Aug, 25-31 Oct, 25 – Delay Events 9 and 10 Occur in this Window, and the Impact the Project Completion Days the Most; by 19 Days



Source: Created by authors

Figure 29: Window 8: 1 Nov, 25-10 Dec, 25 – Delay Events 11,12,13,14,15,16,17 & 18 lie in this Window. But Despite Many Delay Events Occurring, the Overall Impact on the Project Completion is of 5 Days Only



Source: Created by authors

CHAPTER 2

Does Sentiment and Behavioural Biases Shape Equity Decisions? An Investigation in India

Shivika Saxena, Sarah Fatima Sheikh** and Swati Kashinath Patekar****

ABSTRACT

This study examines the extent to which investor sentiment and behavioural biases influence equity investment decisions in India. While rational frameworks such as the Efficient Market Hypothesis (EMH) and Modern Portfolio Theory (MPT) assume logical decision-making, real-world practices reveal significant deviations. Key behavioural patterns such as herd mentality, overconfidence, loss aversion, recency bias, and confirmation bias are investigated. Data is drawn exclusively from secondary sources, including market sentiment indices, financial reports, and news headlines. Quantitative sentiment analysis will map emotional trends against actual equity choices, including Systematic Investment Plan (SIP) participation and stock selection. To structure the research approach, the TCCM (Theory–Context–Characteristics–Methodology) framework will be presented and modified to align with the study’s specific focus on behavioural finance in the Indian context. The study contributes to financial literacy by helping individuals recognize cognitive distortions and adopt strategies that promote rational, disciplined, and informed investment decisions.

Keywords: Behavioural Finance, Investor Sentiment, Equity Investments, India.

1.0 Introduction

The classical theory of finance presupposes that investors are rational and that they process information in an objective manner in order to maximize utility. Efficient Market Hypothesis (Fama, 1970), the Modern Portfolio Theory (Markowitz, 1952) and others are models that assume that markets are effective at incorporating all the information in them to diversify by means of optimal risk-return.

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Nevertheless, empirical deviations such as bubbles, volatility and abnormal trading undermine this rationality leading to the development of behavioural finance which sees the application of psychology to explain investor decision in conditions of uncertainty (Barberis and Thaler, 2003). As the equity market of India is fast growing, retail investors are becoming highly dependent on sentiment based biased decisions in the face of easy access to information particularly among the youthful investors in the age group of 22-30, which is high growth segment.

1.1 Rationale of the study

The investments made in India by retail have been on the rise, with the inflows of mutual funds SIP amounting to over 20,000 crore each month (AMFI, 2024). Although this helps to create long-term capitals, most investors often rebalance portfolios, prematurely cancel SIPs and trade on sentiment, which has a detrimental impact on returns. Social media and digital trading increase the speed of the spread of information, noise, herd behaviour, and FOMO and exacerbate behavioural biases. In spite of its topicality, there is a lack of empirical studies of Indian socio-economic and cultural backgrounds. Since India is a country of demographics, financial literacy and risk culture, it is critical that it should be analyzed contextually. This paper employs sentiment-based behavioural finance to establish systematic patterns, which are used in educating the investor, advising, policymaking, and financial products that match the behaviour of the user.

1.2 Problem statement

Indian retail equity investors often do not act rationally in regard to investment behaviour despite the improved accessibility to financial information, analysis tools and professional advice. Herding, overconfidence, loss aversion, recency bias, and confirmation bias are psychological biases that play a major role in investment decisions, which usually lead to inappropriate results, such as overtrading, poor time to trade in the market, holding on to a loss, and poor performance of a portfolio.

In addition, no formal, data-based constructs exist to objectively quantify the investor sentiment and bias in behaviours in the Indian equity market. This restricts the potential of investors, advisors and institutions to integrate behavioural knowledge into evidence-based portfolio building and risk management decisions.

This study seeks to answer the following questions:

- What are the main ways that thinking errors affect how individual investors in India make choices about stock investments?
- How does what people read, hear, and feel about the market change when they invest and what stocks they pick?

- Do things like age, job, income, and culture change how thinking errors show up or how much they matter?
- Can we use numbers and models to understand how investors usually act, and can this understanding assist us in making better financial plans and tools?

2.0 Methodology of the Literature Review

2.1 Purpose and approach

This review aims to examine how sentiment and biases influence investment decisions in the Indian stock market. We are not just going to summarize what has already been done. Instead, we want to link different ideas together. We will demonstrate how these ideas have evolved, where they align, and what questions remain unanswered. We have used a qualitative approach, looking for common themes, similar to how grounded theory is used in social science. The point is to understand patterns of thought from different sources, like research papers and reports published from 2014 to 2025, rather than to measure things. We have chosen studies based on three main points:

- How ideas about behavioural finance have grown and been used in India.
- Which biases have the biggest impact on Indian investors.
- What an overall investor sentiment, whether positive or negative, affects what happens in the market and how people invest.

2.2 Source identification and selection

To ensure a detailed and reliable study, the review included scholarly articles, working papers, and reports from 2014 to 2025. Key databases like ScienceDirect, Emerald Insight, JSTOR, ResearchGate, and Google Scholar were searched using keywords and Boolean operators. The search terms included:

- “Behavioural finance AND India”
- “Investor sentiment AND stock market India”
- “Behavioural biases AND equity investment”
- “SIP behaviour AND risk perception”
- “Herding bias OR overconfidence OR loss aversion India”

2.3 Method of Analysis

The review organized the findings into five major themes using interpretative analysis and thematic coding:

1. Behavioral Finance’s Development in India
2. Market Behavior and Investor Sentiment

3. Biases in Behavior Improving Investment Choices
4. Sentiment algorithms and digitalization
5. Institutional Leveraging and Debiasing Techniques.

Each subject incorporates direct quotations to strengthen the integrity of the writers' voices throughout the grouping while synthesising empirical information. To understand investor behavior, quantitative approaches like Principal Component Analysis (PCA), Structural Equation Model (SEM), and GARCH volatility models were interpreted qualitatively.

2.4 Maintaining credibility

Cross-verifying results from other studies increased the validity of insights. For instance, Yadav and Chakraborty (2022) and Sardar and Khan (2024) independently verified the sentiment indices' ability to predict NIFTY returns, and Dave and Vaid (2025) and Gabhane et al. (2023) identified similar behavioural patterns among Indian investors, such as herding and overconfidence.

When appropriate, actual quotes are used in this chapter to maintain authenticity. For example, "overconfidence and loss aversion jointly explain more than 60% of poor trading timing among retail investors," according to Dave and Vaid (2025). In a similar vein, Gupta and Goswami (2024) observed that "social media and peer influence dominate analytical reasoning in equity investment choices among young investors." These quotes shed light on the real-life experiences that underlie statistics.

2.5 Moral aspects

Using APA 7th edition referencing, all concepts, quotes, and data have been correctly acknowledged to their original authors. This review adheres to academic integrity and transparency by not reproducing any data without attribution.

3.0 Thematic Literature Review

3.1 Behavioural finance's development in the Indian setting

The constant interventions in the market caused academics and practitioners to start doubting these rational assumptions. The Harshad Mehta scam 1992 was an investment swindle just as much as it was an eye-opener that the elements of trust, media hype and blind optimism could get their way with rationality. In a similar manner, the Global Financial Crisis of 2008 caught the Indian investors unawares when they thought that India had not been hit by the shocks of the rest of the world due to high economic growth. The raw psychology of investors panic selling became more familiar to people because of more recent events like the

COVID-19 crash of 2020. These have led to the emergence of the belief that markets are operating more by emotion than they do by economic data.

This action can be summarized in what Robert Shiller terms as “irrational exuberance” (2000), whereby the collective optimism drives the prices of securities too high in areas that they are not worth. This irrationality tends to boil over in Indian markets when there is a bull run, or a boom in the issue of a new stock, or a sector rally, and it is being fuelled by the financial media and social media. Investors tend to run with the pack instead of doing a logical analysis of risks involved. This fact was also supported by Prosad (2014) who stated that overconfidence and herding behaviour continue to dominate the price changes in Indian equities, as a result of the social aspect of Indian investment.

As behavioural finance developed, Indian scholars started moving away towards the application of Western theories and instead focus on contextualizing the Indian investor behaviour in the context of Indian socio- economic conditions. In India, few monetary choices are made without consulting family members, peers, cultural risk aversion, and financial enlightenment. Sharma and Firoz (2020) established and clarified that the biases of herding, optimism, and disposition effect are involved in various stages of investment decision making. A behavioural analysis of 400 retail investors revealed that even seasoned investors tend to employ illogical behaviour when the markets become turbulent as experience and awareness are overwhelmed by emotion. The recent research supports this idea. Gabhane et al. (2023) have discovered that portfolio decisions are influenced by overconfidence, anchoring, and loss aversion. Most investors hold on to declining stocks, anchor on previous prices or over rate predictive ability thus experiencing poor results.

Behavioral finance has become a widely used paradigm of thinking about Indian markets, as it does not recognize investors as rational actors but as human beings who cope with uncertainty, hope, fear, and ambition.

3.2 Investor sentiment and market behaviour

Investor sentiment is the general attitude or mood of investors in finance. This emotional appeal that is either negative or positive can push the market regardless of economic indicators. It is a manifestation of the combination of feelings, opinions and expectations that influence the perception of the information and reaction of the investors to the market changes. Investors often remain very optimistic thus purchasing more, which increases the prices. The increasing prices support optimism and it becomes a self-generating cycle. On the other hand, pessimism may cause massive sell-offs causing sharp price movements and swings on the market.

A study conducted by Baker and Wurgler (2006) established that investor sentiment greatly affects the stock market activity. Their research revealed that sentiment is a good

predictor of stock returns especially in smaller, risky, non-dividend-paying companies that are hard to value on the basis of conventional financial metrics. Such a conclusion is particularly topical in terms of such markets as India, where there is a high level of information dispensability and speculative transactions.

Building on the previous article, Yadav and Chakraborty (2022) created an Indian investor sentiment index that is based on seven market indicators and ten years of information. Their findings revealed that the short-term trend in NIFTY returns is attributed to a significant extent to sentiment, meaning the fluctuations in stock price are usually influenced by sentiment change, as opposed to by economic fundamentals.

In their study with the help of Vector Autoregression (VAR) and Granger causality models, Sardar and Khan (2024) discovered that the sentiment of the investors Granger-cause the returns in India, which implies that investor sentiment can predict the future changes in prices. Haritha and Rishad (2020) also demonstrated that sentiment as a predictor makes the market volatile hence the noise-trader hypothesis.

Online platforms and social media are creating herding based on sentiment particularly on the part of young online traders in India. Comprehensively, empirical studies affirm that the investor sentiment is decisive in determining prices, the trading volume and volatility in the Indian stock market.

3.3 Behavioural biases influencing investment decisions in India

The Indian stock market is a unique behavioural environment where the decision of the investors is influenced not only by the data but also by the psychological preconceptions. Among them the most notable are overconfidence, herding, anchoring, loss aversion, and confirmation bias.

Belief in a greater predictive power is a major contributor to the trading behavior in India, and the term is referred to as overconfidence. *Dave and Vaid (2025)* discovered that overconfidence and loss aversion jointly contribute to more than 60 percent of overtrading, under-diversification, and overtrading risk tolerance. Likewise, *Rizwana and Zaidi (2024)* also noted that the frequent use of the app and real-time notification increases overconfidence and representativeness bias to provide an illusion of ability that drives speculative trading and consumes returns through transaction costs.

The loss aversion also affects investor behavior, and people do not want to incur losses. *Kahneman and Tversky (1979)* demonstrated that more intensity of losses is experienced than equal gains. On the Indian scenario, *Gautam, Raman, and Kumar (2021)* observed that investors tend to hold the loss-making stocks in hope of rebound, which strengthens the disposition effect and leads to poor performance of their portfolio.

The other common pattern is Herding behaviour, *Sharma and Firoz (2020)* noted how it affects the security selection, and *Prosad (2014)* affirmed its presence both in the bull and bear markets. This trend has been enhanced by digital platforms and social media. *Chauhan and Patel (2024)* and *Chavhan and Waiker (2025)* discovered that risk-taking is taken up by the media discourse and group feeling, and it is frequently subject to independent fundamentals.

Decision making is also distorted by anchoring and confirmation bias. *Khaleel and Dhakshayani (2024)* found out that investors anchored to the previous prices and selectively process information. These trends indicate that the Indian investors are boundedly rational and behave within the predictable psychological boundaries, which aligns with the systematic irrationality theory by *Thaler (2016)*.

3.4 Digitalisation, retail participation, and sentiment amplification

Indian financial markets have experienced a significant revolution within the last ten years through technology which has made the investment process easier and more convenient to millions of people who can only have a mobile phone and internet access. More than 60 million new demat accounts were registered between 2020 and 2025 alone to make India one of the most rapidly expanding retail investor markets in the world (NSE, 2025).

This fast financialization has enabled the young professionals, students, first time earners and investors in smaller towns. Technological ease has however increased behavioural biases too. The aspect of making emotional decisions has gained more ground in place of analytical reasoning as investing turns out to be faster and more convenient. According to *Gupta and Goswami (2024)*, urban investors tend to place more importance on emotion, peer pressure, and a feeling of missing out (FOMO) rather than financial literacy, and social validation and viral stories can become more important than fundamental in stock selection.

This behaviour has been strengthened by gamification which involves price alerts, rewards, and visual progress indicators, which are available in the online trading platforms and which have erased the distinction between investing and entertainment. Media reporting also serves to boost the frenzy in the market, establishing feedback processes where escalating prices contribute to optimism which then leads to further price hikes, but followed by periods of excessive corrections during crunch periods.

Studies also point at geographical and demographical differences. *Kumar and Jha (2024)* discovered that overconfidence was more eminent in some areas whereas herding was the dominant characteristic in the urban places. The younger investors react more to short-term news compared to the older participants (*Rizwana and Zaidi, 2024*). All in all,

digitalization did not wipe off bias but only exacerbated it, so emotion by the investor became a major factor in influencing market activity in India.

3.5 Institutional interventions and debiasing strategies

Behavioural biases are not unique to naïve investors but are the normal working of human processes. Fear, overconfidence, regret, and the desire to be socially validated influence people no matter how experienced and sophisticated they are. However, it is not realistic of expecting investors to be all-rational in circumstances of uncertainty and the flow of information. Consequently, behavioural finance has moved to the behaviour of correcting biases to systems that can aid in making better decisions despite their existence.

One of the most valuable contributions in this field is Nudge Theory by Thaler and Sunstein (2008) that suggests that people need to be steered towards making a better choice but free will at the same time should be preserved. Instead of unwilling the rationality, investment settings can be arranged in a way that detersives the impulsive behaviour and can promote the longer-term thinking.

Francis (2023) underlined the checklist reviewing, rules-based rebalancing, and educating the investors as the methods to curb the emotional behavior. These strategies bring some order in the decision-making process without seeking to transform investor personalities. Also, Gotte (2023) discovered that the emotional reactions of mutual fund investors following a Systematic Investment Plan (SIPs) are more stable, since automation decreases the sensitivity to shifts in the market. Automation in such instances is an emotional controller. Increasing focus is also on institutional support. Rao and Tandan (2025) provided the support of behavioural financial education and social sentiment dashboard to warn investors in times of undue fear or excessive euphoria. Chavhan and Waiker (2025) advocated real-time sentiment analysis to be used in detecting bubbles or panic early.

Although this is an important initiative by SEBI (2024) in financial literacy, their coverage is still smaller than emotional stories on social media. Regulators, fintech platforms, educators, and intermediaries should hence work together in debiasing. It is necessary to not only be aware of these things but have structural and technological nudges in place to translate knowledge into action.

4.0 Insights and Synthesis of Literature

The literature synthesis based on the identified themes can be interpreted as the same and repeating tendencies of Indian investor behaviour. All in all, the studies have shown that the trends in the Indian equity market are not influenced by economic fundamentals, and firm specific information alone, but also due to psychological factors like sentiment, perception, and social imitation.

First, investor sentiment turns out to be a strong short-run force of the market. Empirical research indicates that the variation in the mood of investors is a major predictor of short-term returns and stock volatility. Yadav and Chakraborty (2022) illustrate that sentiment indices are a good explanation of NIFTY returns especially when sentiment is strong. Equally, Sardar and Khan (2024) determine that market returns are Granger caused by investor sentiment, which implies that emotional impetuses are usually the antecedents of price changes. All these findings have a cumulative negative impact on the assumption of complete informational efficiency in Indian markets.

Second, behavioural biases are more likely to cluster up and support each other as opposed to acting independently. Loss aversion, herding and overconfidence often interact in a way that gives rise to cycles of emotional decision-making. Investor fear of loss combined with their overestimation of their predictive capabilities and the tendency to engage in crowd behaviour are a key point in studies by Gautam et al. (2021) and Sharma and Firoz (2020), which shows that investors act poorly due to incorrect timing, poor diversification, and poor responsiveness to market signals.

Third, digitalisation has enhanced behavioural biases instead of eradicating it. In as much as technology has minimized transaction costs and created access, it has also enhanced emotive-driven trading. This study by Rizwana and Zaidi (2024) and Chauhan and Patel (2024) confirms that mobile trading applications, real-time alerts, and social media spur more overtrading, speculation, and the feeling of missing out, among digitally-active retail investors.

Fourth, the investor behaviour is influenced by socio-demographic differences. According to Kumar and Jha (2024), urban investors tend to be overconfident and have a higher trading frequency than rural and semi-urban investors, and the latter are more loss-averse and socially impacted. Age, location, digital exposure and financial literacy have major influence on decision making in situations of uncertainty.

Lastly, the literature proposes that successful debiasing should involve education together with behavioural design. Research by Francis (2023) and Gote (2023) demonstrates that disciplined investing is promoted by behavioural nudges, automatic investment strategies like SIPs, and rule-based rebalancing. In general, the Indian equity market does not come out as a system that is entirely rational, but a system where optimism and anxiety can be seen as interacting constantly.

5.0 Conclusion

Although there has been an advancement in the study of behavioural finance in India, there are a number of gaps that can encourage this research. To begin with, not many studies

have been done to study both of these together to see how individual psychology influences market behavior; most research has either studied individual biases, through surveys (e.g., regression, SEM), or studied market-level sentiment, through time-series (PCA, VAR, GARCH). Second, little is known about young investors (22-30 years) and their utilization of online platforms, social media, and real-time information. Third, biases are not adequately investigated in terms of regional and cultural effects, which restricts the possibility of generalization. Fourth, sentiment and behavioural measures with portfolio performance AI-ready datasets are not available. Lastly, there is still a limited practical use of behavioural insights. This research will fill these gaps by incorporating investor sentiment and behavioural biases to young Investors in India, who are retailers.

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CHAPTER 3

Strategic Responses of Real Estate Developers to Economic Crises

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ABSTRACT

The real estate sector is one of the foundational pillars of the India's economy, encompassing residential, commercial, industrial, and infrastructure development. It plays a vital role in the economic development of nations, acting as both a driver of growth and a barometer for economic stability. Economic crises—whether global or regional—often lead to declining property demand, reduced investor confidence, tighter credit conditions, and increased uncertainty, all of which pose significant challenges to real estate developers. This study, “Strategic Responses of Real Estate Developers to Economic Crises,” examines how leading Indian developers have responded to such challenges. It focuses on the various strategies used by different developers during the COVID-19 pandemic. Through a thorough review of existing literature and a comparative analysis of two major firms—DLF Ltd. and Mahindra Lifespaces—this research identifies various key aspects of resilience such as: financial prudence, operational flexibility, digital transformation, market diversification, and human-resource management, etc. The findings show that developers with strong balance sheets, a proactive mindset towards digital adoption, and adaptable business models were able to recover more quickly and even spot new opportunities during the downturn and suggests a comprehensive framework for strategic responsiveness.

Keywords: Strategic responses, Real estate developers, Economic crises.

1.0 Introduction

Real estate is a critical driver of economic growth as well as a barometer of economic health for any economy.

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It is closely linked to urban development, building and construction, and provides local and overseas investments opportunities in an economy. It has backward and forward linkages with nearly 250 industries including steel, cement, bricks, paint, and labour-intensive service activities. The real estate business is, however, highly cyclical with the overall economy, and for example, during a financial crisis, may see a dramatic drop in demand and investment, less availability of credit, and more overall uncertainty and risk. All of this further complicate real estate.

1.1 Background study

Since India's independence in 1947, successive economic crises have led to a collection of reforms on economic policy which have affected the real estate sector. These include two Balance of Payments Crises in 1957-58, The 1966 devaluation and increasing dependence on foreign aid limited infrastructure and housing spending. The 1970's Oil Shocks increased import prices for India, resulting in inflation and higher prices for raw materials and construction. Following the Economic Crisis of 1991, sweeping liberalization reforms opened up the real-estate market for foreign investors.

The Global Financial Crisis (2008) reduced capital flows. Weak demand for exports was seen. Liquidity pressure on developers increased. Many developers were pushed to affordable housing. Demonetization (2016) affected cash-driven housing deals. Digital transactions and formal funding were the developers' priority. The COVID-19 Pandemic (2020) was the worst contraction in GDP. The labour supply drop and disruptions to the supply chain made digital selling channels, flexible payment plans and financial and operational restructuring the focus. An inflationary environment in the post-pandemic period as well as the conflict in Ukraine (2022-2023) required a general cost optimization and re-scheduling of projects.

1.2 Importance of real estate in economic cycles

The real estate cycle directly mirrors the economy and typically follows the business cycle. During times of economic prosperity, income and credit are more and consumer confidence is high. However, during recessionary periods, financial and employment insecurity along with decreased buyer discretion leads to decreased transactions and capital expenditures.

However, the 2008 Global Financial Crisis and COVID-19 pandemic have put the sector under stress. During the Global Financial Crisis, the Indian real estate market saw a credit squeeze, cancellations of projects and demand subdued because of the global credit crunch. On the contrary, during COVID-19, construction was halted abruptly, reverse labor migration, raw material shortages and changes in product preferences were observed.

The real estate sector is also a key part of post-crisis recovery, with governments using the industry to create jobs, build infrastructure and revive the economy through public-private partnerships and regeneration.

2.0 Literature Review

2.1 Definitions

Economic crises: According to Cazan and Cucos (2012), an economic crisis is defined as a period marked by intense difficulties and disruptions that force change within a system. Within economic terms, crises are generally associated with instability, conflict, and structural adjustment, each is typified by some levels of economic slackness, inflation, and failure of the system.

Strategic Response: According to Kozachenko, Anand, and Shirokova (2021), strategic response refers to a set of decisions and actions that delineate the plans of a particular organization in reaction to a challenging situation in the environment, the main concern of which is how to achieve the objectives of the firm in question and stay profitable. These are situational measures taken by firms to leverage or mitigate environmental conditions that may threaten their survival, operations, or reputation.

2.2 Thematic study

2.2.1 Crisis management frameworks

Research shows that individual firms can adopt long-term calculated resilience responses to their sustainment and future preparedness, including PESTEL analysis, business model innovation, corporate restructuring, and scenario planning (calculated forecasting). Such firm-level responses include retrenchment, perseverance, innovation, exit, M&A, divestitures, vertical integration, and alliances.

In the literature, agility, adaptability, and technological integration have been considered critical for enabling business survival during crises. Construction companies handle crises in a few different ways. Sometimes they try to sidestep the problem, sometimes they jump in and fix it, and other times they get ahead of it or just react as if things unfold. They also work closely with others when needed. Early warning systems, dedicated crisis teams, and plans that can change on the fly are all parts of the strategy. When things get tough, firms might cut budgets, shuffle project priorities, rethink risks, break big jobs into smaller pieces, or narrow the project's focus. Once the situation subsides, they also strive to get their people fired up once more, restore confidence with all parties, and make learnings in order to be prepared to face whatever it might be next.

2.2.2 Operational adaptations

Construction companies do not simply become paralysed when things get rough. They trim the fat, tighten their belt and work at home even at the expense of fewer hours or a reduced paycheck, and find out where the waste slips out the seals. Outsourcing helps. And so does letting a greater number make decisions.

However, cost reduction cannot lend itself. It does matter that professional employees are hired and that new virtual tools are adjusted. The smart ones stay nimble. They massage their profit goals, find niche markets and substitute materials as a way of ensuring that jobs keep flowing. Take the UK during COVID-19. Niazi and Painting (2021) observed that the pandemic disorganized everything: supply chains disrupted, shortage among workers, and health problems slowed down the projects. Companies tried. They experimented with digital, put more emphasis on the project schedules and provided people with more flexibility. The scenario planning became the norm. The authors provide a push to the urgency of being agile, speaking honestly, and drawing the entire crew consisting of clients, teams, suppliers, etc., together in times of chaos.

2.2.3 Financial and market strategies

Scholars who examined the Indian construction industry have identified some of the issues that actually strike hard during a downturn. Business organizations are seeking new customers, dealing with surging material prices, and caught in a downturn of the money companies intend to spend. There were also demonetization and the lack of skilled workers which complicated things.

However, those companies which actually dealt with the situation, i.e., identified the risks in time, kept the costs under control, and adjusted to the market, dealt with the storm better than the rest. In the case of the Public-Private Partnerships, research indicates that the industry is derailed by a group of problems: the difficulty in accessing credit, the increased cost of funds to finance business, lengthy renegotiations, and delays and delays. Those players that survive do not simply ride the wave, they transfer risks, seek superior funding, depend on government guarantees, and count on more aggressive government control.

The construction firms have been forced to be creative with the prices of the material and the rise in inflation. They placed emphasis on intelligent buying, customized the long-term agreements with the suppliers and they apply digital platforms to anticipate the future. Their strategies are to improvise their designs in order to save money, to be prepared with a backup plan and to make decisions at the spur of the moment. Most importantly, collaboration, continued communication, and flexibility of the finances all contribute to the survival of these firms in an aggressive market.

2.2.4 Digital transformation and innovation

Crises provide the business with reality check. One day old methods are no longer applicable and therefore firms have to make up- improvising-sometimes within a short time. The most intelligent ones use their energy to train the employees, implement new services, and plunge into digital tools and green technology.

In this story, construction plays a major role. This is not an industry that is simply a passenger in the ride, it can actually contribute to the economy to recover. The tactics involve befriending with the public sector, initiative towards improved infrastructure and best effort in smart policies. Rather than relying on the hope of improvement, the construction companies can look at the hard times as a time of generating ideas of new ideas and be prepared to meet the future market conditions.

In the event you consider innovation sustainably, the evidence is tough to overlook. Green buildings and modular buildings make companies better and more resilient--that is all. It is no longer an option to digitalize things and ensure that business remains sustainable when all other operations are at stake. Sustainability-oriented companies emerged with fewer casualties during the COVID-19. Such technologies as modularity and 3D printing imply that you require fewer laborers and that they finish the projects faster. And speaking of which, new safety habits, digital communication tools and remote monitoring all become a daily grind.

2.2.5 Policy and regulatory context

Whenever you plunge into affordable housing, you are faced with the same fact, you must join forces with the government in case you want to cushion the risks of investing. The combination of market-rate with subsidized units will allow the developers to make a profit and achieve their social goals. And even when they construct houses people are willing to occupy, houses they can get to without a headache, those units are not vacant. More flexible zoning and faster approvals are continued to be requested by developers. They are also becoming imaginative: rent to own, shared equity, and even the inclusion of informal income as the basis upon which only pay stubs are counted. This is all beneficial in making more people purchase a home.

The real challenge? Staying on your toes. Policies, money and rules can turn over easily- particularly during a crisis. The RERA Act has revolutionized the game. Less fighting, more clarity. By observing the rules, the developers will avoid legal tangles and begin gaining the confidence of buyers. However, not every state is of the same mind. Some get it, some lag behind. Studies point out that a good supervision is necessary- identify risks in catches early and follow-up on a project all the way through and ensure that what you are doing, is what people want.

2.3 Case study for secondary literature

2.3.1 Mahindra Lifespaces developers

Mahindra Lifespaces did not speak theoretically about digital transformation but put it into practice. They introduced online reservations, deployed virtual reality tours and provided buyers with those convenient customer portals that everybody demands now. They became serious as soon as construction resumed. Health examinations became stricter, mobile health clinics appeared, and they recalled employees one by one.

The company also tilted towards ready-to-move-in houses, which actually accelerated the sales and made them safer. Mahindra was a smart player in terms of money. They were highly picky in terms of land purchases, were literally holding cash in reserve, and were able to loan out to make ends meet. However, they targeted the mid-income and affordable housing as they understood that the buyers are consistent even during difficult periods.

2.3.2 DLF Ltd

DLF threw much against the wall to see what would stick. They plunged into the virtual world of exhibitions, e-papers, electronic payments, the entire package. On their commercial areas, they would prefer the tenants to remain, and thus they offered tenants rent freebies and relieved lease conditions.

On the residential front, DLF ceased to introduce new projects, but addressed those that they had initiated. They sold their surplus assets and temporarily ceased land purchases in order to reduce their debt. And even as all this was a-doing, they were coercing vendors to give them better rates and even change to energy-efficient construction, in the hope of saving money in the long run.

During the COVID-19, real estate developers threw down the gauntlet, yet it was possible to observe some of the key trends amid the chaos, remaining financially sound, maintaining flexibility of operations, going more into technology, finding new markets, and collaborating where it made the most sense. Digital transformation was truly impressive- it managed to keep the sales flowing, enabled people to remain connected with the customers and it made it possible to work remotely when things proved to be too difficult. All the developers were playing various financial games.

Others redoubled and acquired assets and grew rapidly, and others scaled back, debted themselves, and piled money. It was all based on their leverage, cash holdings and direction they took in the marketplace. All these playbooks demonstrate the flexibility of the sector. Businesses would make decisions depending on their ability, capacity to address risk as well as where they would want to be in the long-term.

3.0 Research Methodology

3.1 Research design

This study examines the strategic responses of DLF Ltd. and Mahindra Lifespaces to the economic challenges caused by COVID-19 using a comparative case study approach. It combines qualitative analysis of strategic decisions with quantitative evaluation of financial performance to provide a comprehensive understanding of crisis management in the real estate sector. This approach is suitable as it enables a comprehensive analysis of the various ways and underlying reasons why different companies reacted differently to the same crisis.

3.2 Case selection

The purposeful sampling was due to five criteria: both of them are well-established leaders in the market, are both contrasting strategies (DLF is diversified, and Mahindra is focused), have extensive information available publicly, have been functioning continuously within the COVID-19 pandemic, and are very different in terms of scope, geographic location, and strategies used, which allows conducting a comprehensive comparative analysis of both.

3.3 Data collection

The study relies exclusively on the secondary sources of data. The primary sources will be audited annual reports (FY 2018-19 to FY 2021-22) comprising financial statements and management commentary, quarterly reports to investors which include operations updates, and regulatory filings that will be submitted to the stock exchanges. The secondary sources involve industry reports by Knight Frank, and JLL; media reports and press releases; and academic literature, in regard to crisis management. The quantitative approach to the evaluation was provided by the detailed financial data of different real estate companies.

3.4 Time framework

The research design is longitudinal, which includes 2018-2022. It comes in three phases, including the pre-crisis period, 2018-2019 to position the base, the crisis period, 2020-2021, to take advantage of immediate responses, and the recovery period, 2021-2022, to evaluate long-term strategic adjustments. This period of five years is the difference between a crisis response which is reactive and a strategic growth.

3.5 Analysis framework

The analysis reviews strategic responses on twelve major dimensions of financial management and liquidity, digital transformation, operational efficiency, product and market

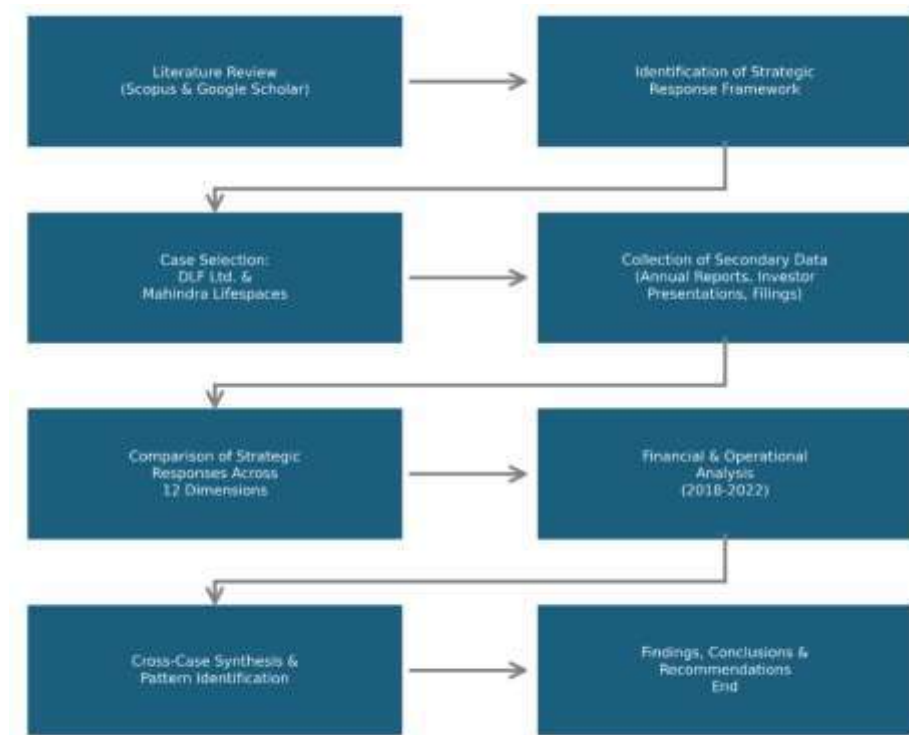
adaptation, geographic strategy, business model, sustainability initiatives, customer engagement, partnership strategies, rental portfolio management, innovation in offerings, and human resource management.

The within-case analysis involved the analysis of the companies separately to identify the specific strategic path of the company. Systematic cross-case comparison categorized responses systematically on all twelve dimensions. The debt-to-equity, the return on equity, the operating margins, and the percentage growth of revenues were determined in the financial ratio analysis. Management statement thematic content analysis determined strategic priorities and crisis narratives. To know causality, timeline mapping was followed to keep track of the order of important decisions.

3.6 Limitations

The main limitations are that it is based on publicly available information that may lack any confidential deliberation, post hoc analysis in management reporting is prone to rationalization bias, and it can only be generalized to these two particular situations, and there is a temporal distance between the annual reporting periods.

Figure 1: Flowchart Representation of Methodology



Source: Created by authors

4.0 Case Analysis

The COVID-19 pandemic revealed inherent disparities in the manner in which the Indian real estate developers managed the economic disruption that no one had ever witnessed before. This comparative study of the two companies, DLF Ltd. and Mahindra Lifespaces, shows two different though effective strategies of crisis management the DLF diversification buffer strategy and the Mahindra focused agility strategy. These opposing strategies can provide useful knowledge on the crisis resilience mechanisms in the real estate industry.

4.1 Pre-crisis foundations and strategic positioning

The pre-COVID (FY18-FY20) showed that the companies had stark structural differences. DLF was at 10-15 times greater size with 8,364-6,707 crore revenues compared to 566-611 crore of Mahindra. The transformational GIC transaction of DLF in 2017 when it sold 33.34 percent of its rental business. The company (DCCDL) generated 12,000 crore and essentially transformed its balance sheet and gross debt has been cut down to 17,491 crores in comparison to 29,200 crores with a stable stream of rental incomes averaging over 3000 crore per year. On the other hand, Mahindra has been a very timid leverage player. Their debt between FY18 and FY19 decreased by 50 percent and dropped to 228 crores as opposed to 459 crores. Their debt-to-equity ratio was also kept at less than 0.3. Nevertheless, the margin of EBITDA decreased to a level of -13% by FY 20. This decrease demonstrated a state of stress in operations even prior to the pandemic.

4.2 Financial resilience: Dual revenue streams vs. Capital efficiency

The mixed-income structure of revenues, which is a combination of residential sales and commercial lease rentals, turned out to be decisive in the case of crisis in DLF. DCCDL and company have been able to gather 95 and 98 percent of office rents during the lockdowns respectively, which is essential to maintain critical working capital stability. As part of its efforts to decrease its gross debt, DLF minimized that to 6,886 crores in FY21 and to 4,182 crores in FY22, or 76 percent of what it was in FY18. Mahindra had suffered devastating 72.8 percent revenue (₹611 crore to 166 crores in FY21) -the worst contraction in the sector. The response of the company resulted in extremely high-cost optimization which was wholly based on internal cash flows but not outside borrowing. With the implicit support of the Mahindra Group, Mahindra has managed to stay on top of its credit rating at CRISIL AA/Stable despite the operations difficulties during the crisis.

4.3 Product and market adaptation strategies

Mahindra has already taken the initiative to change its orientation to affordable and middle-income housing by redesigning the layouts to provide separate home offices and

larger spaces so that the demand for more people to work at home is satisfied. This narrow strategy reacted appropriately to the changes in the pandemic lifestyle, but introduced a risk of concentration, placing the fortunes wholly on the recovery curve of a single market segment. DLF maintained an even product portfolio which comprised of both ready-to-move and under-construction properties at various price points, whether low or high-end. They possessed commercial and retail property as well. This diversification served as a buffer against declines in certain lines and also served as a means of drawing in a new breed of customers, including investors, high-net worth customers and end-users.

4.4 Digital transformation and technological sophistication

Mahindra introduced digital booking portals, virtual site tours that used VR, and calculators of affordability. These tools make the onboarding experience of the buyers a smooth one, with centering on the accessibility of the middle-income people. The new infrastructure installed by DLF comprises AI-based marketing, extensive CRM analytics, WhatsApp, and AI-based lead management. This configuration gives the opportunity of smart customer route and 24/7 answering of queries.

4.5 Operational efficiency: Lean vs. Quality-controlled models

The outsourced model of construction with dashboard monitoring at Mahindra set up fixed overheads that were very low, resulting in the establishment of very variable cost structure that multiplied by the activity level in a short time. This created a reduced breakeven and quick adjustment of costs in downturn.

DLF has used hybrid model where internal PMC controls the execution of the contractors, willing to pay more fixed costs in order to control the quality and maintain the delivery standard. This efficiency versus quality trade-off served the needs of the target market of each company Mahindra lowering the cost per square foot, DLF upholding the premium positioning standards.

4.6 Geographic diversification and business model architecture

Mahindra concentrated on the affordable housing market by focusing in 5-6 metro cities which offered end efficiency in business but risked geographic concentration. The geographical spread of DLF in 10+ cities of North, South and West Indian regions gave it diversification since the local market cycles neutralized each other. This was enhanced by the strategy land bank and mixed-segment developer model used at DLF.

4.7 Post-covid recovery performance

Cumulative strategic differences were brought out clearly by recovery metrics. Mahindra enjoyed slow recovery with 15-20% year-on-year pre-sales growth to FY 22

through limited income shock recovery among the mid-income segment and overreliance on one revenue line. DLF has shown a growth of 136% year-on-year, and record-breaking bookings of over 10,000 crores (new sales: 7,273 crores in FY22). The fact that real estate rentals topped off, along with the luxury segment which was not so shaken by the high-net-worth purchasers as well as the brand loyalty and premium pricing that the company had earned and the diversification of the geographical assets picking diverse regimes of the markets boosted the recovery of DLF.

4.8 Key strategic insights

Revenue Diversification as Major Resilience Factor: Diversification of the model used by the DLF in its mixed residential-commercial-rental was more stable than an exclusive focus on a residential orientation. Positioning of Balance Sheets Counts: Pre-crisis leverage policy was very critical- the various strategies of the companies worked out well in their respective environments. Industry leverage (D/E: 0.12-0.22) has remained at its lowest point at Mahindra with 5.7-6.7 being its borrowing cost whereas DLF has decreased its D/E position (0.50 to 0.12) to its lowest point through deleveraging.

Many Ways to Win: The comparison highlights the fact that different strategic directions may be successful with reference to the organization capabilities and market positioning there is no correct or wrong crisis response. Speed of Recovery is associated with Diversification: Both overcame the crisis, but the diversified business model, in terms of segmentation, geography, and sources of revenue, is clearly better at providing superior recovery speed as demonstrated by DLF.

5.0 Findings and Results

This paper provides a comparison of two real estate developers in India in the COVID-19 crisis. It demonstrates alternative yet efficient ways to address great economic issues. The findings show that resilience can be based on different directions. All these are influenced by the competencies in a company, market location and financial stability of a company prior to the crisis.

5.1 Strategic differentiation

The business model of DLF combining its stable rents through its rental subsidiary, DLF Cyber City Developers Ltd. (DCCDL) combined with the development operations enabled it to survive the crisis compared to others who had not diversified their operations. The rental collections of DLF stood at 98+ and it was able to generate 3000+ crore every year even in the period of lockdowns. This gave it enough working capital to continue with the

operation of DLF, cut its debts and pursue aggressive expansion in case the environment relaxes it. Mahindra Lifespaces was not benefiting out of diversification that competition was involved in, since the company was a pure play residential developer. The company has always had a conservative financial structure with the lowest leverage ratios of any Indian listed developer during the entire period. Debt/equity ratios of Mahindra Lifespaces ranged from between 0.12 and 0.22 (for the period), compared to between 0.12 and 0.50 for DLF. Combined with the strength of Mahindra's AAA rated parent balance sheet, it has enabled the company to continue to enjoy a higher CRISIL AA rating through the crisis.

5.2 Financial performance and recovery

DLF Ltd. performed better financially and in business continuity than Mahindra Lifespaces. The company's FY21 revenue fell 11% from ₹6,083 crore in FY20 to ₹5,414 crore during FY20. DLF remained profitable, with a net profit of ₹1,083 crore. This lesson in business model diversification is further elucidated by another company in the real estate sector, Mahindra Lifespaces, reporting a 72.8% fall in revenues from ₹611 crore to ₹166 crore, and a reported loss of ₹71 crore for the same quarter. The demand recovered following the COVID, which contributed to the operational benefits of DLF. In FY22, the company reported that its pre-sales increased by 136 per cent and were an all-time high of 7273 crore. The pre-sales at Mahindra Lifespaces grew by 48 percent to 1,028 crores. DLF had a five-year pre-sales CAGR of 24 against the 9.6 of Mahindra Lifespaces. It showed that a bigger share of the market was being taken over at DLF.

5.3 Balance sheet transformation

The businesses came out as both stronger with one of the most transformational deleveraging of the balance sheet in the Indian real estate history in the case of DLF. The gross debt decreased to 4,182 crores (FY22) whereas in FY18, it was 17,491 crores, and it fell by 76 per cent whereas the net cash positive trajectory has been attained in the development business in FY22. Mahindra Lifespaces' liquidity remained comfortable, with gross debt peaking at ₹459 crore and interest coverage being better than DLF's. The company's borrowing costs were 5.7-6.7%, the lowest in the industry, due to better credit quality and support from its parent company.

5.4 Market performance and strategic positioning

Both companies had positive five-year stock performance. However, DLF's CAGR of ~33% was superior to Mahindra Lifespaces' 31%, with different risk-return profiles. DLF's rental visibility and sheer scale brings improved earnings visibility, while Mahindra Lifespaces' results are reflective of concentration risks of pure-play residential. The findings

validate the idea of multiple approaches to be successful (depending on organizational situation, resources, and risk attitude), and not a single “optimal” model for all contexts.

6.0 Conclusion and Implications

A benchmark study by DLF Ltd and Mahindra Lifespaces during the COVID-19 pandemic found that there is no single best strategy to succeed in times of crisis. The right calculated choice will depend on the characteristics of the company in line with the contingency theory and the resource-based view.

DLF Ltd.’s superior recovery attributes the diversification buffer utilizing 3 advantages: the scale at 10-15x bigger revenue base, the stable income from rental stream from DCCDL at INR3000 crore plus annually, the geographic diversification pan India. The pre-crisis deals with GIC (2017) helped DLF to reduce gross debt by 76% from FY18 to FY22, ample liquidity during the downturn and the flexibility to recover aggressively. DLF’s pre-sales more than tripled from ₹2485 crore in FY20 to ₹7273 crore in FY22.

While Mahendra Lifespaces adhered to a focused agility strategy based on capital efficiency and housing affordability, during FY21, when revenues fell by 73% (the steepest decline in the industry), it also maintained the sector’s lowest debt-equity ratio of 0.12-0.22 and CRISIL AA rating, the best in the nation during the pandemic. Strong backing from the parent company, low relative borrowing rates (5.7-6.7%) and efficient operations helped it through the downturn. While both companies considered digital transformation of their sales channel, liquidity management through cash, and transparent communication with stakeholders to be critical success factors, their contrasting choices indicate that responses to a crisis depend on an organization’s business model architecture. In broad terms, DLF’s diversification-focused model improved resilience while Mahindra’s concentration-focused model helped cost management and market positioning. Theoretically, this has implications for the planned management literature that shows how multiple types of calculated archetypes can survive in declining industries when they are well-matched with organizational resources and market contexts.

7.0 Recommendations

The real estate developers should select crisis-responsive methods that play to its strengths. Diversified developers, and those with a strong rental business, should use their buffers to avoid forced sales of their assets. Players focused on capital efficiency and flexibility to re-position for new markets in times of crisis. Good financial position pre-crisis such as maintaining appropriate leverage and liquidity reserves. Digital transformation is not

a reactive crisis response but a structural change to be built into the planned framework. Winning developers balance cuts, speed-ups and future-proofing (sustainability, affordable housing) with shaping risk regionally, segmentally and by asset class (which requires scale). Small-scale developers can win through efficiency. They can apply in capital-light joint-venture models. They can excel in niche markets. The niche markets have strong growth and customer loyalty. The developers add value for customers in these markets. Policymakers should allow regulatory flexibility and liquidity and develop sustainable and affordable housing for an increase in system resilience.

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CHAPTER 4

Determinants of Channel Selection for Businesses in the Prefabrication Industry

Nikhil J. Rajurkar and Sharada H. P.***

ABSTRACT

The prefabrication industry is going through a major change in how products (modular homes, precast concrete parts, portable structures) are marketed and sold, largely driven by digital transformation. The study explores broadly how companies in India choose between:

- Online,
- Offline, and
- Hybrid Distribution Channels

Using a cross-sectional approach, we gathered responses from 46 professionals including contractors, architects, suppliers and clients through structured questionnaires. Participants evaluated several factors ~ cost, product complexity, logistics reliability, brand image, after-sales service and digital readiness. The results show that 73.9% preferred a hybrid approach. Logistics reliability and brand reputation had the strongest influence, followed by after sale service and product complexity. Contrastingly, cost ranked lowest, challenging the common view that price dominates B2B decision making. It was found that stakeholders' readiness with digital tools varied; it could be easily adopted by architects and suppliers, while clients still preferred offline interaction before making decisions. Drawing ideas from well-known business theories, a 3-phase approach is recommended:

- Online detailed information
- Offline discussions to build trust, and
- After sale support and services combining digital and offline elements

Keywords: Prefabrication industry, Sales channel selection; Hybrid distribution channels.

1.0 Introduction

The prefab industry is experiencing rapid growth, driven by advancements in technology. The advantage of prefab construction is as follows:

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- Reduced construction time
- Cost efficient.
- Improved quality control

This industry primarily deals with high value products such as precast concrete components which are widely used in infrastructure and commercial construction. The solution for these challenges requires a strategic approach to sales channel selection.

With the rise of digitization, this industry is moving beyond the traditional offline channels adopting digital tools like virtual showroom, augmented reality (AR) and interactive catalogues. This transition is rephrasing how customers interact with suppliers which offers new opportunities to optimize sales and marketing strategies. Hence understanding the determinants is very crucial. Few important parameters to be considered:

- Customer preferences and behaviour
- Pricing
- Supply chain coordination and management.
- Impact of technology

These can help businesses to align their strategies to meet market demands. This research aims to focus on these dynamics and provide actionable insights to help businesses succeed in the sector.

1.1 Research objectives

- To identify factors influencing online v/s offline channel selection for prefabricated product sales in the construction sector.
- To analyse customer trust, satisfaction and decision making when purchasing prefabricated components through online, offline or hybrid channels.

1.2 Problem definition

The following research would serve and provide valuable insights on sales channel selection in the prefabricated industry. The research aims at tackling the following identified issues regarding the sales of prefab products in construction industry ~

- All the products in the prefabricated industry are high value products economically.
- There are logistical complexities (being the key reason for dilemma amongst contractors whether to go for prefab or traditional construction technique).
- The uniqueness of the industry and its products, which have sales potential in both online as well as offline channels. The online channels are going well hand in hand with the growing digitization in the construction industry.

1.3 Limitations of the study

- The study might be restricted to a specific region and might not be applicable to all scenarios.
- Varying levels of digitization in the country might affect expansion of business in future.
- Limited access to reliable data as it is still not a prevailing type of construction in the country.

1.3 Scope of work

- Precast Concrete Components
- Modular Homes
- Portable Structures

2.0 Literature Review

2.1 Preface

The channel selection plays a very crucial role in determining how businesses can engage with their customers and reach out to them, especially in cases of specialized industries such as prefabrication. The following literature review tries to investigate the determinants which influence the decision of online, offline or hybrid sales channel selection within the prefabrication sector. The study focuses on following two core objectives ~

- To determine the key factors driving businesses to choose between online, offline or hybrid sales models, and
- Analysing how customer satisfaction, trust and decision making vary across different channels.

By reviewing about 40 industry and scholarly research papers, this literature review gives a well-structured understanding of the interplay between supply chain logistics, digital transformation, consumer behaviour and firm level strategies channel selection of prefabricated products.

2.2 Theoretical foundations of channel selection

The theory pertaining to channel selection has been extensively explored within the domains of marketing and distribution. Kotler and Keller (2016) propose that decisions regarding channel selection are influenced by characteristics of the market, type of product, objectives of the company and intermediary capabilities. Stern, El-Ansary, and Coughlan (1996) were the ones to introduce Channel Design Framework, which considers the following three factors:

- Competitive Environment

- Needs of the Customer, and
- Economic Factors

Transaction cost economics (Williamson, 1981) also supports several decisions, where comparison between the cost of using a market intermediary versus internalizing the function is undertaken by firms. In the prefabrication industry, which is characterized by its bulky and complex products, the channel strategy must consider logistics, need for customization and post-sales service (Gadde & Håkansson, 2001; Love et al., 2019). In addition to this, Anderson and Coughlan (2002) stresses on the significance of aligning channel strategies with the life cycle of the product & consumer buying processes.

2.3 Digital transformation in the construction sector

As reviewed by Marhani et al. (2020) in a coherent manner confirms that the use of digital tools not only increases efficiency but also enhances customer engagement and transparency. In the prefabrication sector, digital transformation enables the following ~

- Product Visualization
- Order Tracking, and Pricing Comparisons

Lee and Yu (2018) have found that a firm's digital maturity also enhances its competitive positioning by making dynamic inventory management and real-time customer feedback possible. The integration of Augmented Reality (AR) and Virtual Reality (VR) technologies further facilitates decision making of the customer in online contexts (Zhao et al., 2020).

2.4 Consumer behaviour and preferences in prefab construction

The channel choice is significantly impacted by the following three factors:

- Perceived Risk
- Consumer Trust, and

Furthermore, Parasuraman et al. (2005) points out the role of service quality and trust in shaping online behaviour, which is significantly applicable in complex and high cost purchasing such as prefab housing. Cho et al. (2021) adds that the digital literacy, transparency and social influence greatly affect consumer confidence in channel selection.

2.5 Logistics and supply chain considerations

Li et al. (2019) review says that firms with an efficient forward and backward integration are more likely to go for multichannel strategies. Digital tools have also proven to improve the following - Order Scheduling, Delivery Tracking, and Inventory Control. (Zhai et al., 2020; Ding et al., 2022) says that this enables the following two things ~

- Better function of sales, and
- Integration between logistics.

Along with this, Meiling and Johnsson (2017) has also brought to attention that synchronized supply chains enhance the predictability of the project and reduce cycle time. Inventory flows and responsiveness can be significantly improved by integration of ERP and CRM systems across channels (Liu & Liang, 2022). Companies must also take the following factors into consideration while choosing channels ~ Warehouse Location, Delivery Times, and Installation Coordination, all of them which together helps to stitch it all together.

2.6 Cost and investment considerations

Estimations of Cost and Investment Incurred Level Up Chan and Lu (2019) suggest that small firms may opt for the online model due to lower costs associated with maintaining physical infrastructure. On the other hand, companies dealing with high-end prefab products tend to invest in offline experiential trust builders and capability showcasing centres (Luo et al., 2022). This decision is equally affected by return on investment (ROI) and customer acquisition costs. Online channels may have lower customer acquisition costs (CAC), but if there is low consumer confidence, online sales can have trouble with converting clicks to sales. (Ghosh et al., 2021) suggests that the single and high involvement purchases in prefabrication are salient.

2.7 Challenges and barriers

Hurdles to adoption remain even with the changing technology. Gamil and Rahman (2017), talks about the barriers in lack of appropriate skills, evolving and gaps in digital infrastructure as hurdles in emerging markets. Sufficient availability of resources in terms of IT is lacking with most of the prefabrication companies for e-commerce facilitation.

Additionally, the lack of clear online prefab transaction frameworks and fragmented digital transaction ecosystems also create ambiguity (Chen et al., 2021). Not having uniform standards in specifying products and delivery makes it complicated to automate selling.

2.8 Conclusion

Most of the literature examined indicates an increasing preference for hybrid models that combine ease of access and efficiency associated with the internet with the more personal interaction necessitated by trust-building offline. Knowing these factors will assist prefabrication companies in refining channel tactics to gain beneficial competitive position. This also further enhances and helps in refining the decision-making criteria for channel selection, which are more appropriate and relatable to decision making.

2.9 Summary of gaps in literature

There is a remarkably bold absence of research on the digital transformation, consumer behavioural shifts & even the logistics of supply chain frameworks, prefabricated

structures. To begin with, there is a lack of empirical evidence analysing the satisfaction and sales performance stemming from the use of online, offline, and even blended approaches to sales in prefab construction. Finally, the ways in which consumer confidence is built in the online purchase of prefabricated structures has yet to receive adequate focus, especially for transactions of high involvement.

3.0 Research Methodology

3.1 Research design

This study follows three distinctive approaches:

- Cross sectional approach
- Descriptive design
- Exploratory designs.

These helps us to evaluate the factors that influence sales channel selection in the prefabrication industry. The structured cross-sectional survey provided insights into the alignment towards ~ online, offline or hybrid channels from the key industry stakeholders. The descriptive aspect of the study offers a clear overview of current channel selection. The exploratory aspect allows for a deeper understanding of uncommon factors affecting the decision-making process in India. Overall, the culmination of three different approaches provides a deeper understanding of the reasons for a specific channel selection in a digitally transforming market conditions.

3.2 Population and sampling

The study targets individuals directly involved in various stages of prefabrication process ~

- Contractors/builders
- Architects/designers
- Suppliers/vendors
- Clients/end users

These participants were involved as they are primary players of procurement, specifications and purchasing prefabricated products. The participants were chosen based solely on their knowledge or experience and further divide them into groups to ensure fair representation across distinct roles and organization sizes, theoretically known as purposively stratified sampling. This approach was appropriate as insights from key professionals are more valuable than random general responses. A total of 46 participants were involved as a part of pilot group, which was considered sufficient for early analysis and assessing the reliability of the survey.

Table 1: Respondent's Role Distribution

Roles	Number of Respondents
Builders / Contractors	24
Designers / Architects	08
Vendors / Suppliers	07
End Users / Clients (Developer / Private Client)	07
Total	46

Source: Author's Survey Data (2025)

Table 2: Respondent's Organization Size

Size of The Organization	Number of Respondents
Individual / Small Businesses (1 – 10 Employees)	06
Small – Medium Enterprises (11 – 50 Employees)	13
Medium Enterprises (51 – 250 Employees)	24
Large Enterprises (250+ Employees)	03
Total	46

Source: Author's Survey Data (2025)

Profiles indicated by the above represented Table 1 & Table 2 show a dominant representation of Contractors and Medium Sized Enterprises, thus showcasing the practicality in terms of decision making in the prefabrication industry.

3.3 Data collection and instrument

The primary data was collected by conducting a survey in the form of a structured questionnaire shared through google forms. The survey consisted of 29 questions, divided broadly into following distinct categories as mentioned below ~

- Participant Background
- Factual / Preference factors
- Decision Factors
- Alignment to Digital Literacy/Tools
- Perceptions/Beliefs
- Satisfactory levels

3.4 Measurement scales

Multiple measuring scales provided us with insights into various aspects involved.

- Categorical scales ~ Participant background and channel preferences.

- Five-point Likert scale ~ Key determinants like price, coordination reliability, brand reputation, after sales service quality, product complexity, and digital readiness. This ranged from “not important” (1) to “extremely important” (5).
- Agreement and satisfaction scales ~ Comparison of qualitative factors like perceptions/beliefs and satisfactory factors.

3.5 Data collection procedure

The survey link was circulated on online platforms with selected participants groups. Participation was voluntary. The academic purpose of the survey was also informed. Responses were collected over a period; their identity and responses were kept anonymous and confidential to protect participants' privacy and to ensure fair data collection.

3.6 Data analysis techniques

The data collected was analyzed using basic descriptive statistics techniques as follows:

- Frequency distribution
- Percentage
- Average scores

These were appropriate to identify the preferred sales channel and rank the effectiveness of various influencing factors. To draw meaningful insights a comparative analysis across stakeholder groups and channel types was performed.

3.7 Ethical considerations

The study adhered to the standard guidelines at every stage. Participation was voluntary, and completion of survey was taken as an implied consent. Participants' identities were kept anonymous and data collected was strictly used for academic purposes only.

4.0 Data Analysis

Frequency distributions, mean scores and visual representations are used to represent the results with pure clarity and interpretation.

4.1 Channel preference distribution

The respondents were instructed to select their preferred sales channel for:

- Purchasing or selling prefabricated products
- Choosing among online, offline and hybrid options

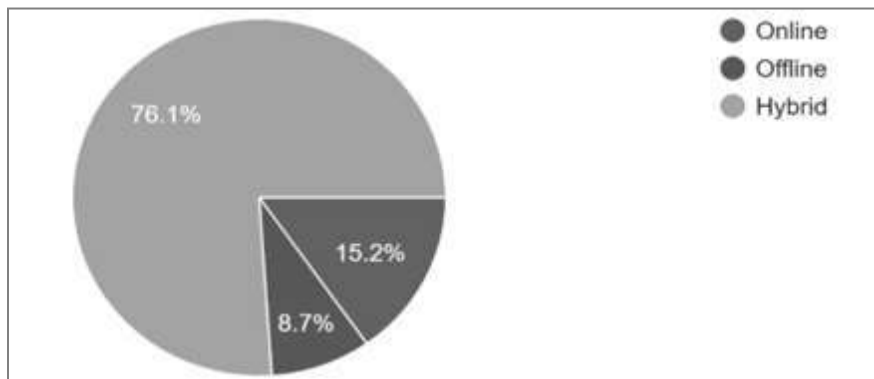
The results present a strong inclination towards hybrid sales channels representing industry need to balance digital efficiency with offline interaction. The descending order

preference of channels are ~ hybrid channels, online channels and offline channels being the least preferred. The reason behind stakeholders preferring hybrid channels is ~

- Digital platforms are convenient and easy to access
- Offline platform facilitates design validation, customization and builds trust

Hence there is a clear shift from traditional sales model to accepting digital literacy particularly among fast-paced growing firms and professionals.

Figure 1: Preferred Sales Channel for Prefabricated Products (n = 46)



Source: Author's Survey Data (2025)

The reasons behind the dominance of hybrid channels among stakeholders are ~

- Complexity of products
- High financial transactions and commitments
- Stakeholder management

Any single channel (offline or online) cannot suffice for the above key characteristics, hence the integration of them is a necessity.

4.2 Importance of channel selection determinants

To understand the key factors behind channel selection, a five-point Likert scale was used. Respondents rated the importance of six determinants accordingly. To identify the relative influence, mean scores were calculated for each determinant. The highest score was recorded for logistics reliability. The crucial indicators of channel selection for the above determinant are:

- Timely Delivery
- Good Coordination
- Handling of Prefabricated Components

Brand reputation is the second most influential determinant. This indicates how trust and credibility play a significant role in reducing uncertainty in customers while choosing products. After sales service and support also ranked high stating the importance of few key factors like:

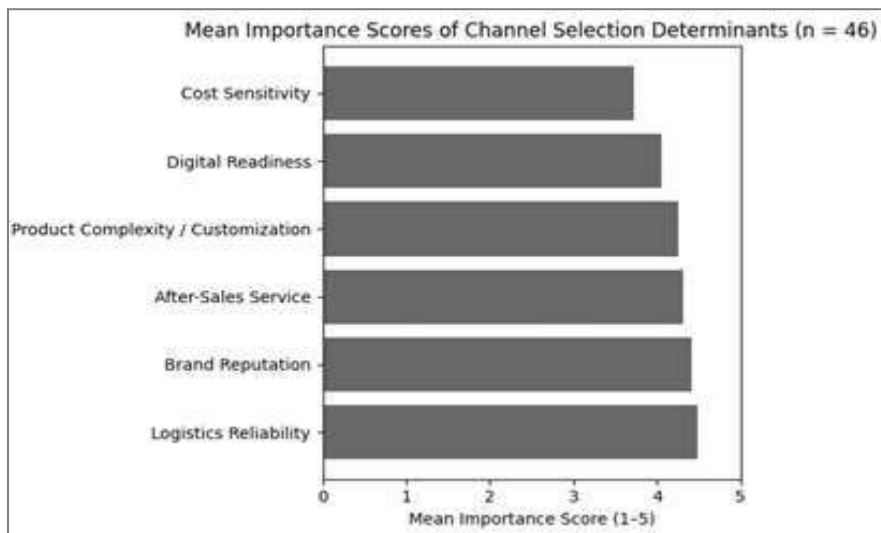
- Repair and Maintenance
- Issue Resolution
- Long Term Service Relationship specially for High Monetary Purchases

Product complexity and customization is another important determinant highlighting the factors like:

- Technical Specifications
- Design Coordination
- Customization

Digital readiness although being an integral part ranked lower indicating lower confidence and capability in adapting to digital tools. Cost sensitivity ranked the lowest, indicating it is the last factor considered while making decisions in purchasing or selling prefabricated products.

Figure 2: Mean Importance Scores of Channel Selection Determinants (n = 46)



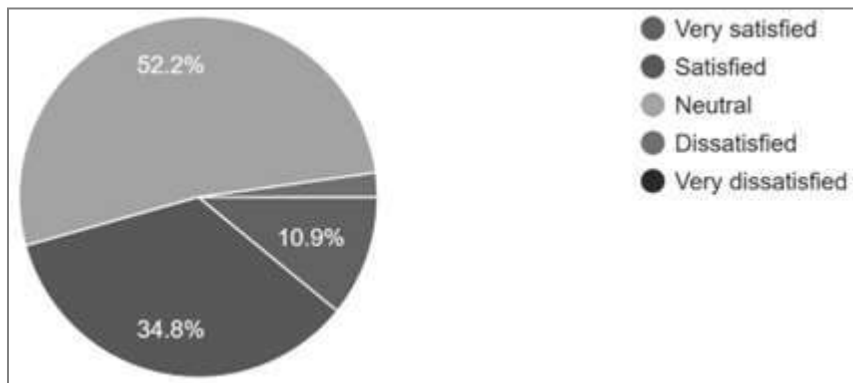
Source: Author's Survey Data (2025)

Hence the ranking of determinants indicates that economic factors are secondary to functional and technical considerations in the decision-making process of channel selection in prefabricated industry.

4.3 Satisfaction across sales channels

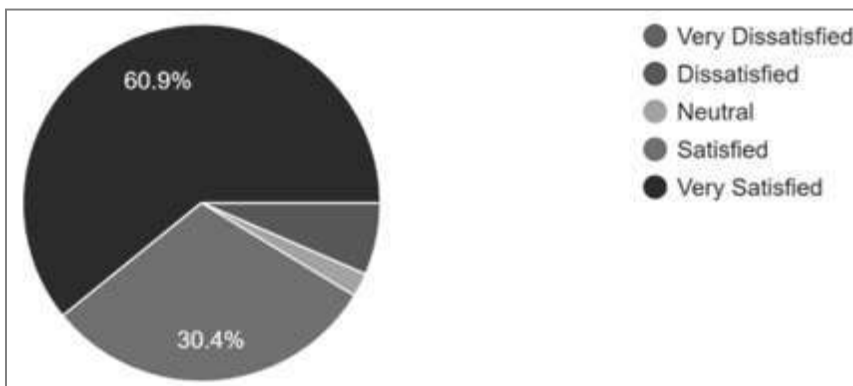
Satisfaction levels related to selection of channels ~ online, offline and hybrid were evaluated by calculating mean satisfaction scores for effective comparison among the channels. The results show strong inclination towards online channels recording high satisfaction levels, mostly among respondents who value factors like ~ Easy Access to Information, Speed of Communication and Transparency. Hybrid channels recorded the highest score indicating the integration of digital and physical elements will lead to reassure both efficiency and trust related needs. Although physical interaction was crucial for channel selection, offline channels recorded low scores due to their limitations like ~ Scalability, Slower Processes and Reduced Flexibility.

Figure 3: Average Satisfaction Levels Across Channels of Preferred Choice (n = 46)



Source: Author's Survey Data (2025)

Figure 4: Average Satisfaction Levels Across the Hybrid Sales Channels (n = 46)



Source: Author's Survey Data (2025)

The results strongly suggest that hybrid channels not only dominate but deliver satisfactory user experience. The ability of hybrid channels to integrate online convenience and offline reassurance is the prominent key driver in prefabrication industry.

4.4 Summary of key analytical insights

The above analysis significantly highlights three important insights:

- The preferred channel is hybrid sales channel among the stakeholders of prefabrication industry.
- The major influential determinants are logistics reliability, brand reputation and after sales service while cost sensitivity is the least considerate.
- To address issues like complexity and trust, hybrid sales channel recorded the highest satisfactory levels.

These insights form a solid foundation for further discussions in the following sections to come and to help us derive a suitable accurate conclusion.

5.0 Results and Findings

The focus is on the following three parameters:

- Focus on dominant trends
- Stakeholder behavior & Implications of pattern in sales channel selection.

5.1 Predominance of hybrid sales channel strategies

The prominent takeaway from data analysis is the strong preference for hybrid sales channels among the respondents. Also, integration of online and offline channels emerged as the most suitable approach among the stakeholders. The above preference suggests how complexity, high financial involvement and customization can be carried out efficiently with transparency. The two major aspects hybrid channels facilitate are:

- To leverage digital tools during early phase of buying process which eases out parameters like information about the product, product comparison and preliminary evaluation.
- Offline interactions allow for design validation, easy negotiations and real time decision making.

Hence the results strongly promote that any of the channel individually would not suffice the demands of the prefabrication industry.

5.2 Determinants influencing channel selection

The findings suggest that economic considerations are secondary to operational and relational determinants in making channel selection. Logistics revealed as the most influential factor, highlighting three important aspects:

- Role of delivery coordination
- Accuracy in scheduling
- Supply chain integration

After sales and service also was ranked under top three influential determinants, which deliberately focuses on:

- Reinforcing trust
- Importance of long-term support
- Quick issue resolution
- Prolonged service in high transaction sales

To the contrary, cost sensitivity ranked the lowest. The above findings challenge conventional assumptions that price is the most dominant factor that drives channel selection.

5.3 Stakeholders differences in digital readiness

Higher comfort and inclination towards usage of digital tools was seen in architects and suppliers depicting their constant involvement in software systems. With a little resistance towards use of digital platforms and digital tools by clients and users they preferred offline interaction to make an informed decision.

Physical interactions are valued more as they could address concerns like quality, customization and investment risk. Contracts and builders showed affinity for integration of online and offline mediums:

- Digital tools for coordination and accessibility to information
- Offline interaction for final decisions related to execution.

5.4 Satisfaction outcomes across sales channels

Hybrid channel indicated the highest satisfactory levels, as they diligently balance efficiency & trust. Online channels are valued for easy accessibility & transparency. While offline channels are valued in customer relationship management, credibility & trust. Despite the offline channels being still relevant, it indicated lower satisfactory levels due to their limitations in flexibility & slow processes.

5.5 Alignment with research objectives

Overall, the findings reveal that hybrid sales channel selection is the most suitable approach in prefabrication industry sales. The primary drivers for channel selection are logistics reliability, brand reputation, after-sales service and support and product complexity by overshadowing the conventional cost sensitivity factor. Hence the hybrid sales channel is bound to deliver the ultimate satisfaction for all the stakeholders.

6.0 Conclusion and Implications

The study's main agenda is to evaluate the determinants influencing sales channel selection – online, offline or hybrid in the prefabrication industry. Drawing insights from responses by industry stakeholders sets a clear picture into how customers and firms make decisions on channel selection. The key elements upon which the decisions are taken are ~

- High product complexity
- Logistical challenges
- Trust intensive transactions

The findings reveal that hybrid sales channel is most suitable and has an effective approach which suffices for the prefabrication industry. The integration of digital tools with offline interaction has advantages like ~

- High efficiency and productivity
- Relational assurance
- Maximum reach by use of digital tools
- Customization and trust ensure through offline interaction

The above parameters make the decision-making process faster which in turn increase the monetary value of sales in prefabrication industry. The uncertainty in providing financial commitment, technical valuation and coordination among stakeholders becomes almost negligible. From the results, logistics reliability emerged as the prominent influential factor valuing the importance of on time delivery, scheduling coordination and supply chain integration. This reinforced conventional values like trust, credibility and long-term support shaped the channel selection. Hence, in contrast to traditional notion that cost would make or break the deal, it emerged to be one of the last concerns prioritizing risk reduction and service assurance. Architects and suppliers were more open to accepting the use of online channels. Clients and end-users preferred offline interaction at key decision stages. This suggests the need for combining both ~ online and offline channels effectively to meet the expectations of all the stakeholders in the prefabrication industry.

6.1 Implications for theory

Based on the existing theories, the findings support few existing frameworks like ~ Channel design theory, Resource based view & Transaction cost economics. The results define how hybrid sales channels help firms to manage key parameters like ~ Transaction uncertainty, Leverage organizational capabilities & Alignment of channel design with customer needs. The study is an addition to the limited existing research on the topic sales channel selection, especially in a growing sector like prefabrication industry by offering real time evidence from a developing market context.

6.2 Implications for practice

The study strongly suggests strategically investment in hybrid sales channel for practitioners in prefabrication industry. It strongly claims that online and offline channels are not to be seen as different verticals. The focus of firms to be prominently on logistics reliability and coordination, enhancing after-sales service and support, and building brand trust and reputation through integration of both the channels. Digital tools will initially help in maximum reach to customers and at early decision-making stages. For validation, customization and customer relationship management, offline interactions to be adopted.

6.3 Implications for policy and future research

On a broader level, the findings suggest better industry standards and stronger digital infrastructure for smooth integration of online and offline channels. More studies in future can build on this research by using large samples, observing trends over time or even comparing them at global level to have clear and better understanding on how sales channel strategies impact a business in prefabrication industry.

7.0 Recommendations

7.1 Managerial recommendations

Prefabrication firms should focus on using hybrid sales channels that combine both online and offline channels. Digital platforms can be used for easy information availability, sharing information and initial comparisons. Offline engagement will enhance customization process, negotiations and customer relationships. It strongly suggests treating both the channels as one and not as different verticals for firms to improve customer trust and overall sales performance.

7.2 Operational and digital strategy recommendations

Logistics reliability being the prominent factor in channel selection, firms should focus on coordination between sales, supply chain and installation teams. To reduce delays and uncertainties firms should mainly invest in the following as mentioned below and expand in detail in further after the pointers to be considered ~

- Delivery planning systems
- Real-time tracking
- Cross functional communication

Firms are strongly encouraged to adopt digital tools. Online platforms enhance features like product visualization, digital drawings and documentation along with offline interaction for assurance and trust and wherever necessary in key decision stages. Training

sales and technical teams to adopt both digital and physical channels is essential for smooth and consistent customer experience.

7.3 Industry and policy-level recommendations

At the industry level, improved standardization of digital frameworks and guidelines for transaction can support mass adoption of hybrid sales models. Industry associations and policymakers should encourage and promote digital skill development. They should also provide good infrastructure support mainly for small and medium-sized firms to expand and grow. This reduces barriers in adopting digital tools and will hence improve channel efficiency across prefabrication sector.

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CHAPTER 5

Adoption of AI Tools in Corporate Learning Pedagogy

Roshni Kumari, Ruchi Bhilare**, Ankita Singh** and Soumi Rai****

ABSTRACT

Artificial Intelligence has developed extremely fast during the recent years and has already begun transforming the manner in which learning and training processes and programs take place within organizations. Previous methods of corporate learning were largely executed in form of classroom learning and predetermined training programs which are no longer individual. Nonetheless, most organizations are gradually implementing AI-based applications to make the learning process more efficient, time saving, and effective to meet needs of individual employees (Holmes et al., 2019). This paper is an attempt to determine how firms are introducing AI tools into their learning systems, through such frameworks as technology Acceptance Model (TAM) (Davis, 1989) and Unified Theory of Acceptance and Use of technology (UTAUT2) (Venkatesh, Thong, & Xu, 2012). The study was modified to be a mixed research approach. A structured questionnaire was used to gather quantitative data and they were analysed using Relative Importance Index (RII). Simultaneously, semi-structured interviews with corporate trainers were used as the means of collecting qualitative data by employing snowball sampling method. As findings of the study demonstrate, anticipated performance enhancement, perceived utility of AI tools, and presence of organizational support are relevant when it comes to the adoption of AI. Majority of trainers believe that AI assists in personalizing learning process and saving time as well as advancing skills. Nevertheless, there are still concerns that pertain to data privacy, ethical concerns, and general organizational barrier (Holmes et al., 2019). The analysis concludes that not only technology is important to successful and long-term implementation of AI in corporate learning. Leadership support, coherent moral codes, and frequent training of trainers are also crucial. Such study contributes to existing body of research in the area of technology adoption, as the researcher implements TAM and UTAUT2 (Venkatesh et al., 2012) in the process of corporate learning and provides valuable insights to organizations that consider the use of AI in a responsible way.

Keywords: Artificial Intelligence, Corporate Learning, Technology Adoption, Organizational Readiness, Training Innovation.

1.0 Introduction

The modern business world has become fast-changing with technology, globalizing, digitally

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disruptive, and with rapid skill obsolescence. Companies in all sectors are being placed under continuous pressure to not only increase the ability of the working group, but also to increase productivity, innovativeness, cost efficiency. Consequently, the corporate learning and development (L&D) operations have become avoidance functions that add value as strategic facilitators of organizational competitiveness and long-term viability.

The classical corporate forms of learning that largely depend on classroom learning, frozen e-learning sessions, and standardized training courses are increasingly being ineffective to meet the dynamic business demands. These models usually do not consider the different profiles of learners, different levels of skills as well as demands of role that change rapidly. Organizations are therefore in search of technology-based solutions that would enable provision of scalable, adaptive, and outcome-based learning experiences.

Artificial Intelligence has become a disruptive technology that can radically change corporate learning pedagogy. Artificial intelligence can be used to develop intelligent tutoring systems, adaptive learning platforms, conversational agents, automated assessment engines and learning analytics dashboards to help organizations transition to a data-driven approach to learning rather than a reactive training strategy. Through these tools, it is possible to monitor the engagement and performance of learners in real-time, anticipate the existence of skills gaps, as well as continuously optimize learning interventions (Holmes et al., 2019).

Along with these benefits, AI tools usage in corporate learning setting is not even. As technologically mature organizations have started exploring the use of AI in their training environments, other organizations continue to experience challenges associated with the lack of digital infrastructure, trainer preparedness, change resistance and ethical issues. Concerns about data privacy, algorithmic bias, transparency and compliance with regulations also make the process of adoption more complicated, especially in organizations that deal with sensitive employee and business data (Holmes et al., 2019).

Corporate trainers are at the centre of this change. Trainers who are change agents, instructional designers and facilitators have ability to guide the perception, implementation, and use of AI tools in learning. Their affirmation of AI technologies can largely influence the attitude of learners and condition the presence of a deep application of AI or its shallow performance (Holmes et al., 2019).

It is thus important to know the determinants of AI in corporate learning pedagogy. Technology adoption theories offer theoretical models used to analyze user acceptance and usage. Technology Acceptance Model (TAM) (Davis, 1989) focuses on perceived usefulness and ease of use as factors that predict adoption whereas Unified Theory of Acceptance and Use of Technology (UTAUT2) (Venkatesh, Thong, & Xu, 2012) expands on this view, introducing new constructs like social influence, facilitating condition and habit as well as price value.

The research examine how AI tools can be adopted in corporate learning pedagogy by incorporating the TAM and UTAUT2 (Venkatesh, Thong, & Xu, 2012) models. The study concentrates on the views of corporate trainers and will be based on a mixed method design. Taking an analytical approach to study of performance-driven motivations and the contextual constraints, the research set out to equip a detailed and empirically-based explanation of AI adoption dynamics within corporate learners.

2.0 Literature Review

2.1 Artificial intelligence in corporate learning

Artificial Intelligence the computational systems that can execute processes normally performed by the human intelligence are called artificial intelligence, such as learning, reasoning, prediction, and decision-making. AI applications are getting integrated in learning management systems, virtual learning platforms and performance support systems in corporate learning settings. These applications are adaptive learning engines, intelligent tutoring systems, automated assessments systems, chatbots and predictive learning analytics (Holmes et al., 2019).

According to previous studies, AI-based corporate learning styles can also be useful in improving training through personalization, scaling, and real-time feedback. Using AI systems, the behaviour of learners, their level of engagement, assessments and patterns of progression are studied to make suitable content delivery. This kind of adaptability based on data is a solution to shortcomings of single-fit training models, especially in an organization with a wide learner base and functional specialists. The AI-based learning analytics also enable organizations to elevate training impact more closely and focus learning results on strategic business goals (Holmes et al., 2019).

Nevertheless, researchers warn that introduction of Ai in corporate learning is not a technical endeavour. The success of AI-powered learning is subject to organizational culture, ability of trainers, and governance systems. Heavy automation without pedagogical guidance can lead to lack of motivation in learners and shallow learning. Therefore, AI is generally considered as an additive resource, i.e., something that can improve human-based teaching, but not substitute it.

2.2 AI-enabled personalization and learning effectiveness

Among most frequently mentioned advantages of AI use in the corporate pedagogy, personalised learning should be listed. AI applications apply algorithms to examine personal learner traits of previous knowledge, learning rate, work job specifications and past performance. On the basis of this analysis, individualized learning paths, testing and feedback

systems are produced. Empirical research shows that individualized learning enhances learner engagement, satisfaction and knowledge retention. Personalized increase the relevance and application of training in corporate setups where time is a critical factor and the individual competencies of the job are of utmost importance. Continuous learning process through AI-based personalization helps to recognize the emerging skills gaps and suggest specific interventions. As trainer, it can be observed that personalization made with the help of AI can be performed with more knowledge. Trainers are able to concentrate on instructional tasks that are of higher order like mentoring, coaching and contextual problem solving and AI takes care of repetitive and analytical jobs. This semi-teaching style enhances general pedagogical performance.

2.3 Technology Acceptance Model (TAM)

Technology Acceptance Model hypothesizes that attitude variables, are major predictors of technology adoption. Perceived usefulness is a measure that indicates levels of perception of person using the system that it leads to higher job performance and Perceived ease of use measures amount of effort necessary to use system (Davis, 1989).

TAM (Davis, 1989) has been greatly used in research considering adoption of educational technologies, e-learning platforms and digital tools of collaboration. Results are always consistent showing that perceived usefulness is a more significant factor in influencing behavioural intention than ease of use. This means that we could expect users to go through usability hurdles provided that technology gives them quantified in performance.

Perceived usefulness is manifested in the context of AI-based corporate learning tools as a high quality of learning, efficiency, personalization, and accuracy of evaluation. Perceived ease of use also affects adoption by making it easy to operate especially at early stages of implementation. TAM therefore offers a structural basis on explaining the acceptance of AI tools by trainers (Davis, 1989).

2.4 Unified Theory of Acceptance and Use of Technology (UTAUT2)

UTAUT2 (Venkatesh, Thong, & Xu, 2012) builds on the previous adoption models by adding other constructs that apply to the organizational and consumer settings. These are performance expectancy, social influence, facilitating conditions, habit and price value. UTAUT2 (Venkatesh, Thong, & Xu, 2012) can be especially relevant to the corporate learning scenario in which use of technology is conditioned by institutional policy, leadership decisions, and availability of infrastructure.

Performance expectancy is closely related to perceived usefulness and indicates the level of improvement in training results and efficiency caused by AI tools. Facilitating conditions include the accessibility of technical infrastructure, organizational support, and

training resources required to be used in the long-run. Social influence is used to indicate the effect of leadership encouragement and peer behaviour on adoption level. The continuation of technology use is described by the habit construct which includes regular assimilation into work practice whereas perceived cost benefits trade-offs is determined by the price value. UTAUT2 (Venkatesh, Thong, & Xu, 2012) thus offers a holistic perspective on the study of both the first and second-order adoption of AI tools in corporate learning pedagogy.

2.5 Organizational change, trainer readiness, and resistance

The literature on organizational change points out that the introduction of technology is commonly followed by technology resistance that emanates due to uncertainties, skills, and perceived threats to professional identity. In the case of corporate learning, the trainers might be unwilling to adopt AI because they fear lack of relevance, decrease in instructional autonomy, or rise in surveillance.

Research has shown that, preparation of capability and readiness of trainers is very important in alleviating resistance. The acceptance is increased with the help of well-organized training programs, participatory implementation strategies, and articulated communication of the augmentative nature of AI. Leadership assistance also justifies the use of AI and removes anxiety surrounding change.

2.6 Ethical, privacy, governance considerations

Ethics have become the core of the argument on AI adoption. Corporate learning environments are usually a subject to delicate employee information, corporate expertise, and confidential communications. Issues regarding data privacy, algorithmic bias, transparency, regulatory compliance affect the adoption.

Moderating variables in technology acceptance are trust and ethical assurance. Crystal governance structures, use of clear data usage policies and adherence to legal requirements are necessary in creation of confidence between trainers and learners. The adoption of AI in a responsible manner hence involves need to harmonize technological innovation with ethical accountability.

3.0 Research Methodology

3.1 Research Design

The proposed research takes the mixed-method research design to investigate quantitative and qualitative aspects of AI implementation in corporate learning pedagogy. Both survey-based analysis and in-depth interviews allow to triple triangulate the findings, as well as to improve the validity and strength of results.

3.2 Sampling technique

Snowball sampling was used to select corporate trainers who had experience in application of AI tools in training and development. The first participants were identified through professional networks and referrals, and further ones were identified through recommendations of the participants. Such a method was suitable due to the niche character of the target population and exploratory character of the study (Holmes et al., 2019).

3.3 Data collection

A structured questionnaire was used to collect quantitative data that were measured among respondents. The questionnaire employed the five-point likert scale and scales of construct in accordance with TAM (Davis, 1989) and UTAUT2 (Venkatesh, Thong, & Xu, 2012) which were performance expectancy, effort expectancy, facilitating conditions, social influence, habit, price value and ethical concerns. The qualitative data would be collected as a result of semi-structured interviews with the targeted corporate trainers. The interviews addressed AI perception, adoption issues, organizational assistance, and expectations.

3.4 Data analysis techniques

The Relative Importance Index (RII) was used to prioritize the importance of factors of adoption. Transcripts of qualitative interviews were summarised, denoised, and put through thematic analysis and AI-aided transcript mining. The theme analysis was conducted by examining the frequency of words to determine the prevalent themes to use during AI adoption.

4.0 Data Analysis

4.1 Relative Importance Index (RII)

In paper, RII was used to prioritize the variables that affect the adoption of AI tools in corporate learning pedagogy and, thus, allow organized interpretation in accordance with the constructs of TAM (Davis, 1989) and UTAUT2 (Venkatesh, Thong, & Xu, 2012).

4.2 RII Results: Performance expectancy and perceived usefulness

Performance expectancy proved to be the most significant predictor of AI adoption. Variables of learning effectiveness, personalization, and efficiency registered the RII highest values, which means that the respondents agreed the most. The dominance of these variables implies that, above all, corporate trainers' resort to using AI tools in case they can provide quantified changes in the quality of training and training outcomes. Results are a strong confirmation of the construct of Perceived Usefulness of TAM and Performance Expectancy in UTAUT2 (Venkatesh, Thong, & Xu, 2012). The trainers are open to employing AI in pedagogy in case its role in effectiveness and efficiency is obvious.

Table 1: RII Results

Variable	RII Value	Interpretation
AI enhances learning through personalization	0.81	Strongly perceived as the most critical benefit
AI improves overall training efficiency	0.78	Viewed as a key performance enabler
AI simplifies administrative training tasks	0.78	Reduces trainer workload significantly
AI improves assessment accuracy and feedback	0.78	Enhance instructional precision

Source: Created by authors

4.3 RII results: Effort expectancy and ease of use

The variables of expectancy regarding effort had significantly moderate levels of RII, which reflected overall nature of respondents in that they tend to find AI tools within their control and easy to master. Although the start-up issues were reported, trainers reported issues to be reduced over time (Holmes et al., 2019).

Table 2: RII Results

Variable	RII Value	Interpretation
AI tools are easy to learn and operate	0.75	Low perceived complexity
Initial challenges reduce with experience	0.73	Learning curve stabilizes over time

Source: Created by authors

These findings confirm the TAM hypothesis that perceived ease of use is an indirect facilitator of adoption because it strengthens perceived usefulness. Nevertheless, evidence has also indicated that usability is not enough but effort expectancy should be reinforced with sufficient training and organizational support in order to maintain adoption (Davis, 1989).

4.4 RII Results: Facilitating Conditions and Organizational Readiness

Facilitating conditions became one of the most important determinants of AI adoption, and the importance of organizational infrastructure, technical support, and training mechanisms need to be highlighted.

Table 3: RII Results

Variable	RII Value	Interpretation
Organizational support for AI transition	0.79	Strong requirement for institutional backing
Availability of infrastructure and resources	0.72	Moderate readiness across organizations
Adequate training provided to trainers	0.67	Identified skill and capability gap

Source: Created by authors

The lower value of RII on adequacy of training process indicates that there is a serious obstacle to successful use of AI. Although organizations can commit resources to AI technologies, they will not use them optimally without paying adequate attention to preparation of trainers and their competencies. These results are high in relation to the construct of UTAUT2 (Venkatesh, Thong, & Xu, 2012) namely Facilitating Conditions, which directly impacts actual usage behaviour (Venkatesh et al., 2012).

4.5 RII Results: Social influence, habit, price value

The value of RII between social influence and those variables associated with habits was moderate and high, which underscores importance of organizational culture and frequent use in ensuring continuations of adoption of AI.

Table 4: RII Results

Variable	RII Value	Interpretation
Leadership encouragement influences adoption	0.74	Managerial support legitimizes AI usage
Peer usage encourages AI adoption	0.75	Social norms reinforce acceptance
AI tools are used routinely in training	0.76	Evidence of habit formation
Benefits justify financial investment	0.77	Positive perception of price value

Source: Created by authors

These results suggest that adoption of AI is not a personal choice, but it is greatly influenced by leadership support and social behaviour. The habit formation implies that AI tools are shifting toward being experimental to embedded pedagogical practice, which confirms that UTAUT2 (Venkatesh, Thong, & Xu, 2012) is based on need to continue using tools after initial intent (Venkatesh et al., 2012).

4.6 RII Results – Ethical concerns and trust

The highest RII value were obtained in case of ethical considerations, which indicated high levels of responsibility in corporate trainers in relation to use of AI.

Table 5: RII Results

Variable	RII Values	Interpretation
Ethical regulation of AI tools is necessary	0.81	Critical condition for acceptance
Concerns regarding bias and fairness	0.69	Moderate apprehension
Data privacy and security concerns	0.71	Conditional trust in AI systems

Source: Created by authors

The fact that ethical regulation is rated highly means that trainers do not object to use of AI but prudent and discriminating. Trust and ethical governance is thus considered moderating variables that affect perceived usefulness and behavioural intention.

4.7 Qualitative transcript mining analysis

The qualitative data collected by conducting semi-structured interviews underwent process of transcript mining and thematic analysis to complement and put into perspective the quantitative data. All transcripts of the interviews were initially re-collated and purged of filler words, repetitions and interviewer prompts in order to provide clarity in the analysis. The purified textual data were then processed under AI-assisted word frequency and thematic clustering method to give conceptually related NVivo-based qualitative data analysis.

High-frequency words that were identified during the transcript mining process were AI, training, learning, quality, engagement, personalization, support, leadership, privacy, ethics, and human. The predominance of these words points to dimensions of centrality as a result of which corporate trainers perceive and sense adoption of AI in learning pedagogy.

One of the most powerful themes that have come out of analysis was close relation of AI with the increased training effectiveness. AI tools were always characterized by trainers as factors that enabled enhanced engagement of learners, expedited understanding, and enhanced coherence between training content and needs of the learners. Analytics and feedback mechanisms that were driven by AI were also seen as especially useful when tracking learner progress and determining which areas need instructional interventions. This qualitative observation supports the quantitative results of performance expectancy and perceived usefulness (Holmes et al., 2019).

The other theme that was prominent was AI as an enabler of personalization and skills cultivation. According to the trainers, AI-based learning routes allow focused upskilling and reskilling, as they focus on personal competency holes. Corporate training wise, this ability was considered to be essential in facilitating lifelong learning and labour mobility. The trainers emphasized that because AI-assisted diagnostics enables trainer to concentrate on the strategic facilitation instead of manual evaluation.

One of the important contextual themes that came out was organizational and leadership influence. According to interviewees, leadership support, organizational clarity, and peer acceptance played an important role in their readiness to adopt AI tools. Trainers in organizations where the leadership was actively promoting AI initiatives told them they felt more confident and receptive to experimentation. On other hand, there were no clear guidelines and institutional backing leading to guarded or selective embrace (Holmes et al., 2019). Ethical issues and data privacy was another major thematic cluster. The trainers were more cautious of use of AI tools to capture the sessions, generate transcripts, and assess the

behaviour of the learners. Misuse of data, breach of confidentiality, bias in algorithms, among others, were all demarcations that raised concerns in adoption particularly in high-stakes or sensitive learning environments. These findings demonstrate that ethics and trust are not peripheral problems but are central determinants that identify behaviour of AI adoption.

Lastly, the motif of human enhancement versus prostitution was repeatedly made. Those who worked as trainers vehemently said that AI ought to act as an aid instead of replacing the role of a human trainer. Emotional intelligence, contextual judgement, mentoring, and facilitation were considered to be quite human abilities that can never be replicated by AI. This is a strengthening aspect of hybrid pedagogy model where AI has increased efficiency and insight and pedagogical control is still held by human trainers.

On the whole, qualitative transcript mining proves the fact that AI implementation in corporate learning pedagogy is viewed as performance sensitive, contextual, and ethically constrained. The qualitative data give RII analysis its richness and complexity and enhance the explanatory strength of constructs of TAM and UTAUT2 (Venkatesh, Thong, & Xu, 2012) in the context of corporate training.

5.0 Findings / Results

5.1 Performance expectancy and perceived usefulness

The RII analysis indicates that performance expectancy and perceived usefulness registered the highest index values, which means that AI-enabled personalization, enhanced training effectiveness, enhanced assessment accuracy, and administrative efficiency are main triggers of adoption. Qualitative transcript mining supports this trend by mentioning terms of effectiveness, quality, personalization, and engagement repeatedly, which can be explained by the attention of trainers to outcome-oriented advantages. These results correspond to previous studies that have stated perceived usefulness as the ultimate predictor of technology acceptance and indicated the beneficial effect of AI-enabled personalization on learning performance (Davis, 1989; Holmes et al., 2019).

5.2 Effort expectancy

The results show that effort expectancy is not a dominating factor but a supportive one in the adoption of AI and the RII values are moderately high which implies that AI tools are not seen as being excessively complicated by trainers. According to results of the interview, the initial usability issues are reduced as the experience and reuse increase, and less effort is perceived over time. This trend can be matched with TAM that suggests influence of perceived ease of use indirectly on adoption by fortifying perceived usefulness (Davis, 1989).

5.3 Facilitating conditions and organizational readiness

Facilitating conditions proved to be an influential factor in AI adoption, and high RII scores of organizational support and infrastructure imply that adoption heavily relies on the institutional willingness, whereas lower RII scores of training adequacy show that there is gap in capacity. Qualitative analysis reveals that approach of implementing it systematically, providing technical assistance, and supporting the leadership facilitates an easier adoption process, and lack of training and ambiguous policies inhibit the application despite the perceived utility. These findings are in line with UTAUT2 which determines facilitating conditions as direct indicator of technology use in organizational settings (Venkatesh et al., 2012).

5.4 Social influence

RII findings mean that encouragement of leadership and peer usage has moderate effect on adoption of AI, which implies that concept of social context could influence readiness of trainers to use AI tools. Findings of interview indicate that leadership approval removes uncertainty and legitimizes use of AI, which enhances trainer confidence when implementing AI. This trend is similar to UTAUT2 that mentions social influence as reinforcing variable, especially in initial phases of technology adoption (Venkatesh et al., 2012).

5.5 Habit formation and sustained usage

Variables related to habits showed rather high RII, which means that routine use facilitates the continuation of AI adoption, and frequent users demonstrated less effort expectancy and increased reliance on AI when it comes to performing routine training activities. Qualitative results illustrate that with repetitive exposure, AI tools are integrated into training processes, and initial attitudes are not relied upon. This tendency is consistent with UTAUT2 that recognizes habit as factor of further use of technology (Venkatesh et al., 2012).

5.6 Ethical trust

Ethical issues had the highest RII scores especially in rights to privacy of data, transparency, and regulatory procedures, which shows that the role of ethical governance as a precondition of AI adoption is factual. The analysis of transcripts reveals that often, privacy, trust, and accountability are mentioned, and trainers are conditional about AI tools according to understanding in the data treatment and algorithm transparency. The results are in line with the existing literature which places trust and ethical assurance as moderator variables in technology acceptance (Dwivedi et al., 2019).

6.0 Conclusion and Implications

The paper has discussed the implementation of Artificial Intelligence tools in corporate learning pedagogy through the combined use of the Technology Acceptance Model and Unified Theory of Acceptance and Use of Technology (Venkatesh, Thong, and Xu, 2012). The mixed- method research design was applied to study, which involved quantitative analysis along with qualitative input of corporate trainers that made it possible to understand what drivers' adoption more effectively and what are the experiential aspects of AI application within corporate learning settings.

Results show that use of AI in corporate learning is mainly value and performance based. The strongest predictors were perceived usefulness and performance expectancy, which means that the trainers are encouraged to use AI tools in case they contribute to improved learning effectiveness, efficiency, and personalization. Facilitating factors like institutional support, and leadership engagement as well as technical infrastructure proved to also have a huge impact on results of adoption, whereas comparatively low focus on training sufficiency reflects the current gap in the ability to use the technology fully, despite technological presence.

The perceived social influence and addition further stimulated the long-term adoption, where acceptance of leadership and peers made it easy to integrate AI tools into regular pedagogical routines. Results provide empirical evidence of TAM and UTAUT2 applicability to corporate learning setting and further expand these models using ethical assurance and trust as context moderators, which supports the significance of the human-centred and ethically sound approach toward AI integration.

7.0 Recommendations

- **AI Governance:** have a clear governance structure to handle ethical use, data privacy, transparency, and regulatory compliance a means to establish trust and address the issue of surveillance and prejudice.
- **Trainer Capability Development:** Introduce unceasing development and learning initiatives regarding AI-related proficiency, integration and data interpretation to improve trainer preparedness and diminish skill-associated opposition.
- **Phased Implementation:** Have a pilot-based, roll out to assess the effectiveness, overcoming situational issues, and proving value prior to increasing adoption.
- **Leadership Endorsement:** Proactive leadership support should be ensured by means of resources distribution, communication, and reinforcement of the culture of experimentation and learning.

- **Augmentation Focus:** Place AI as augmentative technology that supplements effectiveness of instruction without replacing a key role of human trainers.

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Declaration: I here by declare that the research paper titled “Adoption of AI Tools in Corporate Learning Pedagogy” submitted to the “NLPGRS-2026” is my original work and has not been generated using any artificial intelligence tools or assistance. I confirm that content has been checked for plagiarism and that similarity index of paper is below 10%. I understand that any violation of this declaration may result in rejection of the paper or disciplinary action as per institutional guidelines.

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CHAPTER 6

Comprehensive Performance Indicators for Public Private Partnership Projects in India

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ABSTRACT

PPP projects have grown to be critical for the development of urban infrastructure across the world, enabling investment, innovation and risk sharing between public and private sectors. In India, urban infrastructure is being developed by the PPP-based metro projects as per National Metro Rail Policy- 2017. Investment has been substantial, however the risks of cost overruns, ridership shortfalls, delays over securing land and poor governance continue. This study constructs a thorough India-specific framework for evaluating the performance of PPP metro projects. This framework includes nine dimensions: financial performance, project performance, risk management, market viability, governance and compliance, environmentally sustainable development, stakeholder relations, innovation and technology adoption, and safety and health performance. Based on a comprehensive review of literature, consultation with 42 professionals, and AHP analysis, the KPIs were identified, weighted, and ranked. The results indicate that the Safety & Health, Governance & Compliance and Stakeholder Relations are the most influential factors to assess PPP metro performance in India. The framework helps to enhance planning, accountability, decision-making capabilities and gives practical guidelines. Future research could utilize this framework to test against real-world case studies to demonstrate its relevance and prioritize sub-factors according to contextual significance.

Keywords: Public Private Partnership (PPP), Metro Project, Framework, Analytic Hierarchy Process (AHP), Key Performance Indicators (KPI's).

1.0 Introduction

Public-private partnerships (PPPs) constitute a major mechanism for infrastructure

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development worldwide, wherein public authorities and private sector participants collaborate in the financing, design, construction, and operation of large and complex projects (Robert Marschinski, 2009). In India, programs like the National Infrastructure Pipeline as well as sector specific guidelines are actively encouraging PPPs in the country to attract additional funds by the private sector to support faster delivery.

During the time period of 2014-2024, India has settled on 1,825 PPP projects in the sectors of airports, electricity, information and communication technology and waste management and the total investments done in the projects have reached up to US\$295.56billion. (Department of Economic Affairs, 2024). Nevertheless, with this large scale, systematic PPP performance assessment in India is still disjointed, thus hindering evidence-based governance and sustainability in the long term. One of the main weaknesses is the lack of an integrated, India-specific framework which is sensitive to the peculiarities of the regulatory, institutional and socio-economic environment of the country. Multidimensional factors are widely ignored by international structures that are usually finance-oriented and fail in the Indian setting that is marked by very different structures of governance, capacity limits and stakeholder interactions that do not match those seen in the advanced economies(Zhang, 2005) (Malaeb & Hamzeh, 2018).

This trend is particularly evident in the metro rail sector, where investments have reached ₹2.5 lakh crore (US\$28.86 billion) over the past decade under the National Urban Transport Policy's Metro Rail Policy Component (2017), which explicitly mandates private sector participation. Still similar projects face high costs, low ridership, revenue deficit, delays due to land acquisition, poor governance and prevalent inefficiencies (Ministry of Housing and Urban Affairs, 2023) (Ahmad et al., 2022).

The current study fills this gap by developing a context-specific Performance Evaluation Framework (PEF) that fits in the context of an Indian PPP infrastructure with particular reference to metro rail. The framework generalizes best practices across the globe but incorporates India specific variables hence going beyond the traditional financial indices to include technical efficiency, quality of governance, stakeholder satisfaction and concerns to sustainability. The research has two major objectives. Firstly, it begins by reviewing and critically examining the existing PPP frameworks with the aim of coming up with transferable indicators that can be used to fit the Indian scenario. Second, it utilizes both the stakeholder consultations and the Analytic Hierarchy Process (AHP) to rank, weight, and combine indicators into 9 dimensions to create a valid, empirically based framework. These objectives will be achieved with the help of a mixed-methods design, comprising a systematic literature review, application of AHP, and consultations with stakeholders. The significance of the study lies in yielding scholarly innovation in a theoretically sound, empirically examined, multidimensional approach to Indian PPPs, to fresh financial biases and to scholarship in the

field of emerging-economy governance. In a practical sense, the framework provides policymakers, regulators, and business parties with evaluation instruments that would boost the success of the projects, repair the gaps, and make investments of the metro rail sustainable. In terms of policy formulation, the framework can provide practical information that can fine-tune PPP in their plans; thus, enhancing further mobilization of the population of the privates and efficient infrastructure provision in the country.

2.0 Literature Review

2.1 Introduction and context

Key Performance Indicator (KPI) models are fundamental mechanisms that appraises the effectiveness and sustainability of Public-Privately-owned Partnership (PPP) infrastructure projects. In the last two decades of academic work, KPI systems have been broadened to include more than the traditional cost-time quality metrics, with aspects of governance, innovativeness, involvement of stakeholders, and sustainability being introduced. In this review, eight major frameworks (see Annexures) are evaluated: (Ahmad et al., 2022), (Yuan et al., 2009), (Yuan et al., 2012), (Ugwu & Haupt, 2007), (Muhammad & Johar, 2017), (Hossain et al., 2019), (Mohamad et al., 2018), and (JPR, 2022), which reflects the conceptual progress in the field of PPP performance measurement (Table 1). There is an acute gap between these international models and their pertinence to the unique institutional, regulatory and working environment in India. This Ambiguity can be attributed to the federal system of governance in India, legislation of land-acquisition, and institutions of varying capacities in different states and municipalities and ineffective data reliability at the public administration.

2.2 Comparative framework analysis

The structures have developed into primitive cost- time- quality indicators to multidimensional frameworks that involve governance, sustainability, stakeholder participation, and innovation.

Table 1: Review of 8 Selected Frameworks

Framework	Authors (Year)	Paper Title	Core Focus Areas	Key Contribution
Framework 01	Ahmad et al. (2022)	Developing a Performance Evaluation Framework for PPP Projects	Contract design, cost-time performance, service quality, stakeholder relations, sustainability	Provides one of the most comprehensive, contract-centric KPI sets (40 KPIs) linking operational performance with socio-economic and sustainability outcomes

Framework 02	Yuan et al. (2012)	Developing KPIs for PPP Projects: Questionnaire Survey and Analysis	Project basics, finance, innovation, stakeholder satisfaction, project processes	Empirically validated KPIs (41 KPIs) integrating governance, innovation, and learning into PPP performance; includes fuzzy TOPSIS analysis for lifecycle phase prioritization
Framework 03	Ugwu & Haupt (2005)	KPIs and Assessment Methods for Infrastructure Sustainability	Environmental, social, resource utilization, health & safety	Introduces sustainability-driven KPIs (44 KPIs) emphasizing lifecycle environmental and social impacts; pioneering framework for developing-country infrastructure contexts
Framework 04	Yuan et al. (2009)	Selection of Performance Objectives and KPIs to Achieve VfM	Governance, finance, innovation, stakeholder management, project process	Strong focus on value-for-money through balanced managerial and financial indicators; emphasizes governance and risk management integration
Framework 05	Zayyanu & Johar (2007)	Conceptual Framework for Evaluating PPP Success	Governance, procurement, investment climate, risk allocation	Emphasizes institutional and governance conditions over operational metrics; highlights success factors approach rather than performance measurement
Framework 06	Hossain et al. (2018)	Performance Indicators of PPP in Bangladesh	Planning, financing, transparency, lifecycle performance, socio-economic impact	Developing-country-oriented framework (42 KPIs) addressing implementation and institutional capacity gaps; closest to Indian context in global literature
Framework 07	Mohamad et al. (2018)	Performance Indicators for PPP Projects in Malaysia	Financial sustainability, marketability, innovation	Focuses on financial robustness and innovation but limited coverage of social and governance aspects
Framework 08	Nuno & de Gaia (2022)	Performance Measurement and Evaluation of PPPs: A Systematic Review	Traditional KPIs, stakeholder, lifecycle, innovation, accountability	Synthesizes global PPP KPIs and introduces emerging dimensions such as BIM utilization and accountability; reflects latest thinking on infrastructure digitalization

Source: Created by authors

2.3 Conceptual evolution and key patterns

Initial studies such as Ugwu and Haupt (2005) emphasized environmental, social, and financial dimensions of project performance. Later works by Yuan et al. (2009, 2012) expanded this scope by incorporating governance, risk management, and learning within value-for-money assessments in developed contexts like Australia, Canada, and the United States. Recent frameworks (Hossain et al., 2019; JPR, 2022) recognize institutional capacity and socio-economic outcomes in developing economies but still treat them as secondary factors. The Bangladesh framework by Hossain et al. (2019), while similar to India's context, prioritizes governance processes over regulatory and institutional barriers.

2.4 KPI analysis and local adaptation

Analysis of eight frameworks revealed convergence across 17 KPI pairs and 48 clusters among 251 indicators, primarily focusing on project management (29.9%) and financial performance (17.9%). Core KPIs such as cost, time, quality, risk, and environmental management are consistent, whereas innovation, social impact, and safety remain underrepresented.

Existing frameworks emphasize isolated dimensions, often ignoring local regulatory capacity and institutional diversity. In India, KPI adaptation must reflect specific legal and financial contexts—such as RFCTLARR (2013), VGF, InvITs—and align with oversight from NGT, SEBI, RBI, and CAG to address socio-political and environmental factors absent in global PPP frameworks.

2.5 Consolidated Indian specific framework

The proposed framework identifies four guiding principles that collapse shifts 12 categories into 9 to get rid of 23% of redundancies without covering essential aspects (Table 3):

- Principle 1: Operational Integration- Combines time, quality and facility measurements to Project Performance and introduces land acquisition delay and monsoon-impact measures.
- Principle 2: Financial Consolidation unites Value for Money, marketability and tariff measures to Financial Performance with an Inflation Sensitivity Index and a VGF Ratio.
- Principle 3: Governance Convergence- absorbs contract execution into Governance Compliance, such as RTI rates and monitoring amendments.
- Principle 4: Risk Specialization—Standalone due to India's political/regulatory risks.

This style combines international best practices with Indian needs producing an integrated but rational framework.

Table 2: Consolidated Framework for Indian Metro PPP projects

Core Category	Subcategory (KPI)	KPI (Global + India-Specific)	Significance
Financial Performance	Cost Management	- Construction Cost Variance & Growth	Controls budget overruns and enhance financial predictability for stakeholders.
		- Operational Cost	Ensures long-term financial sustainability and service quality maintenance.
		- Inflation Sensitivity Index	Critical for managing India's volatile inflation environment.
		- Subsidy Dependency Ratio	Indicates financial reliance on public funding and affects project sustainability.
		- Local Currency Financing Ratio	Reduces foreign exchange risk in financial planning.
	Profitability & Value for Money	- Sustainable Profitability	Ensures private-sector viability and attractive investment.
		- Value for Money Test	Validates the efficiency and appropriateness of PPP approach.
	Tariff & Subsidy Mechanisms	- Tariff/Toll Adjustment Mechanism	Balances affordability for users and financial viability for operators.
		- Viability Gap Fund Utilization	Ensures optimal allocation of public resources.
Project Performance	Schedule & Delays	- Construction Time Variance & Growth	Identifies bottlenecks and facilitates improved project delivery.
		- Project & Concession Period Duration	Ensures effective resource utilization and timely project handover.
		- Land Acquisition Delay Days	Critical in India where land acquisition often causes major project delays.
		- Monsoon Delay Days	Supports seasonally adjusted planning and risk mitigation.
	Coordination & Interfaces	- Agency Coordination Index	Reduces bureaucratic delays and improves multi-stakeholder cooperation.
		- Interface Management	Minimizes conflicts and smooths transition across project lifecycle stages.
	Quality & Facilities	- Quality Control	Maintains asset integrity and minimizes rework/maintenance costs.
		- Facility Management	Prolongs asset life and sustains service quality.
		- Safety & Health Management Systems	Protects worker welfare and ensures regulatory compliance.
Risk Management		- Risk Management System	Improves project resilience and risk awareness.

	Risk Identification & Mitigation	- Force Majeure Incident Frequency	Measures vulnerability to external shocks.
		- Policy Change Impact Score	Essential for managing regulatory risk, especially in emerging markets.
		- Credit Quality Index	Helps evaluate financial risk and partner reliability.
		- Fair Risk Allocation	Prevents scope creep and cost disputes.
Environment & Sustainability	Environmental Compliance	- EIAR Compliance	Ensures environmental protection and legal compliance.
		- NGT Compliance Rate	Mitigates legal risks related to environmental issues.
		- Local Biodiversity Impact Index	Demonstrates commitment to ecological sustainability.
	Resource & Emissions	- Waste Management	Minimizes environmental pollution and regulatory penalties.
		- Renewable Energy Integration Ratio	Supports carbon reduction and operational cost savings.
	Long-Term Sustainability	- Benefit Sustainability (Long-Term vs Short-Term)	Aligns project objectives with sustainable development goals.
		- Scalability & Replicability	Maximizes knowledge transfer and investment efficiency.
	Stakeholder Relations	Community Engagement	- Community Involvement
- Panchayat Consultation Score			Ensures grassroots democratic participation and transparency.
- Local Employment Ratio			Promotes inclusive economic development.
- Displacement Compensation Timeliness			Helps maintain community goodwill and legal compliance.
Satisfaction & Trust		- Stakeholder Satisfaction	Drives continuous improvement and accountability.
		- Public Client Satisfaction	Ensures alignment with public policy and expectations.
		- Trust Building	Strengthens partnership and cooperation.
		- Responsiveness to Complaints	Maintains service quality and reputation.
Innovation & Technology	Technology Adoption & R&D	- Technology Innovation	Improves efficiency, reduces costs, and enhances service quality.
		- Local Technology Adoption Rate	Supports local industry and aligns with ‘Make in India’ policies.
		- R&D Investment	Drives innovation and competitive advantage.

	Digitalization	- R&D Collaboration Count	Accelerates knowledge transfer and innovation diffusion.
		- Digitalization Index	Enhances transparency, monitoring efficiency, and data accuracy.
		- Technology Transfer	Builds capacity and supports sustainability.
		- Learning Organization Setup	Fosters innovation culture and process improvement.
Governance & Compliance	Transparency & Accountability	- Good Governance	Builds stakeholder confidence and supports ethical project management.
		- RTI Compliance Rate	Empowers public oversight and trust.
		- Disclosure of Project Information	Increases transparency and stakeholder engagement.
		- Audit Finding Closure Time	Ensures proper control and accountability improvements.
	Contract Governance	- Contract Framework & Flexibility	Supports project adaptability and risk management.
		- Contract Amendment Frequency	Reflects contract robustness and operational adaptability.
		- Dispute Resolution Provisions	Minimizes disputes and project delays.
Safety & Health	Occupational Health & Safety	- Health and Safety Management Systems	Protects workforce and reduces legal/operational risks.
		- National Injury Frequency Rate	Tracks safety culture maturity and effectiveness.
		- Accidents, Injuries & Fatalities	Monitors risk control and continual improvement.
Market & Commercial	Market Viability & Financial Health	- Increased Marketability	Ensures revenue generation and commercial success.
		- Shareholders' Financial Ability	Reduces financial risks and supports project completion.
		- Availability of Financial Market	Enhances financial agility and cost optimization.
		- EIRR Variance	Indicates accuracy of economic forecasting and long-term value creation.

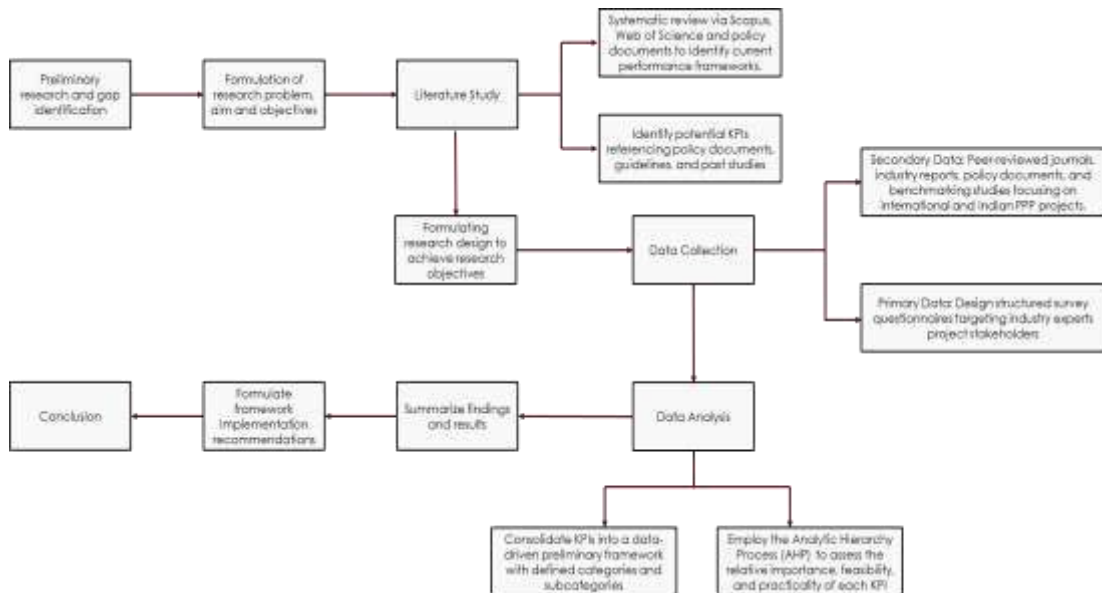
Source: Created by authors

3.0 Methodology

The proposed research design is a mixed-method research design combining systematic literature review, framework synthesis, expert consultation, and quantitative analysis via the Analytic Hierarchy Process (AHP) to create an inclusive performance measurement framework of Public- Private Partnership (PPP) metro projects in India (Figure

1). The nine-phase approach guarantees the rigor, reproducibility and applicability to the Indian infrastructure situation. Key Performance Indicators (KPIs) are empirically weighted using the quantitative approach based on structured expert judgment and conceptually define and make them related to their context using the qualitative validation approach.

Figure 1: Research Methodology Framework for PPP Project Performance Evaluation



Source: Created by authors

3.1 Literature review and framework development (Phases 1-3)

A systematic review was conducted using Scopus and Web of Science databases covering 2005–2025. The keywords “Public–Private Partnership KPIs,” “PPP performance indicators,” and “infrastructure project performance measurement” were used. Papers were selected based on direct relevance, methodological transparency, and quantifiable indicators, resulting in 38 screened studies. Of these, 18 empirically verified frameworks were analysed through standardized extraction templates, revealing eight comprehensive frameworks with common focus areas such as financial performance, operational efficiency, stakeholder satisfaction, risk management, and value for money.

Findings from these frameworks were synthesized into 12 KPI packages encompassing 59 individual performance indicators. To adapt the framework to India’s context, policies such as the National PPP Policy, Infrastructure Vision 2025, and National Metro Rail Policy 2017 were integrated. These ensured inclusion of social impact

measurement, environmental sustainability, and community engagement dimensions. The final KPI packages included: Financial Performance, Project Performance, Risk Management, Environment and Sustainability, Stakeholder Relations, Innovation and Technology, Governance and Compliance, Safety and Health, and Market and Commercial Dimensions.

3.2 Sample design and data collection (Phases 4-6)

A purposive sampling method was adopted to ensure representation of diverse stakeholder perspectives. Forty-two respondents were selected based on their involvement in PPP infrastructure projects, knowledge of metro systems, and understanding of performance measurement techniques. Respondents had between 1 and 30 years of relevant experience and represented major metro projects across Delhi, Mumbai, Pune, Hyderabad, Bangalore, and Nagpur. This diversity enhanced the reliability and generalizability of responses.

Primary data were collected via a web-based survey that included two core components: (1) KPI definitions and operational descriptions, and (2) hierarchical AHP pairwise comparison matrices. A three-level hierarchical structure was applied with the overall objective—PPP metro performance evaluation—at Level 1, nine KPI categories at Level 2, and their respective indicators at Level 3. Saaty's 1–9 scale was used to assess relative importance, while reciprocal values (1/3, 1/5, 1/7, 1/9) were applied for inverse comparisons. The questionnaire was pre-tested for clarity and consistency. Supplementary information was gathered from peer-reviewed journals, government documents, industry reports, and benchmarking studies to strengthen validation.

3.3 AHP Computation and Validation (Phases 7-9)

AHP calculations were performed using Microsoft Excel's matrix functions. The Consistency Ratio (CR) was computed for each respondent as $CR = CI/RI$, with a threshold of 0.20 deemed acceptable per Saaty's guideline. Out of 42 responses, 34 exhibited consistent judgments, indicating reliability and producing a retention rate of 80.95%. The geometric mean method aggregated individual priority vectors, preserving the ratio-scale character of AHP data. Derived normalized weights reflected expert consensus and were classified into four priority tiers: High (>15%), Medium–High (10–15%), Medium (5–10%), and Low (<5%).

3.4 Framework integration and limitations

Quantitative AHP results were integrated with qualitative feasibility assessments to refine the framework. Indicators with high weights but low practicality were reviewed and adjusted. The final framework presented a hierarchically structured, data-centric synthesis

reflecting both international benchmarking and Indian stakeholder priorities. However, limitations include the narrow focus on Indian PPP metro projects, restricting broader generalizability. The purposive sampling, while ensuring expert input, may introduce selection bias. Finally, the dependability of AHP outcomes rests on the coherence of expert judgments. Despite these limitations, the approach ensures methodological rigor and contextual validity for evaluating PPP metro performance in India.

4.0 Data Analysis

4.1 Data transformation and processing

Raw pairwise comparison judgments were transformed analytically into measurable priorities, integrating expert knowledge with mathematical processing (Decision Making Using Analytical Hierarchy Process, 2025). Forty-two AHP questionnaires were converted into a group consensus priority vector over nine performance indicators. Respondents, stratified by career experience (1–10, 11–20, and 21+ years), rated comparisons using Saaty's 1–9 scale. The process involved: (1) building positive reciprocal matrices, (2) normalizing columns and averaging rows to approximate eigenvectors, and (3) aggregating results via the geometric mean.

Table 2: Construction of Positive Reciprocal Pairwise Comparison Matrices for Respondent 32 (R32)

COMPARISON MATRIX									
	Financial Performance	Project Performance	Risk Management	Environment & Sustainability	Stakeholder Relations	Innovation & Technology	Governance & Compliance	Safety & Health	Market & Commercial
Financial Performance	1.00	5.00	3.00	5.00	3.00	0.33	1.00	1.00	0.20
Project Performance	0.20	1.00	1.00	3.00	1.00	0.20	1.00	3.00	0.20
Risk Management	0.33	1.00	1.00	3.00	1.00	0.20	1.00	3.00	0.20
Environment & Sustainability	0.20	0.33	0.33	1.00	0.20	0.14	0.20	1.00	0.11
Stakeholder Relations	0.33	1.00	1.00	5.00	1.00	0.20	1.00	3.00	0.20
Innovation & Technology	3.00	0.20	0.20	7.00	3.00	1.00	5.00	7.00	1.00
Governance & Compliance	1.00	1.00	1.00	0.20	0.20	0.20	1.00	1.00	0.20
Safety & Health	1.00	0.33	0.33	1.00	0.20	0.14	0.33	1.00	0.20
Market & Commercial	5.00	5.00	5.00	9.00	5.00	1.00	5.00	5.00	1.00
Sum	22.07	28.67	27.67	30.00	28.00	1.42	28.33	29.00	2.21

Source: Created by authors

Table 3: Matrix Normalization and Priority Vector Calculation

NORMALIZED DATA										
	Financial Performance	Project Performance	Risk Management	Environment & Sustainability	Stakeholder Relations	Innovation & Technology	Governance & Compliance	Safety & Health	Market & Commercial	Priority Vector
Financial Performance	0.08	0.25	0.17	0.13	0.18	0.10	0.05	0.03	0.06	0.12
Project Performance	0.02	0.05	0.06	0.08	0.06	0.06	0.05	0.10	0.06	0.06
Risk Management	0.03	0.05	0.06	0.08	0.06	0.06	0.05	0.10	0.06	0.06
Environment & Sustainability	0.02	0.02	0.02	0.03	0.01	0.04	0.01	0.03	0.03	0.02
Stakeholder Relations	0.03	0.05	0.06	0.13	0.06	0.06	0.26	0.17	0.06	0.10
Innovation & Technology	0.25	0.25	0.28	0.18	0.30	0.29	0.26	0.24	0.30	0.26
Governance & Compliance	0.08	0.05	0.06	0.13	0.01	0.06	0.05	0.10	0.06	0.07
Safety & Health	0.08	0.02	0.02	0.03	0.01	0.04	0.02	0.03	0.06	0.03
Market & Commercial	0.41	0.25	0.28	0.23	0.30	0.29	0.26	0.17	0.30	0.28
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Source: Created by authors

4.2 Consistency assessment and data quality control

Matrix consistency was tested through the Consistency Index (CI) and Consistency Ratio (CR), with $CR < 0.20$ considered acceptable. For $\lambda_{\max} = 10.11$ and $n = 9$, $CI = 0.14$ and $CR = 9.6\%$, indicating reliable coherence. Of 42 responses, 34 met the threshold (mean $CR = 11.94\%$), yielding an 80.95% retention rate. The eight inconsistent responses ($CR = 22.6\text{--}79.2\%$) were excluded to preserve methodological integrity.

Table 4: Consistency Analysis - Lambda Max Calculation

LAMBDA CALCULATION										
Financial Performance	Project Performance	Risk Management	Environment & Sustainability	Stakeholder Relations	Innovation & Technology	Governance & Compliance	Safety & Health	Market & Commercial	Sum	Consistency Vector
0.12	0.30	0.18	0.12	0.29	0.09	0.07	0.03	0.06	1.25	10.61
0.02	0.06	0.06	0.07	0.10	0.05	0.07	0.10	0.06	0.59	9.91
0.04	0.06	0.06	0.07	0.10	0.05	0.07	0.10	0.06	0.60	9.97
0.02	0.02	0.02	0.02	0.02	0.04	0.01	0.03	0.03	0.22	9.53
0.04	0.06	0.06	0.12	0.10	0.05	0.34	0.17	0.06	0.99	10.22
0.35	0.30	0.30	0.16	0.48	0.26	0.34	0.24	0.28	2.72	10.37
0.12	0.06	0.06	0.12	0.02	0.05	0.07	0.10	0.06	0.65	9.72
0.12	0.02	0.02	0.02	0.02	0.04	0.02	0.03	0.06	0.35	10.17
0.59	0.30	0.30	0.21	0.48	0.26	0.34	0.17	0.28	2.93	10.53
Lambda										10.11

Source: Created by authors

4.3 Pairwise comparison matrices, priority weights and aggregation

The aggregated 9×9 reciprocal matrix ($a_{ij} \times a_{ji} = 1$) gave stable eigenvalues with tolerable deviations. Using Saaty's invariance principle ($Aw = \lambda w$), normalized eigenvectors produced the priority weights. Group-level aggregation through geometric mean preserved ratio-scale properties. Final weights ranked Safety and Health (25.14%) and Governance and Compliance (18.99%) highest, reflecting strong coherence and prioritization of safety and regulatory compliance in India's PPP infrastructure context.

Table 5: Aggregation of Individual priorities using geometric mean approach

Aggregation of Individual Priorities (AIP)																																					
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	R32	R33	R34	Geometric Mean	Normalized Weight	
Financial Performance	0.11	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.27	0.32	0.35	0.36	0.03	0.04	0.03	0.03	0.04	0.03	0.04	0.04	0.04	0.03	0.04	0.03	0.04	0.39	0.12	0.14	0.03	0.047	5.61%	
Project Performance	0.06	0.04	0.05	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.25	0.17	0.20	0.07	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.24	0.18	0.06	0.17	0.02	0.036	4.35%	
Risk Management	0.04	0.08	0.09	0.07	0.07	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.15	0.10	0.11	0.14	0.07	0.05	0.06	0.05	0.05	0.05	0.05	0.07	0.07	0.07	0.05	0.15	0.05	0.06	0.16	0.05	0.066	7.89%	
Environment & Sustainability	0.02	0.07	0.07	0.07	0.07	0.07	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.11	0.05	0.09	0.04	0.05	0.06	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.10	0.11	0.02	0.05	0.06	0.058	6.97%
Stakeholder Relations	0.08	0.11	0.17	0.14	0.12	0.11	0.11	0.11	0.11	0.11	0.10	0.11	0.08	0.08	0.07	0.08	0.09	0.12	0.10	0.11	0.12	0.10	0.10	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.09	0.09	0.10	0.11	0.11	0.105	12.65%
Innovation & Technology	0.03	0.07	0.05	0.07	0.08	0.09	0.05	0.06	0.06	0.07	0.07	0.07	0.09	0.05	0.06	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.06	0.26	0.08	0.05	0.056	6.74%	
Governance & Compliance	0.32	0.27	0.26	0.25	0.25	0.24	0.21	0.21	0.21	0.22	0.22	0.21	0.12	0.04	0.03	0.03	0.04	0.22	0.23	0.21	0.21	0.23	0.22	0.22	0.21	0.22	0.21	0.20	0.23	0.11	0.04	0.07	0.14	0.23	0.158	18.99%	
Safety & Health	0.08	0.26	0.20	0.23	0.25	0.25	0.37	0.36	0.36	0.36	0.36	0.35	0.22	0.03	0.14	0.06	0.13	0.33	0.34	0.35	0.35	0.33	0.35	0.33	0.35	0.33	0.35	0.36	0.34	0.21	0.05	0.03	0.04	0.34	0.209	25.14%	
Market & Commercial	0.27	0.08	0.08	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.33	0.03	0.06	0.03	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10	0.11	0.03	0.02	0.28	0.10	0.11	0.097	11.67%	
SUM																																		0.832		100.00%	

Source: Created by authors

5.0 Results

Analytical Hierarchy Process (AHP) analysis of pairwise comparisons with nine evaluation criteria monitored resulted in a normalized distribution of the weight that confirmed the relative importance of each individual criterion to outcomes of the success of PPP projects in the Indian infrastructure scenario. The results indicate that there is a stratified priority system through the evaluation system, and this is systematically explained as follows.

5.1 High-priority criteria (≥15% Weight)

- Safety & Health** turned out to be the most significant evaluation criterion with normalized weight of 25.14% with over a quarter of the total evaluation weight. This finding indicates acknowledgment of stake holders that occupational health and safety measures, hazard controls, risk mitigation measures and welfare of workers are major success factors in the PPP infrastructural projects. The strong focus on Safety and Health takes the traditional financial measures out of the respondent list, which points to a paradigm shift toward triple-bottom-line assessment approaches that encompass both social and occupational aspects along with financial feasibility. The observation is in line

with the modern days practice of infrastructure management that is more focused on the protection of human capital.

- **Governance Compliance** was rated second with a normalized weight of 18.99 %, which points to the extreme significance of regulatory compliance, openness of decision-making procedures, and institutional accountability systems in PPP systems. This weighting was based on the fact that in Indian context there is special focus on compliance with the provisions of the Right to Information (RTI), regulations of the audit frameworks, and governmental multi-layered approval. As a requirement to deliver partnership success and sustainable value delivery within a project, stakeholders clearly emphasize the elements of clarity in the contractual governance schemes and institutional settings.

5.2 Medium-high priority criteria (10–15% weight)

- **Stakeholder Relations** with the weight of 12.65% emphasizes the great importance of community involvement, trust-building in relations between the public and the partner companies, and institutional attention to the stakeholder reactions. This is a criterion in Indian PPP context that covers the compulsory consultation in panchayats, compensation mechanisms on displacement and the community benefit-sharing. The stakeholder weightings revealed in the weighting are that there is great stakeholder relations to reduce the effects of social risks and increase the project legitimacy among the larger public constituency.
- **Market Commercial** considerations were given a weight of 11.67%, the balance to be between commercial viability and protection of the public interest. This package includes financial capacity evaluation of the shareholders, market attractiveness evaluation and the financing methods. The specified weight reflects the fact that involvement in the private sector requires the established capacity to achieve sustainability of returns and guarantee consistency of revenue streams due to the necessary use of relevant mechanisms of adjusting tariffs and implementing strict demand forecasting procedures.

5.3 Medium priority criteria (5–10% Weight)

- **Risk Management** has a weight of 7.89% and it deals with the organized approach of identifying, assigning, and eliminating risks in the project within the partnership lifecycle. The moderate weighting does not diminish the risk management aspect of the entire evaluation setup as it represents the trust of stakeholders towards contractual and institutional arrangements that they have in addressing the overall risks holistically. The comparatively less priority than governance and safety can indicate that the respondents perceive risk management as an institutional facilitator but not an independent source of success.

- **Environment Sustainability and Innovation Technology** are the ones that belong to the medium-priority band with the weight of 6.97% and 6.74% respectively. Environmental factors, such as adherence to regulations of the National Green Tribunal (NGT), integrated waste management, and protection of ecosystem, are mandatory compliance factors, but are rated lower than the safety and governance factors. Likewise, the innovations in technology and research and development investment are considered as enabling capabilities that improve the project delivery, instead of being the major determinants of evaluation, perhaps based on the stakeholder perception that the adoption of technology is situational and secondary to institutional maturity.

5.4 Lower priority criteria (<5% Weight)

- **Financial Performance**, with a weight of 5.61, had a surprisingly small prioritization, appearing as the eighth in the list of the nine evaluation criteria. This finding is a marked contrast to the traditional practice of infrastructure evaluation, which has long held cost management and return on investment as the key success metrics. The reduced weighting can be seen as the trust that stakeholders have in existing financial assessment tools (Internal Rate of Return, Net Present Value and debt-service-coverage-ratio calculations) and their acknowledgment that monetary analysis, needed as it is, remains an inadequate single measure of success evaluation. Alternatively, the same result could also reflect stakeholder acknowledgement that financial sustainability is a by-product of good governance, stakeholder management and strong risk mitigation instead of a standalone cause.
- **Project Performance**, which includes schedule adherence and cost variance indicators, had the lowest weight at 4.35 or under 5 percent of total evaluation weight. Although the operational factors, performance metrics also seem to be regarded as end measures of the effectiveness of antecedent success factors, and not as evaluation drivers. This weighting implies that the stakeholders will be more interested in preventative and foundational measures (safety, governance, stakeholder relations) rather than reactive outcome measures because it is an advanced evaluation philosophy that values root causes of success over symptom-based metrics.

5.5 Framework validation against extant literature

The priorities obtained using Analytic hierarchy Process are quite consistent with the findings provided in the academic literature, at the same time providing significant results which are specific to the situation of the Indian public-private partnership. The following comparative analysis reveals the trends of corroboration and dissimilarities which are local to the setting:

5.6 Alignment with existing frameworks

The existing research by Ahmad et al. (2022), Yuan et al. (2012), and Kukah et al. (2024) is consistent and unanimous regarding the factors that determine the success of PPP projects is the presence of governance structures, risk allocation mechanisms, and managing relationships with stakeholders. These results are corroborated by the high weightings of Governance Compliance (18.99 %) and Stakeholder Relations (12.65 %) in the current study, and the findings can be generalized to the wider applicability of the principles across geographical and sectoral frontiers.

5.7 Context specific insights

Safety and Health (25.14 %) attract such strong weight that it can be inferred that the regulatory priority in India differs, and this weight is further increased by the labor-intensive character of urban infrastructure projects, particularly those which are carried out in metropolitan construction. This greater focus on Governance Compliance is in tune with that of India, with its multilayered system of approval, with central government, state governments and municipalities, and compulsory transparency provisions created under the Right to Information Act of 2005. These situational determinants support the relevance of the appraisal framework in the Indian PPP system.

5.8 Divergence from traditional practice

The somewhat low weight given to Financial Performance (5.61%) is a significant deviation of the traditional paradigm of infrastructure analysis, in which the traditional concern of cost management and pay back is always the major issue. This finding is an implication that the stakeholders involved in the Indian PPP milieu, faced with the challenge of overrating a critique of holistic success, are more likely to deemphasize financial performance in favor of institutional and social aspects. The identified trend is conditioned by the development of PPP policy frameworks, gradually incorporating the mechanisms of social accountability and sustainability as the direct policy requirements, thus indicating the shift in the direction of the development of a multidimensional evaluation of the achievements in the sphere of the public-private partnership.

6.0 Conclusion

Public-Private Partnership (PPP) development of urban transport infrastructure via metro projects has evolved to be a major strategy in India. Nevertheless, the existing performance assessment remains disjointed, with existing frameworks, in the majority, being restricted to financial measurements and the conventional Value-for-Money (VfM) measures.

These tools fail to reflect crucial dimensions like governance, sustainability and stakeholder issues. The paper fills this gap by advancing a context-bounded model of performance evaluation of PPP metro projects in India, built on the basis of a thorough mixed-method methodology.

The study is based on the institutional, regulatory and socio-economic reality of India including land acquisition inefficiencies, contractual uncertainty and invariable small ridership-issues usually omitted in global PPP models. Applying a systematic synthesis of eight globally accepted assessment frameworks, with a nine-phase research process through the systematic literature review, framework synthesis, and expert judgement using the Analytic hierarchy Process (AHP), the research determined 251 Key Performance Indicators (KPIs) as falling into 13 themes. These have been summarized into 9 KPI packages with 59 indicators that are specific to the metro PPP environment of India.

The results of the AHP indicate a change in the perception regarding the determinants of PPP success by experts. The highest weighted criterion was Safety and Health (25.14) then Governance and Compliance (18.99) and Stakeholder Relations (12.65) with a total significance of over 56. More conventional metrics like Financial Performance (5.61%) and Project Performance (4.35) were slightly lower, and a paradigm shift in thinking about evaluating only financial and delivery-specific measurements to multidimensional measurements with greater emphasis on institutional governance, workforce safety, community and sustainability.

The suggested framework will help policymakers and practitioners with a solid base to prioritize investments, distribute risk, and evaluate performance in its entirety. It can enhance more accountability in government-private relations, help in the early detection of risks in projects, encourage the long-term social and environmental benefits, and empower the PPP governance institutional capabilities in India.

The study is confined to metro projects only and bases its analysis on expertise perception and not longitudinal outcome data, but such limitations raise potential opportunities to future studies. The possible leads are: empirical testing with operational metro case studies, comparative analysis of South Asian PPP transit systems, machine learning based on dynamic KPI weighting and longitudinal assessment of framework efficacy in enhancing project results.

Comprehensively, this research has created a scientific and policy-relevant basis on how to enhance PPP performance assessment in the Global South. It gives India the flexibility, transparency, and multidimensional structure that has the potential to enhance economic efficiency, social equity, and environmental sustainability in the development of urban infrastructure.

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CHAPTER 7

A Real Time Analysis of Project Management Methodologies in Different Sectors

Lay Shah, Lawanya Makde**, Vini Gupta*** and Avinash Bagul****

ABSTRACT

In today's competitive project management environment, it is crucial to study the project management methodologies (PMM's) tailored to suit the project environment for different industries. To assess each PMM's practical applicability, information was gathered through an online survey of project managers from different industries. By comparing PMM's such as PMBOK, Agile-SCRUM, Lean Construction, ISO 21500, and hybrid approach across different industries, the best methodology applicable for the specific industry was identified. Such analysis can help provide more flexibility and control to the project managers working in varied environments. The findings reveal that the hybrid method is the most flexible and successful in diverse environment projects through integration of the merits of the conventional and agile practices. With the help of these insights project managers can choose project management methods tailored to suit specific work environment resulting in better resource usage, management of risk proactively and take decision based on facts, enhancing the project delivery and overall organizational performance.

Keywords: Project Management Methodologies (PMM), Agile-SCRUM, Hybrid Approach, Comparative Analysis.

1.0 Introduction

The art of Project Management (PM) has a history dating back to pre-history as demonstrated by works of wonders of engineering like the Great Pyramid of Giza and the Great Wall of China.

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According to the records of past, these activities employed the initial management forms like certain existing hierarchies of oversight and stratified workers that were the forerunners of the asset allocation in contemporary times. Nevertheless, the origin of PM as a scientific field of study is said to be the invention of Gantt chart by Henry Gantt in 1917, a tool that contributed to the development of formal planning. During mid-20th century there were sophisticated military projects during systemization stage such as the Polaris project by the U.S Navy. Systemization stage called for strict quantitative mechanisms like the Critical Path Method (CPM), Program Evaluation Review Technique (PERT) and Work Breakdown Structure (WBS) and lined PM as a separate discipline. These practices were later enumerated in professional organizations like the Project Management Institute (PMI) and the International Project Management Association (IPMA). In 1987, Project Management Body of Knowledge (PMBOK) Guide was published, and together with ISO standards (10006 and 21500), this gave the industry an international, process centric outline.

The inflexibility of the traditional plan-focused models was made even more evident as complexities of various projects especially in the IT and infrastructure sectors increased. This required a paradigm shift on Agile methodologies- Scrum and Extreme Programming (XP)- which focuses on the iterative development, collaboration with stakeholders and high adaptability. Therefore, modern organizations are moving towards embracing hybrid structures, which combine the structural governing force provided by PMBOK with the dynamism of Agile to meet the dynamic needs. At the same time, project monitoring and control has been revolutionized by the digital revolution. The cooperation of real-time analytics and interactive dashboards has facilitated the use of data to monitor. Notwithstanding these developments, successful implementation still poses a challenge and is usually marred by the inconsistency in the data, cost of acquisition, as well as a failure to align the company strategy with operational measurements.

2.0 Literature Review

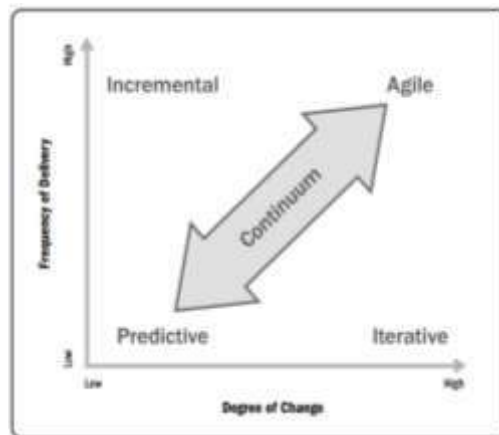
2.1 Characteristics of Project Life Cycles

Table 1: Characteristics of Four Categories of Life Cycle

Approach	Requirements	Activities	Delivery	Goal
Predictive	Fixed	Performed once for the entire project	Single delivery	Manage cost
Iterative	Dynamic	Repeated until correct	Single delivery	Correctness of solution
Incremental	Dynamic	Performed once for a given increment	Frequent smaller deliveries	Speed
Agile	Dynamic	Repeated until correct	Frequent small deliveries	Customer value via frequent deliveries and feedback

Source: Created by authors

Figure 1: The Continuum of Life Cycles

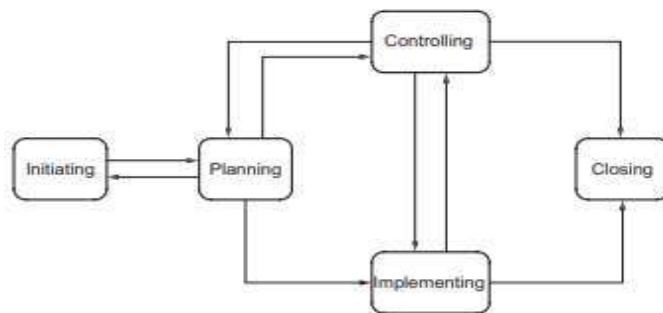


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2.2 Guideline on Project Management, ISO 21500: 2012

ISO 21500 has knowledge areas rather than subjects used in place of those of PMBOK and fewer processes, 39, replacing the 49 processes, but is functionally equivalent. The standard is not prescriptive but is descriptive, which allows flexibility in its implementation. (Binder et al., 2014)

Figure 2: Process Groups Interactions



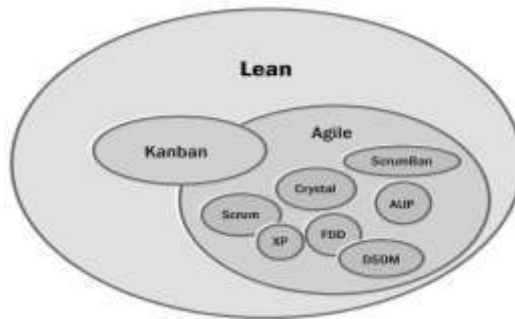
Source: Created by authors

2.3 PMBOK Guide – 6th Edition

The 6th version recognizes five process groups, ten knowledge areas, and 49 processes. The processes are characterized by the inputs, tools, and techniques, as well as outputs. It is most appropriate in large and complex projects and regulation-driven projects. (Čabarkapa, 2019).

2.4 Agile approaches

Figure 3: Agile is a Blanket Term for Many Approaches



Source: Created by authors

Agile is a set of frameworks and practices in line with the Agile Manifesto. Agile falls in the field of the Lean philosophy and focuses more on working solutions rather than documentation. (Binder, et al., 2014)

Table 2: Overview of Agile and Lean Methodologies

Method	Description
Scrum	Most popular Agile method; uses fixed-length sprints, roles (Scrum Master, Product Owner), and ceremonies (Daily Standups, Reviews).
XP (Extreme Programming)	Focuses on technical excellence with practices like test-first, pair programming, continuous integration.
Crystal	Emphasizes people over processes and tailor's practices to project size and criticality.
FDD (Feature-Driven Development)	Model-driven, iterative method focused on building and designing features.
DSDM (Dynamic Systems Development Method)	Emphasizes full project lifecycle and active user involvement.
AUP (Agile Unified Process)	A simplified version of Rational Unified Process tailored to Agile values.
Scrum-Ban	Hybrid of Scrum and Kanban, combining iterative planning with continuous flow.
Kanban	Although shown slightly outside core Agile, it's a Lean method emphasizing visual workflow, limiting WIP (Work in Progress), and improving flow. Often used with Agile for visual project tracking.

Source: Created by authors

2.5 Lean project management

Lean project management maximizes the value and reduction of waste via continuous improvement. Ballard and Howell visualize projects as transient production systems, which are sustained by stable systems. Koskela states that development of production systems and their design need to be a subject of project management. (Ballard and Howell, 2002)

2.6 Scrum methodology

Scrum is an Agile model which is built on iterative and incremental development suited for dynamic requirements. Scrum has short sprints, role definitions (Product Owner, Scrum Master, Development Team), and formal events to facilitate empirical control of the process and constant improvement. (Sachdeva, 2016)

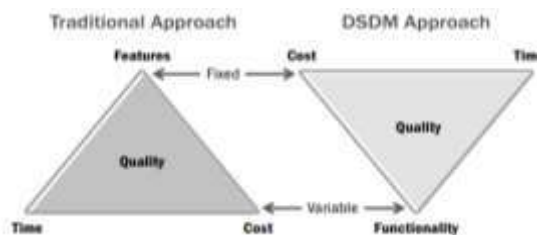
2.7 Extreme Programming (XP)

Extreme programming (XP) is based on the short development cycles and practices like the pair programming, test-first development, continuous integration and refactoring. XP encourages customer collaboration, shared code ownership, and a sustainable rate of work, which is effective in producing the high-quality software development with fluctuating demands. (Yasvi and Malecha, 2019)

2.8 Dynamic Systems Development Method (DSDM)

DSDM is an organized Agile model that focuses on constrained delivery. Time, cost, and quality are fixed at an early stage whereas the scope is changed by prioritization. (Zafar et al., 2018)

Figure 4: DSDM Approach to Constraint-Driven Agility



Source: Created by authors

3.0 Research Methodology

Currently landscape of PM within the infrastructure and real estate sectors is defined by the demand for both control and adaptability increasing. Traditional methodologies such

as the Waterfall model or PRINCE2 have been the traditional foundation for construction projects in the past because of their focus on planning in sequence and strict regulatory compliance. The inherent limitations of these static frameworks in engineering projects are because of integrating technological framework and volatile market conditions. Conversely, Agile methodologies, while proving to be extremely effective in software development settings with emergent requirements, are often inadequate for providing the necessary structural governance for managing a large-scale capital project. This difference calls for “Hybrid” approach comprising of predictive structured control and adaptive agility.

Object of this research is to measure the appropriate PM methodology in different industrial sectors, using quantitative approach this research examines the common project management practices by a structured survey and gather information related to dimensions of agility, compliance, control and rigidity. To validate the hypothesis that hybrid method provides best fit for multifaceted challenges this research check for the methodology suitability.

3.1 Research philosophy and design

The positivist philosophy that the social phenomena such as project management maturity and efficacy of methodologies can be objectively measured by the technique of systematic observation and statistical analysis. This epistemological stance allows us to submit testable hypotheses regarding the links between the project characteristics such as, stability of the requirements, interaction with the different stakeholders and the method adequacy. The research initially accurately describes the present state of the project management practices in the sample population, segmented response based on industries to illustrate the sector specific trends. It then explores how different dimensions of project management like “Organizational Agility” and “Fixed Requirements” interlink and load onto latent factors that signify theoretical methodologies. This two-pronged approach describes what is happening and explains the preferences that are behind the choice of certain methodologies.

3.2 Population and sampling

The target population includes project management personnel, engineers and people working in project management who are actively involved in project execution in various sectors. The sampling frame was stratified to ensure representation from high impact industries (Construction and Infrastructure, Information Technology (IT), Banking and Finance, Manufacturing, Healthcare, and Research and Development (R&D)).

The final data set contains valid responses from N=66 participants. Although this is a modest sample size, strict statistical validation methods, such as the Kaiser-Meyer-Olkin

(KMO) index of sampling adequacy and Bartlett’s Test of Sphericity, were used to find that the data is adequate for multivariate analysis. The respondents represented a mix of roles ranging from site engineer to portfolio manager and therefore offered a broad perspective on project management practices. The segmentation of the industries enables a comparative analysis, making it possible to separate sector-specific constraints (e.g. regulatory compliance in banking, or physical constraints in construction) and universal tendencies towards hybridization.

3.3 Instrumentation and response coding

The primary data collection comprising of 35 core questions (Q1-Q35) designed to understand dynamic environment from the various project management methodologies. Items were measured using a five-point Likert scale, numerically coded as follows:

- 1 = Strongly Disagree
- 2 = Disagree
- 3 = Neutral
- 4 = Agree
- 5 = Strongly Agree

The survey design partitions these 35 items into seven different sections (Sections A through G), which address a different dimension for the execution of a project. These dimensions form the independent variables for the analysis and are critical for the calculation of “Dimension Scores” which form the basis of the Methodology Orientation Matrix.

3.4 The methodology orientation matrix

A key part of this research is to compute the dimension scores to specific PM methodologies. This matrix helps to interpret the results of a survey and identify the best methodology to use for a particular respondent or industry group.

Table 3: Methodology Orientation Matrix

Dimension Pattern	Indicates Suitability For
High Score A + High Score B + High Score E	Waterfall (Predictive, Sequential, Rigid)
High Score C + High Score D + High Score F	Agile (Adaptive, Iterative, Customer-Centric)
High Score E + High Score G (specifically Q31, Q34)	Six Sigma (Process Control, Quality Focus)
High Score F + Q33	Lean (Efficiency, Waste Reduction)
Mixed High Scores Across Sections A - F	Hybrid (Balanced, Adaptive-Structured)

Source: Created by authors

The central thesis of this research is based on the definition “Hybrid”: a pattern of mixed high scores on opposite dimensions (i.e. high documentation and high agility). This pattern suggest that governance requires Waterfall along with the Agile in contemporary projects rather than either of the approach in isolation.

3.5 Methodology index scores

Index Scores gives the quantitative suitability resulting from an average of weighted score to each methodology. These indices make it possible to directly compare methodologies within each of the industry sectors on a numerical basis.

Agile Suitability Index: Calculated as the average of scores from Innovation (Q8, Q9), Organizational Agility (Q11, Q12, Q14, Q15), Customer Interaction (Q16-Q20), and Flexibility (Q26-Q30).

Interpretation: Index 4.0 = Highly Suitable; 3.0 - 3.9 = Moderately Suitable; < 3.0 = Low Suitability.

Waterfall / PRINCE2 Suitability Index: Calculated using Fixed Requirements (Q1-Q5), Sequential Processes (Q6, Q7, Q10), Risk (Q21-Q25), and Q31.

Lean / Six Sigma Suitability Index: Calculated using specific waste-reduction and quality-control items (e.g., Q28, Q29, Q33 for Lean; Q22, Q24, Q25, Q34 for Six Sigma).

4.0 Data Analysis

4.1 Overview of the data set

The analysis was conducted on a dataset of 66 respondents (Analysis N = 66). The dataset comprises 35 ordinal variables (VAR00001 through VAR00035) corresponding to the survey items. Preliminary data screening confirmed the integrity of the dataset, with no missing values reported for the variables included in the factor analysis. This sample size, while compact, is statistically sufficient for exploratory factor analysis given the strength of the correlations observed.

4.2 Data plan and analysis

The analysis of the data goes through four rigorous stages with the help of the software called as the Statistical Package for Social Analysis (SPSS): The computation of means and the standard deviations for all the 35 variables in order to get to know the central tendencies of the respondents. This procedure helps to recognize the most prevalent practice. Subsequently, the suitability of the data for multivariate analysis is checked by the KMO measure of sampling adequacy and Bartlett's test of sphericity. Principal Axis Factoring (PAF) using Varimax rotation is then used to determine the latent structures in the data. This step is very important for construct validity, to ensure that the items that are supposed to measure "Agility" load onto one statistical factor (that is, separate from "Structure").

Finally, the data are aggregated by industry to compare the Methodology Index Scores (Agile vs. Waterfall vs. Hybrid) and triangulate these findings with the qualitative literature." This framework suggest that conclusion drawn regarding the Hybrid approach are

not only theoretical but backed up with evidence linking survey data with statistical factors and eventually with standards of industries.

4.3 Descriptive statistical analysis

The descriptive statistics reveal the first layer of assignment and operation reality of the respondents. From the mean and SD for each variable, it is possible to understand the collective “mindset” amongst the project managers surveyed. The scale is 1 “Strongly Disagree” to 5 “Strongly Agree” and 3 being “neutral”.

Table 4: Descriptive Statistics for Key Variables

Variable	Section	Description	Mean	Std. Deviation
VAR00014	C (Agile)	Team Autonomy & Agility	3.3871	1.06131
VAR00020	D (Agile)	Customer Collaboration	3.3871	1.16443
VAR00015	C (Agile)	Adaptability to Change	3.3548	0.97673
VAR00033	G (Lean)	Waste Reduction	3.3065	1.00145
VAR00012	C (Agile)	Iterative Planning	3.3387	1.17269
VAR00006	B (Waterfall)	Strict Sequential Process	2.5323	1.47901
VAR00003	A (Waterfall)	Fixed/Frozen Requirements	2.5968	1.32392
VAR00005	A (Waterfall)	Rigid Scope Definition	2.6935	1.33783
VAR00001	A (Waterfall)	Linear Execution	2.8710	1.28655

Source: Created by authors

The highest mean scores in the whole dataset are related to Agile and collaborative traits. Variables VAR00014 and VAR00020 both showed a mean of 3.3871, which was a strong consensus on the importance of team autonomy and customer collaboration. The relative lower standard deviations for these things (around 1.0-1.1) indicate that this is a widely shared opinion across the diverse industries sampled. On the other hand, variables related to traditional Waterfall rigidity were lowest. VAR00006 (Strict Sequential Process) had the smallest mean value of 2.5323 and VAR00003 (Fixed Requirements) came close to it with 2.5968.

This pattern suggests that across sectors Projects managers are rejecting the notion of process being strictly linear and no changes in upfront processes. While the scores of Waterfalls are lower, they are not non- existence (approaching the neutral score of 3.0). This would suggest that, even though rigidity is not liked, structured planning (VAR00001, mean 2.87) is recognised as making up part of the workflow. The combination of high scores for Agile and moderate scores for Waterfall offers the first statistical proof of a hybrid environment.

4.4 Multivariate analysis: Exploratory Factor Analysis (EFA)

In order to validate the underlying structure of these preferences and ensure that “Agility” and “Structure” are indeed two distinct dimensions that coexist, an exploratory factor analysis was performed.

4.5 KMO and Bartlett's test

Before the data were extracted, the data suitability was evaluated. The Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy gave a value of 0.616. A value greater than 0.60 is regarded as an acceptable minimum to indicate that there is enough common variance among the 35 variables to proceed to a factor analysis.

Bartlett's Test of Sphericity produced an approximate value of 1286.290 for chi-square, 595 degrees of freedom, and $p < 0.001$ for the level of significance. This highly significant result rejects the null-hypothesis (that the correlation matrix is an identity matrix) and confirms that meaningful correlations are present between the variables and that dimension reduction techniques can be used.

4.6 Total variance explained

Used the Principal Axis Factoring (PAF) in extracting latency in factors. The results of the analysis showed 5 dominant factors, with Eigen values greater than 1.0, these factors can explain about 48.5 per cent of the total variance in the data.

Table 5: Total Variance and Interpretation

Factor	Total Eigenvalue	% of Variance	Cumulative %	Interpretation
1	8.863	25.324	25.324	Agility/Flexibility (Dominant Factor)
2	4.177	11.934	37.258	Process Optimization (Lean/Six Sigma)
3	2.431	6.946	44.204	Traditional Structure (Waterfall)
4	2.088	5.965	50.169	Risk & Compliance
5	1.860	5.315	55.484	Documentation/Reporting

Note: The sums of the squared loadings for extraction are slightly different because of the PAF procedure (Factor 1 total = 8.349).

Source: Created by authors

Analysis of variance distribution: In the scree plot to accompany this analysis there is a very clear elbow after the second factor, and then the slope flattens off more slowly after the fifth factor. The fact that Factor 1 (Agility), explains more than 25 per cent of the variance, more than twice than Factor 2, underlines the primacy of responsiveness in the cognitive frameworks of respondents. Nonetheless, the continued importance of Factors 2, 3 and 4

suggests that Process, Structure and Risk do not turn out to be the subsumes of Agility but are independent, driving factors of project management practice. this independence suggests the hybrid model. if the relation between structure and agility were perfectly negative then they would load onto opposite end of single factor. Their division into distinct factors means that they can be pursued at the same time.

4.7 Rotated factor matrix

To interpret factors, Varimax rotation (with regulation of Kaiser) was performed. The rotation converged after 8 iterations, which gave a better segregation of variables. Absolute values greater than 0.5 coupled loadings implies that they have robust relations.

Factor 1: The “Agile” Construct

- VAR00019 (.703) – Adaptability
- VAR00014 (.680) – Team Autonomy
- VAR00017 (.670) – Customer Feedback
- VAR00016 (.613) – Iterative Delivery
- VAR00015 (.564) – Flexibility

Analysis: This factor heavily loads variables from Sections C and D. It represents the “Agile” methodology. It is the strongest factor, confirming that agility is the primary differentiator in the dataset.

Factor 2: The “Process Efficiency” Construct

- VAR00028 (.702) – Waste Reduction
- VAR00029 (.616) – Continuous Improvement
- VAR00033 (.588) – Lean Practices
- VAR00034 (.571) – Efficiency Metrics

Analysis: This factor corresponds to Section G and parts of Section F, representing Lean and Six Sigma methodologies.

Factor 3: The “Traditional Structure” Construct

- VAR00006 (.740) – Sequential Processing
- VAR00001 (.686) – Linear Planning
- VAR00010 (.641) – Heavy Documentation
- VAR00008 (.633) – Formal Approvals
- VAR00007 (.608) – Phase Gates

Analysis: This factor forms a classic model of the Waterfall methodology (Sections A & B). Critically, it is in co-existence with Factor-1. This represent the independence in itself and not the inverse of Factor-1 variance in dimension. This empirical evidence is the statistical linchpin for the hybrid approach; that is, a project manager can

achieve high scores on both factors, Factor-1: Agility, and Factor-3: Structure, without having to be mutually exclusive.

Factor 4: The “Risk & Compliance” Construct

- VAR00022 (.719) – Risk Mitigation
- VAR00023 (.626) – Regulatory Compliance
- VAR00024 (.814) – Quality Standards

Analysis: This represents the PRINCE2 or Six Sigma elements of risk and quality control

4.8 Reliability and model fit

So, the model fit may get established from the reproduced correlation matrix and the residual table. The analysis detected 261 non-redundant and > 0.05 absolute values of their values (43 per cent). While lower percentages are best, this magnitude is acceptable for the kind of exploratory research which is performed in social sciences, in which human behaviours and preferences commonly have a considerable unique variance. The covariance matrix further gives relationships. We observe high positive covariances between Agile variables that are indicative of high internal consistency within the Agile dimension. On the other hand, the covariances between Waterfall variables (e.g., VAR00001) and Agile variables (e.g., VAR00012) tend to be low or negative (e.g. -0.234), reflecting the validity of methodological distinctness.

5.0 Results

5.1 Establishing the hybrid paradigm

The combination of the results of descriptive statistics and factor-analytic results lead to a definitive conclusion that the contemporary project management is a hybrid paradigm. This data suggest there is not an isolated choice in between the “Waterfall” and the “Agile”. Instead, they support a model where these different methodological elements, or Agility, Structure, Process Efficiency and Risk Management, are chosen and blended based on the project needs.

The “Methodology Orientation Matrix” suggests a framework for such a conclusion. The matrix supports this pattern as “mixed high scores across A-F.” Descriptive analysis supports this pattern. Section C & D have high score (means are around 3.3), meaning that we have very good agreement with Agile principles. Adherence to structure can be calculated from the Section A & B displaying of moderate scores (means ranging from 2.6 to 2.8). Section E scores high, showing the importance of risk and compliance continue (Factor 4) Surveyed population suggest that the hybrid approach is not only a theoretical compromise but empirical reality also because of triangulation of data.

Table 6: Methodology Suitability Index Scores by Industry

Industry	Agile Index	Waterfall Index	PRINCE2 Index	Lean Index	Six Sigma Index	Hybrid Index
IT	4.3	2.6	2.8	3.5	2.9	4.1
Construction	2.5	4.2	4.0	3.2	3.8	3.9
Banking	2.8	4.1	4.3	3.0	4.2	3.7

Source: Created by authors

5.2 Information Technology (IT)

The IT is the sector with the highest affinity for Agile (4.3), which is consistent with the industry's need for quick iteration and software delivery. Nevertheless, the hybrid score (4.1) almost compares to the pure Agile metric. This congruence means that even in an Agile-dominated space, “pure” Agile is often supplemented by structural elements - probably to make it work for corporate governance purposes, budgeting, or compliance with regulatory mandates. Accordingly, the data suggest that IT projects are making the migration from “Scrum” to “Structured Agile” (hybrid).

5.6 Construction and infrastructure (Real Estate)

The construction sector is the strongest proponent of the hybrid thesis. Historically considered a stronghold of Waterfall (4.2), this sector has an unexpectedly good score of hybrid suitability recorded (3.9). This increased score is fuelled by the mass integration of real-time analysis and technologies such as IoT and BIM in the construction lifecycle. Though the physical building phase is still sequential (foundation before roof), the way in which information and supply chains are managed, and changes are made during the design stage require high Agility (Factor 1) and lean efficiency (Factor 2). The data shows that construction does not leave Waterfall and improve it by making it more agile, adding feedback loops, to manage the multifaceted complexity of contemporary real estate building. Score of Six Sigma of 3.8 indicate the preoccupation with process variation and wastage reduction.

5.4 Banking and finance

The banking sector shows a strong preference for PRINCE2 (4.3) and Six Sigma (4.2), considering an inevitable need to comply, mitigate risks and for auditability. However, the hybrid score (3.7) is still sizeable, perhaps a reflection of the FinTech revolution. While core banking systems require high compliance (Factor 4), development of customer facing applications and digital services requires Agility (Factor 1). Consequently, banks run on two systems; a hybrid for “change the bank” initiatives, and a Waterfall/PRINCE2 framework for “run the bank” operations.

5.5 The role of real-time analysis

Traditional Waterfall is dependent on static, retrospective reporting - which is low scoring with respect to real time responsiveness. Pure Agile, on the other hand, relies on tacit knowledge and Gurus being back-to-back with one another, which is hard to scale in large infrastructure projects. To take advantage of the Agile adaptive responsiveness, PM can track “Cost variance” (Waterfall) and “Cycle time” (lean) using real time dashboards in satisfying the rigour designed by the stake holder. The Factor Analysis showed that Factor 2 (Process Efficiency) is distinct. The results of the factor analysis indicated the reify ability of the Factor (Process Efficiency). This factor is the effectively the measurement stratum that Ables the hybrid model by providing a common language among the Agile teams and the Waterfall governance board.

5.6 Second order insights: The evolution of “Waterfall”

A second and critical order insight that flows out of the descriptive statistics is the redefinition of “Waterfall.” The comparatively low mean for “Fixed Requirements” (VAR00003, mean 2.59), even for the Construction sector, suggests that the textbook definition of Waterfall, with requirements that are frozen at day one, has largely become obsolete in practice.

Implication: What is currently labelled as “Waterfall” in the industry is in reality a proto-hybrid model, structured, phased approaches which still allow considerable scope change and iteration. This observation helps establish the case for a formalised “Hybrid” methodology that codifies these practices instead of making them an exception made from a rigid plan.

Figure 5: Word Cloud



Source: Created by authors

Figure 6: TreeMap



Source: Created by authors

6.0 Conclusion

The condition of this thesis was to evaluate the effectiveness of various project management methodologies and test and validate the feasibility of a Hybrid approach in the context of Infrastructure and Real Estate. Through a rigorous quantitative analysis of the responses of 66 professionals in the field of projects, with the support of Exploratory Factor Analysis, the research set out was able to reach the objectives thereof.

The evidence is conclusive: by using the Methodology Orientation Matrix it shows that the dominant operational reality is Hybrid. No statistical isolation in “Agility” and “Structure” is implying that these are not mutually exclusive philosophies but complementing toolsets in project management. Furthermore, the Methodology Suitability Index has an overall high Hybrid suitability score (high scores: >3.7) irrespective of historical industry inclinations (e.g., IT responsibilities toward Agile, Construction toward Waterfall) for all the different sectors analyzed.

6.1 The imperative of the hybrid approach

The data do support the conclusion that Hybrid Project Management is the best way to manage complex and contemporary environments, and specifically Infrastructure and Real Estate. The Construction sector scores highly on both the Hybrid and Six Sigma suitability metrics, a move away from the twenty-first century management paradigm rigidity. While respecting the long-term critical paths we can use iterative and adaptive approach in short

term while the real time analysis can be facilitated by the digital tool enabling Agile in Construction sector.

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CHAPTER 8

Delay Analysis and Remedial Measures for the Project – Execution of 3 Nos Individual Rural Piped Water Supply Projects Balasore District & Mayurbhanj District in Odisha – A Case Study Approach

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ABSTRACT

The Water Supply and Sanitation Project (Name - The Water Supply and Sanitation Project, Odisha, Balasore/ Mayurbhanj Nos. 3 individual Rural Piped Water Supply Scheme, 05 years O&M under one package) faced some critical challenges that influenced its implementation. Among the main problems, one can single out Right of Way delays, as the necessity to get the approval of several departments stifled the work, and disruptions in the supply chain that resulted in a lack of materials. Lack of availability of professional manpower was also an impediment to quality and time schedules of projects [12]. Also, the site was located in the area prone to cyclones and frequent flooding especially in and around the intake well which was the recurrent source of interruption in the past 2-3 years. These issues underscore the importance of proper planning, resources management and mitigation strategies to eliminate the natural and operational barriers in infrastructure projects [8]. Project Coordinate Latitude: 21.521° N, Longitude: 87.532° E.

Keywords: Delay Analysis, Supply Chain Disruption, Environmental impact on construction project, Construction Delay, Supply Chain Management.

1.0 Introduction

This paper investigates the causes of delay through an integrated approach; the objectives of the project are:

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1. Identify and evaluate the key factors causing delays in the execution of rural piped water supply projects in Bhograi, GB Nagar, and Saraskana blocks. This includes:
 - Raw material issues.
 - Supply chain disruptions.
 - Unavailability of skilled manpower.
 - Natural and site-specific challenges (cyclone-prone area and flood-affected regions).
2. Assess the impact of delays on project timelines, quality, and operational efficiency, as well as the consequences for the local population's access to water.
3. Propose and prioritize remedial actions to mitigate current and future delays in the project execution, focusing on:
 - Improved supply chain management.
 - Workforce training and allocation.
 - Contingency planning for natural disasters.
4. Suggest enhancements to the project management framework that can better address site-specific issues and integrate preventive measures into the project lifecycle.

2.0 Literature Reviews

2.1 Implementation of construction supply chain flow based on SCOR 12.0 performance standards

M. N. Sholeh, A. Nurdiana, B. Dharmo, and Suharjono [10] overviewed of the application of SCOR version 12.0 as a performance measurement tool of the construction supply chains in a building project in Indonesia. The experiment used SCOR processes of Plan, Source, Make, Deliver, Return and the Enable in the procurement and the use of ready-mix concrete and steel in a precast construction setting. With the help of SCOR Level 1 performance attributes, reliability, responsiveness, agility, cost, and asset management efficiency, the authors evaluated indicators such as perfect order fulfilment, order fulfilment cycle time, supply chain adaptability and the total cost of the supply chain management. The findings have shown that the SCOR 12.0 is applicable to the construction projects by the contextualization of manufacturing-related measures to site-related operations. The paper determined that SCOR offers a systematic and extensive means to assess construction supply chain performance and helps to make superior decisions with the assistance of project-level data and stakeholder contributions.

2.2 Managing supply chain risks and delays in construction projects

Panova and Hilletoft [7] examined how supply chain risks and delays in construction projects are managed with focus on the difficulties with uncertainties in material

flows and disruption. Construction industry is highly complex and fragmented in its nature, and thus lean principles are hard to put into practice. The authors instead promote an agile paradigm in solving the variability and inefficiencies in a supply chain. The study is based on qualitative and quantitative approaches, such as the dynamic modelling and Monte Carlo simulation, which evaluate the effects of delays on the project schedules and costs. An imaginary construction project is adopted to illustrate how the delays in the material supply may result in huge cost-overruns and long payback time. The paper has emphasized the need to keep safety stock in distribution centres to counter the disruptions even though this would lead to additional warehousing expenses. The major conclusions show that the probability of disruptions, as well as their magnitude, is escalated by the construction delays, the discounted payback period is extended by almost five months, and the net present value (NPV) is decreased by 17%. The paper highlights the importance of highly developed risk assessment techniques, including dynamic modelling paired with Monte Carlo simulation to take into consideration the uncertainties related to the building project that can change over time.

2.3 Barriers to supply chain management implementation in construction

Kim and Nguyen [5] showcased the obstacles that prevent the adoption of Supply Chain Management (SCM) in construction sector. The authors determined that there are 22 main barriers, the most important one of them being lack of effective leadership, incompetence of the SCM parties, and missing knowledge about the concept of supply chain. These barriers were categorized into five causal factors, which include: (1) absence of knowledge and competence, (2) not being supported and actively engaged by the parties, (3) having to deal with culture and adversarial behaviour, (4) lacking the contract system, and (5) inherent challenges in SCM. This research indicated that the most important impediments were leadership and competence inadequacy, whereas industry fissures and short-term project connections were seen to be less severe.

2.4 Cyclone preparedness and response plan

Gujarat Cyclone Preparedness Response Plan [14] highlights how natural disasters like cyclones, floods and earthquakes are very susceptible to construction projects and contribute to their delays. Such incidences upset project schedules, infrastructure is destroyed, and important resources are reallocated to emergency response and recovery. Natural disasters bring about uncertainty and complexity in the construction processes and need disaster resilience strategies. With an extremely sensitive coastline that is 1,600 km long as pointed out by the Cyclone Preparedness Response Plan (2014), infrastructure in the region is particularly exposed to high-speed winds, flooding, and storm surges. Historical facts indicate that severe cyclonic storms have caused enormous destruction to infrastructure like

the one that hit Gujarat in 1998 that resulted into the deaths of more than 1,100 people and a loss of billions of India rupees. This is because such occurrences result in construction delays caused by work in-progress destruction, disruption of supply chain, labour unavailability, and diversion of financial and human resources to reliefs. As per the plan, the risk of a 100-year return period, cyclone on about 248000 residential buildings will result, which is an example of the magnitude of the possible construction delays.

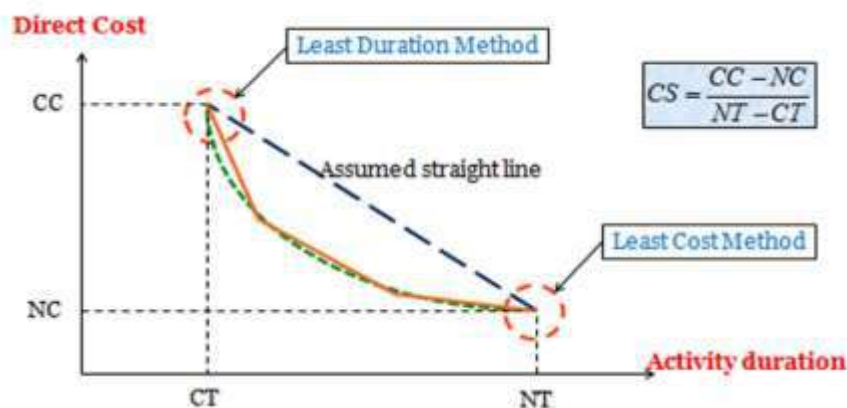
3.0 Research Methodology

This study aims to investigate how delay analysis impacts infrastructure development initiatives, identify its primary causes, and evaluate effective method based on real project evidence. To achieve this objective, the study adopts Crashing Technique [15], integrating quantitative techniques. This approach enables a comprehensive understanding of delay analysis by combining numerical project data with experiential insights from industry professionals.

3.1 Research design

The goal of this research is to study the phenomenon of postpone analysis in infrastructure projects, identify its primary causes, and evaluate effective method based on real project evidence. To achieve this objective, the study adopts Crashing Technique [15], integrating quantitative techniques. This approach enables a comprehensive understanding of delay analysis by combining numerical project data with experiential insights from industry professionals.

Figure 1: Direct Cost Curve for an Activity



Cost Slope = (Crash Cost – Normal Cost)/ (Normal Duration – Crash Duration)

Source: Created by authors

In cost estimation developing approximation of the cost of the resources needed to complete the project activities. There are cost component those are Direct Cost, Indirect Cost (Project over head & General overhead), Markup or profit & Risk contingency. In schedule crashing reduce original CPM duration of a project to meet a specific deadline in the least manner. In crashing reduce duration by using more productive resource and extending the working hours.

Identify the critical activity with least cost slope then possible duration shorten multiply with Indirect cost. Then calculate total cost = Direct cost + Indirect cost. Reduce the duration of the activity until its crash duration is reached or until the critical path changes. Continue crashing select second minimum cost slope activity from critical path for further crashing. Continue until no further shortening is possible and then crash point reached. Then Compare delay cost data getting from site and crashing cost.

The window analysis method [8] [15], also known as the contemporaneous period analysis or snapshot method, involves breaking down the total duration of a CPM schedule into manageable time segments or windows, such as monthly intervals. The delays occurring within each of these time frames are then examined in sequence, with a focus on the critical paths As planned versus as-built (Total time) method. [15]

The as planned versus as-built method, often referred to as the “total time method” or “net impact method,” essentially involves comparing two schedules. This approach operates under the assumption that the contractor does not cause any delays, while the owner is responsible for all delays. [15]

A descriptive and analytical case study approach also adopted to solve major issue related to supply chain management. The research focuses on identifying delay-related issues across the construction supply chain and mapping them to SCOR processes [9] [10] and performance attributes. The methodology follows the approach recommended in construction-based SCOR applications, where manufacturing-oriented SCOR metrics are contextualized for project-based environments.

The Supply chain operation reference model is adopted in the study as a tool to evaluate supply chain performance of the project which will helps us find and diagnose supply chain related delays in a Rural Water Supply and Sanitation (RWSS) construction project. The methodology followed a systematic, multi-stage approach integrating field-level data collection, understanding scope, performance measurement, and categorization of activities based on SCOR process attributes & SCOR performance attributes, & defining the key Performance Index for the SCOR process and Performance attributes and at last preparing a SCOR model which identifies the causes of delay measures against KPI's and suggesting actionable measures to prevent delay.

The RWSS project located in Balasore district (Bhograi Phase-II, GB Nagar, Saraskana) faced delay due to some supply chain activities like material management issues, communication mismatch, delayed plan approvals, and other statutory approvals. The scope of the SCOR application was restricted to supply chain-related activities affecting project planning, procurement, execution, delivery [7], returns, and enabling systems. This ensured that the analysis remained focused on supply chain-induced delays rather than design or structural deficiencies.

Investigation of causes for delay:

- One of the major issues was related to land acquisition & clearance issue from the government [1], [8] which caused delay in project.
- Issues related to statutory approvals and design approvals and last-minute changes in working drawings.
- Improper planning of resources like late procurement issues [7], [6], frequent material shortages [1], [8], [11], vendor related delays, Payment clearance issues.
- Subcontractor related issues like non availability or inefficiency contributing to delay in the project.
- Productivity loss due to adverse weather conditions [11], [14] (rain, heat, flooding), ranging from 6–20%. Seasonal constraints affecting excavation, concreting, and pipe-laying activities.

3.2 Data collection methods

In our project we collect the site data like RA Bill, Contract documents, Annual operating plan, PA Bill, MSP Schedule. Then taken one segment of the project Bhograi. Going with Bhograi separated critical activity Name those critical activity Topographic Survey, Intake well, RWRM, WTP, CWRM, ESR, Distribution, Compound Wall, Testing, O&M respectively A, B, C, D, E, F, G, H, I, J. Then use crashing technique and compare the actual cost of the project with delaying cost of the project and prepare conclusion.

Data were also collected through a structured questionnaire survey administered to construction professionals actively involved in infrastructure project execution. The respondents included project managers & planning engineers,

The questionnaire included both quantitative and qualitative questions covering SCOR processes [9], [10] such as planning, sourcing, execution, delivery, and coordination, along with performance attributes including reliability, responsiveness, agility, cost, and asset utilization [12]. Responses were collected on aspects such as schedule preparation and updates, drawing and approval delays, material shortages [7] [1], [8], [11], subcontractor [5] performance, productivity losses due to weather, payment delays, rework occurrence, and cost impact of delays. The collected responses provided practical, site-level insights into real

project conditions and formed the basis for SCOR-based performance analysis and delay assessment in this research Secondary Data Collection

4.0 Data Analysis

In our project we followed window analysis method [8], [15]. Where we took a part's critical path of the ongoing project. There we took that crucial activity of the projects on the critical path. Then calculate pending cost and remaining duration of the project activities to complete the project. Calculate direct cost to complete the project. Calculate approximate cost to complete the project. Then reduce the duration of the project using crashing technique [2], [4] on remaining duration. Then we show the increased cost using crashing technique [2], [4] is less than the project cost required to complete the project. In crashing technique [2], [4], we increase resource and manpower and reduce the indirect cost. But to complete the project normally indirect cost is more loss will be more.

Table 1: Project Activity Details

Activity	Progress Percentage	Remaining Percentage	Total days	Remaining Days	Total Amount (in Cr)	Remaining Amount
A	96%	4%	232	10	1.09	0.05
B	53%	47%	420	199	5.46	2.58
C	91%	9%	195	17	15.28	1.33
D	24%	76%	544	411	16.37	12.37
E	73%	27%	510	136	25.09	6.67
F	96%	4%	390	14	12.00	0.43
G	90%	10%	585	58	21.28	2.11
H	49%	51%	360	184	0.55	0.28
I	0%	100%	184	184	1.09	1.09
J	0%	100%	60	60	10.91	10.91
		Total	3480.00	1272.44	109.12	37.82

Source: Created by authors

Table 2: Indirect Cost Assumption

Indirect cost (10 % of Direct Cost)	3.782190977
	0.002972401
	29724.01103
Approximate Rs/day	30000

Source: Created by authors

Table 3: Activity Details with Remaining Duration

Activities	IPA	Duration	Normal Cost
A	B	10	0.05
B	C	199	2.58
C	D	17	1.33
D	E	411	12.37
E	F	136	6.67
F	G	14	0.43
G	H	58	2.11
H	I	184	0.28
I	J	184	1.09
J	End	60	10.91
			37.82

Source: Created by authors

Table 4: Cost Schedule Table

Cycle No	Duration	Direct Cost (Cr.)	Indirect Cost (Cr.)	Total Cost (Cr.)	Remarks
1	212	37.82	0.636	38.4579	Crash @212 days for D
2	15	38.46	0.045	38.5029	Crash @15 days for B & D
3	48	38.50	0.144	38.6469	Crash @48 days for B & D & H & I
4	76	38.65	0.228	38.8749	Crash @76 days for B & D & E & H & I
5	2	38.87	0.006	38.8809	Crash @2 days for B & D & E & G & H & I
6	41	38.88	0.123	39.0039	Crash @41 days for B & D & E & G & H & I & J
7					
Extra Cost require to complete (In Cr.)				1.1820	

Source: Created by authors

Table 5: Crash Duration

				10000000
D	212	30000	6360000	0.636
B & D	15	30000	450000	0.045
B & D & H & I	48	30000	1440000	0.144
B & D & E & H & I	76	30000	2280000	0.228
B & D & G & H & I	2	30000	60000	0.006
B & D & G & H & I	41	30000	1230000	0.123
	394			

Required Extra cost to complete the project without crashing:

Source: Created by authors

Table 6: Delaying extra Cost Data from Site

Project data	
Revenue	327453671
Revenue	
Turnover as per Client Billing	283487660
Differential Entry (Shadow BOQ - Client Billing)	43966011
Direct Cost	251829625
Other Income	
Other Income	0
WIP	
Direct Cost	
Material Cost	121467651
Labour Charges	325281
Composite Work Charges	90803235
Quality Expenses	1359291
Electricity Charges	355328
Diesel Expenses	3711542
Consumable Asset	29153130
Design & Consultancy Charges	1649500
Rate & Tax	2741855
Safety Expenses	87091
Water Charges	175720
Other Project Cost	42272082
Employee Cost	
Local Staff Salary	3541521
Regular staff salary	21027157
Staff Welfare Expenses	661267
Construction Expenses	
Machinery Repair and Maintenance	103255
Site Expenses	-14798
Equipment and Machine Rent	5260820
Security Expenses	2989326
Other Expenses	
Labour Charges	
General Repairs and Maintenance	63063
Sundry Expenses	1487010
Vehicles Running & Maintenance Chg.	3297081
Printing and Stationery	163736

Business Development Charges	505
Communication Exp.	144536
Travelling Expenses	197436
Professional and Legal Charges	1971
Rates & Taxes	
Rent-Office/Guest house/Others	1482675
Insurance Charges	187327
Charity & Donation	
Bank Guarantee & Financial Charges	1678193
War. Gur Exp	3274537
War. Gur Exp	
War. Gur Exp	3274537
Interest on Capital Employed	11335829
Mob Adv Interest	
Interest on Capital Employed	
WCI Int	
Interest on Capital Employed	11359135
Int. Capital Emp.	-23306
Depreciation	4816198
Depreciation on Fixed Assets	
Depreciation on Fixed Assets	4816198
HO Exp	4420625
HO Exp.	
HO Exp.	4420625
RO/DO Exp	5468476
DO EXP	
DO EXP	5468476
Forex	14
Forex	
Forex	14
IND AS TO	-49048044
INDAS Revenue	
INDAS Revenue	-49048044
INDAS Adjustment	
INDAS Adjustment	
INDAS Adjustment	
Grand Total	-53084330

Source: Created by authors

This section presents a detailed analysis of the data collected through the questionnaire survey and supporting project documents. The objective of the analysis is to assess the supply chain management performance and identify the most significant factors contributing to delay of the project. Collected responses were aggregated and categorized under SCOR processes. Delay issues were then linked to relevant SCOR performance attributes like Reliability, Responsiveness, Agility, Cost & asset Management. Delay issues were also categorized based upon SCOR process attributes like plan, source, make, deliver, return, and enable to identify weak areas within the supply chain.

4.1 Categorization into SCOR process

Table 7: SCOR Process Table

Score Category	Issue From RWSS Project
Plan	Forecasting challenges due to land issues; schedule updates only monthly/quarterly.
Source	Late procurement requests; vendor production delays; quality rejections.
Make	Rework due to late/changed drawings; batch rejection; low productivity during weather.
Deliver	Material delivery delays; <90% on-time delivery; restart time after stoppage: 3–7 days.
Return	Returned materials due to mismatch or site unreadiness; 5–20% rejection rate.
Enable	Lack of GPS-enabled training to drivers; lack of digital dashboards; weak supplier visibility.

Source: Created by authors

4.2 Performance attributes & issues

Table 8: SCOR Attributes Table

Attribute	Issue From RWSS Project
Reliability	Frequent delays in drawing approvals, material shortages, and subcontractor inefficiencies.
Responsiveness	Client/PMC responsiveness rated 2–3; delays in RA bill certification and drawing resubmissions.
Agility	Inflexibility in handling weather disruptions and late procurement requests.
Cost	5–10% increase in project cost; return handling costs; payment delays impacting vendors.
Asset Management	Labor & equipment utilization varied (51–90%); delays due to idle resources.

Source: Created by authors

4.3 Suggested KPI's for RWSS project

Table 9: Key Performance Table

Score Category	KPI's
Plan	Forecast Accuracy (%), Schedule Update Frequency, Risk Anticipation Score (1–5)
Source	Supplier On-Time Delivery (%), Procurement Lead Time, Material Rejection Rate (%)
Make	Rework Rate (%), Cycle Time (days), Labor Utilization (%)
Deliver	On-Time Delivery (%), Restart Time (days), Delivery Accuracy (%)
Return	Return Rate (%), Cost per Return Load (₹), Drawing Rejection Rate (%)
Enable	% of GPS-Trained Drivers, IT Adoption Rate (%), Client Responsiveness Score (1–5)

Source: Created by authors

Table 10: SCOR Framework

SCOR Category	Key Issues Identified	Relevant KPI's	Performance Attributes Impacted	Analysis & Insights	Actionable Suggestions
Plan	- Forecast demand misaligned with actual execution - High demand variability due to land clearance delays - Schedule updates only monthly or quarterly	- Forecast Accuracy (%) - Demand Variability Index - Schedule Update Frequency - Risk Anticipation Score (1–5)	- Reliability - Asset Management	- Inflexible planning led to idle resources - Land issues not anticipated during tendering phase	- Conduct land feasibility during DPR stage. - Use rolling wave planning for dynamic updates - Use Material Resource planning with VED, ABC analysis. - Include risk registers for weather, permissions
Source	- Late procurement requests - Vendor production delays - Quality rejection of aggregates and materials	- Supplier On-Time Delivery (%) - Procurement Lead Time (days) - Material Rejection Rate (%)	- Reliability - Cost	- Procurement delays caused work-front idle time - Poor vendor coordination increased rework	- Prequalify vendors based on past performance. - Implement digital procurement tracking. - Maintain buffer stock of critical materials.

Make	- Rework due to late/changed drawings - Low productivity during weather events - Batch rejection due to mix ratio issues	- Rework Rate (% of total work) - Labor Utilization (%) - Productivity Loss due to Weather (%)	- Reliability - Cost - Responsiveness	- Rework affected 5–20% of total work - Weather caused 0–5% productivity loss - Skilled labour shortage in remote areas	- Tie-up with local ITIs for trained manpower - Use modular construction to reduce weather impact - Improve drawing approval turnaround time
Deliver	10–25% delays due to material shortages - Restart time after stoppage: 3–7 days 15–30 days delay due to drawing approvals	- On-Time Delivery (% within 90 min) - Restart Time (days) - Delivery Accuracy (% of spec-compliant deliveries)	- Agility - Cost - Reliability	- Delivery delays compounded by poor site readiness - Restart lag increased idle labour cost	- GPS-enabled delivery tracking - Site readiness checklist before dispatch - Assign delivery coordinators for critical materials
Return	- Returned materials due to mismatch or site unreadiness 5–20% rejection rate of materials - No root cause analysis system	- Return Rate (% of total loads) - Drawing Rejection Rate (%) - Root Cause Distribution (%)	- Reliability - Cost - Responsiveness	Rejected drawings delayed execution by >30 days	- Implement root cause tagging in ERP - Use digital drawing approval workflows - Train site engineers on specification compliance
Enable	- Only 60–70% of drivers trained in GPS routing - No supplier performance dashboard - Weak digital monitoring systems	- Client Responsiveness Score (1–5) - Supplier Visibility Index	- Agility - Cost - Reliability	- Lack of digital tools reduced visibility - Client responsiveness rated 2–3 in survey.	- Develop supplier performance dashboards - Train drivers and site staff on GPS tools - Use mobile apps for client/PMC approvals

Source: Created by authors

5.0 Findings / Results

This section presents the key findings derived from the survey data, project comparisons, and case-based observations discussed in the data analysis. The findings highlight the dominant patterns, critical issues, and practical implications of cost escalation in infrastructure projects.

Table 11: Cost Comparison for delay

From Crashing extra cost required	1.1820	Cr
Without Crashing cost required	5.308433008	Cr

Source: Created by authors

The SCOR-based analysis indicates that delays in the RWSS project occurred across multiple supply chain processes [7], [8], [11]. In the Plan stage, inadequate risk anticipation related to land, approvals, and weather resulted in 31–40% and above 40% of delays due to late drawings and permissions, affecting planning reliability. The Source process faced frequent material shortages [1], [8], [11] caused by late procurement and vendor delays, reducing supply chain reliability and responsiveness. During the Make stage, rework due to late or revised drawings and weather impacts affected 5–20% of total work, increasing time and cost. In the Deliver stage, less than 90% on-time material delivery and 3–7 days required to restart work after stoppages reflected weak responsiveness and coordination. The Return process showed 5–20% rejection rates due to specification mismatches, while limited digital tools [6], [13] and moderate client/PMC responsiveness in the Enable process reduced visibility, agility, and overall supply chain performance.

From SCOR performance perspective, Reliability and Responsiveness were the most affected attributes, followed by Cost and Asset Management Efficiency. Survey data indicated a 5–10% overall increase in project cost [3], [4] due to supply chain delays, while labour and equipment utilization [12] varied widely between 51–90%, reflecting idle resource losses during stoppages.

6.0 Conclusion

This research shows whether we employ crashing technique [15] [2], [4], adding resource and manpower then we can accomplish the project at a shorter time through cutting indirect costs of the project. We can finish that activity that are not influenced by those projects critical path and make appropriate plans. This does not necessitate the crash technique 4.2 cr. cost needed to complete the project. that would be a big figure on the part of the company to bear their indirect costs. Therefore, crashing technique [15] [2], [4] and adding resource and manpower should be embraced. And the SCOR model [9], [10] can be a useful model to analyse delays in the supply chain of construction when it is adjusted to the project-based settings. The research determined major delay drivers associated with planning, procurement, execution, and coordination using SCOR processes and site-level questionnaire information. The analysis has revealed that the primary causes of the RWSS project delays include the delay in approvals, insufficient planning on land and permissions, poor supplier

performances, and insufficient use of digital. The paper emphasizes that the digital tools [6], [13] and the active risk management can significantly decrease the delays and the cost overruns by enhancing the reliability of planning, the coordination between the suppliers, and the responsiveness. Overall, the use of the SCOR-based performance measurement strategy helps to make decisions based on the data and enhance the efficiency of the supply chain during construction projects.

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CHAPTER 9

Enhancing Resilience of Financial Institutions to ESG (Environmental, Social, and Governance) Risks

*Apurwa Mandlik**

ABSTRACT

The world is growing at a very fast pace and in today's financial scenario, ESG (Environmental, Social, and Governance) risks have transitioned from being just reputational concerns to becoming a major factor with severe financial consequences. Banks and financial institutions are facing increasing pressure from investors, customers and regulators to showcase their dedication and commitment towards sustainability and responsible business practices. Regulatory bodies worldwide are tightening their scrutiny of ESG risks, introducing new rules and reporting requirements targeted at ensuring greater transparency and accountability in the financial sector. This study examines how ESG risks influence traditional financial risks such as credit, market and operational risks and proves the interconnectedness between internal and external ESG factors. It examines the integrated nature of internal and external ESG risks and their impact on financial performance to enhance the resilience of financial institutions. By assessing current risk management practices, this study proposes a comprehensive framework for integrating ESG considerations into risk management strategies. With this approach, one can aim to foster long-term stability and promote sustainable growth within the financial industry.

Keywords: ESG Risks, Financial Institutions, Risk management, Financial Risk Assessment, Sustainability.

1.0 Introduction

The global financial environment has been recently going through a major shift in dynamics. This is due to the focus moving from purely financial metrics to a more integrated study of the institution's behaviour. At the very centre of the shift is Environmental, Social, and Governance (ESG) integration. Originally, ESG was looked upon as a framework for ethical investing, however in recent times it has evolved into a more primary assessment technique for sustainability and risk associated with financial institutions.

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1.1 Understanding ESG and ESG risks

Environmental, Social, and Governance (ESG) are a set of non-financial performance measures that include Environmental issues such as carbon footprints, climate change resilience, Social issues such as labour practices, privacy, community and Governance issues such as board diversity, executive compensation, anti-corruption policies. ESG Risks are the possible negative financial impacts to the organization that could be provoked by these issues. For example, Environmental risks appear as “physical risks,” which mean threats that can occur by natural events such as hurricanes, floods, etc. due to global warming. In social & governance risks, these appear in the form of Lawsuits, Fines and Disastrous reputation.

1.2 Materiality to financial institutions

Financial institutions including banks, investment firms, as well as insurance companies, the risks associated with E, S, and G have become financially material rather than what can be viewed as “externalities” (indirect costs or benefits). In the case of banks, ESG indicators directly affect credit risk and the quality of assets. (Atif & Searat, 2021) For insurance agencies, environmental factors determine the validity of underwriting as well as the occurrence of claims. (Chiaramonte, Dreassi, Paltrinieri, & Piserà, 2020) For investment firms, the ESG indicators play a significant role in the relevant fiduciary requirement, as lower ESG performance can result in “stranded assets,” as well as lower portfolio returns. (Gibson, Glossner, Krueger, Matos, & Steffen, 2022) Although the financial materiality is clear, the irony is that there is a lack in the literature about the examination of these risks on the three financial intermediaries mentioned (banks, investment firms and insurance agencies), specifically in relation to the risk of default, which is the likelihood of a financial institution failing to repay its debts.

1.3 The need for an integrated approach

The current model of Risk Management tends to view “ESG Risk” as a mere compliance requirement, rather than as an important factor while assessing solvency issues. There is a clear requirement for a study to be conducted to fulfil this need for creating an ESG-Risk Framework. The framework will enable institutions to:

- Measure how fluctuations in ESG factors affect traditional risk types such as market, credit, and operational risk.
- Strengthen resilience by identifying early warning signs of financial stress caused by sustainability failures.
- Standardize reporting to reduce ESG-related greenwashing, which often hides the true risk profile of many firms.

By developing a strong framework, financial institutions are prepared to manage sustainability-related risks and ensure their extra savings funds and risk appetites reflect the realities of the 21st-century economy. The goal of this study is to fill the current gap that exists within the literature by studying how ESG integration affects institutional default risk and long-term financial stability of an institution.

2.0 Literature Review

ESG factors are changing how banks evaluate a company's financial strength and overall stability. Instead of focusing only on traditional financial metrics, banks now also consider environmental, social, and governance issues to better understand long-term risks and opportunities. Traditional credit risk models rely on past financial data and are now considered as weak in capturing non-financial and qualitative risks which threaten long term solvency. Theoretical frameworks like stakeholder theory suggest that ethical management and attending to the interests of all stakeholders fosters long-term success and risk mitigation. In contrast, agency theory offers an "overinvestment" perspective, indicating that ESG activities have the potential to inflate an agency cost when managers prefer their reputation more than the profit of shareholders, thereby increasing the firm's leverage and resulting in an increase in default risk. (Korzeb, Karkowska, Matysek-Jędrych, & Niedziółka, 2025)

2.1 ESG and the stability of the financial system

Traditional bankruptcy models (such as the famous Altman Z-score model of 1968) focused more on financial ratios, but newer approaches suggest addition of ESG factors are vital for predicting the stability of institutions. (Ongena, Andries, Sprincean, & Aevoae, 2022) highlight that the performance of ESG factors is inversely related to the systematic risk, providing stability during volatile market conditions. The same goes for insurance industry as it also needs stability. (Chiaramonte, Dreassi, Paltrinieri, & Piserà, 2020) learned that sustainability has proven to play a vital role in improving the stability of the insurer during turbulent markets. In the asset management industry, the role of sustainability has been underlined by (Hartzmark & Sussman, 2018), which points out that sustainability funds can actually perform as a "loyalty" asset, since the withdrawal rates of investors tend to be lower than those of normal funds during turbulent markets.

2.2 ESG impact to credit, default, and underwriting risk

The crux of the recent literature is concerned with how ESG profiles affect a company's risk profile. In banking industry, (Atif & Searat, 2021) and (Bukreeva & Grishunin, 2024) prove that high levels of ESG disclosure are associated with lower default

risk as they improve transparency and risk management. In the insurance industry, this relationship works in a different manner, with the core being underwriting risk rather than credit risk. According to (Brogi, Cappiello, Lagasio, & Santoboni, 2022) non-life insurers that incorporate ESG factors into their underwriting activities are better prepared to assess risk accurately and price their long-term liabilities more effectively, leading to improved financial stability over time. In particular, (Palmieri, Ferilli, Stefanelli, Altunbas, & Geretto, 2024) found that certain ESG pillars, specifically “Social” and “Governance,” are increasingly essential to liability risk measurement for corporate policyholders with policy performance, indicating that those with low ESG performance ratings are at an elevated risk of legal and operational disputes.

2.3 Impact of climate change on portfolio allocation

Environmental factors are changing how much risk financial intermediaries are willing to take. Within the industry of asset management, (Gibson, Glossner, Krueger, Matos, & Steffen, 2022) and (Egli, et al., 2022) conclude that there is an increased focus on the “E” quality of companies within institutional investment holdings. This focus is to avoid “stranded assets” due to carbon pricing regulations.

For insurers, “double materiality” has become a challenge related to climate risk. According to Martí et al. (2024): “Climate-related physical risks pose a threat to the frequency of claims on the liability side, whereas transition risks pose a threat to the value of the investment portfolio of the insurer.” This requires an entirely new revamping of existing traditional models, as observed by (Kalfaoglou, 2021) who states that climate-related risks are now the main driver of long-term solvency for both lenders as well as underwriters.

2.4 Governance, reputational risk, and “ESG washing”

The Governance pillar, however still remains the anchor for managing internal risks of an institution. According to (Venturelli, Pedrazzoli, Pennetta, & De Novellis, 2025) and (Mandas, Lahmar, Piras, & Lisa, 2023), exaggerating claims related to sustainability is creating “reputational contagion,” particularly within investment firms and banks, where a lack of transparency can lead to market-wide valuation corrections, and greater regulatory scrutiny.

2.5 Performance and emerging market conditions

The financial effects of ESG are not the same everywhere. According to (Azmi, M., Houston, & Karim, 2020) show that in emerging markets, the impact of ESG on banking performance depends on the quality of a country’s institutions. In investment decisions, (Khan, Serafeim, & Yoon, 2016) state the importance of materiality, finding that firms

generate excess returns only when they focus on ESG issues that are financially relevant to a specific industry of the target company. Finally, (Korzeb, Niedziółka, Szpilko, & Pietro, 2024) and (Meiratri & Kunaifi, 2025) find that challenges in ESG integration are now key drivers of long-term default risk and financial stability across global markets.

2.6 Regulatory turning point and AI-driven ESG integration (2025–2026)

As the financial industry moves into 2026, research shows a clear shift: ESG is no longer seen as a secondary risk, but as a core financial risk on the same level with liquidity and credit risk. This shift is driven by the (European Banking Authority's ESG Guidelines, 2025) which require banks to fully integrate ESG factors into credit risk management by January 2026. (ESG risks in 2025: Responding to regulatory and supervisory pressure, 2025) describes 2025 as a turning point for European banks, as regulators moved beyond reviewing ESG policies to closely examining actual climate and environmental risk exposures in lending decisions. Similar trends are emerging in developing markets. (Hamdouni, 2025) find that AI-based FinTech tools are increasingly critical for addressing ESG data gaps, helping banks reduce excessive risk-taking and maintain stable performance during periods of rapid, innovation-driven growth.

2.7 Biodiversity and human rights as emerging ESG factors

The meaning of “materiality” has expanded in recent years. (Material E, S and G factors in 2026, 2025) identifies nature and biodiversity as the next major source of financial risk, highlighting that nature-dependent sectors such as agriculture and construction account for around 10% of global GDP and are increasingly exposed to “nature-related tipping points”. Further, (Wang, Yuxin, Dong, & Zhu, 2025) and show that the social pillar of ESG, once seen as the most difficult to measure is now closely linked to credit growth through greater transparency in human rights and labour practices. (Nguyen, Uyen, & Thuy, 2025) further find that while environmental disclosure strongly affects credit risk through non-performing loans, social transparency plays a key role in supporting long-term financial resilience, especially in the post-pandemic economic environment.

2.8 Conclusion: ESG beyond reputation

The reviewed literature clearly shows that ESG has moved beyond reputation management. (Pangaribuan & Idrianita, 2024) argue that active ESG integration is now essential for the long-term survival of banks. (Mabe & Simo-Kengne, 2025) further note that, across global banking systems, the ability to withstand FinTech-related financial stress while preserving ESG standards will shape competition in the late 2020s. As a result, the framework

proposed in this study is timely, highlighting the need for financial institutions to move from passive ESG adoption toward genuine systemic resilience.

3.0 Research Methodology

The study uses qualitative research designed on an econometric survey analysis. This approach involves collecting company metrics from financial professionals at a single point in time excluding any manipulation. By using this design, the survey can gather a wide range of information about how financial professionals understand, react to, and incorporate ESG risks into their decision-making processes. As a result, the research design helps provide a holistic understanding of an institutions response to ESG risk integration within the financial sector. The study follows a research philosophy that confirms the existence of an objective reality but accepts the presence of biases in the understanding of that reality, as the study depends on empirical data that is quantifiable. With this philosophy in mind, the study determines the relationship of ESG variables with traditional risk models through data analysis. This helps create objective findings and conclusions.

Primary data were collected in the present study through the use of a structured online questionnaire catered to a group of professionals working in financial institutions, including commercial banks, investment firms, and insurance companies.

The research population was targeted at professionals whose work describes and involves Risk Management, ESG/Sustainability, and Credit Analysis, among other related functions; hence, it is most related to tasks associated with ESG risk integration within financial institutions.

The methodologies used in the paper were both purposive sampling and snowball sampling techniques. This was because purposive sampling was used in identifying the targeted respondents with professional skills in the area of ESG and financial risk management. Even if the proposed target sample size was set somewhat higher, the analysis is grounded on 81 valuable and complete responses (N=81). While this is a small number, it is deemed a sufficient number for the undertaking, both for exploration analysis, in as much as a higher degree of seniority is considered on the part of the respondents.

This questionnaire is designed to capture both quantitative and qualitative insights into ESG risk perception, materiality, governance integration, and financial decision-making within financial institutions. The survey comprises 20 structured questions, employing a mix of binary (Yes/No), multiple-choice, ranking, and Likert-scale response formats, along with selected open-ended questions for qualitative elaboration.

The data collected was then analysed using descriptive statistical analysis to determine dominant trends among various institutions based on percentages as well as mean

ranking. The opinions gathered in the open-ended questions were analysed to determine themes in the current and future concerns among the participants in the processing of ESG risks. As a result of being an exploratory analysis and having a small sample size for analysis, this analysis seeks patterns or insights at an institutional level instead of statistical inference.

4.0 Findings/Results

The results of the primary survey were analysed to determine the extent of awareness among financial institutions regarding the risk factors associated with ESG. A total of 81 valid responses were obtained, which gave an insightful understanding of the awareness among financial institutions about the risk factors associated with ESG. The analysis focused on identifying to what extent are ESG risk factors understood, integrated into decision-making processes, and considered material to financial performance and long-term sustainability.

4.1 Participant background and understanding ESG risks

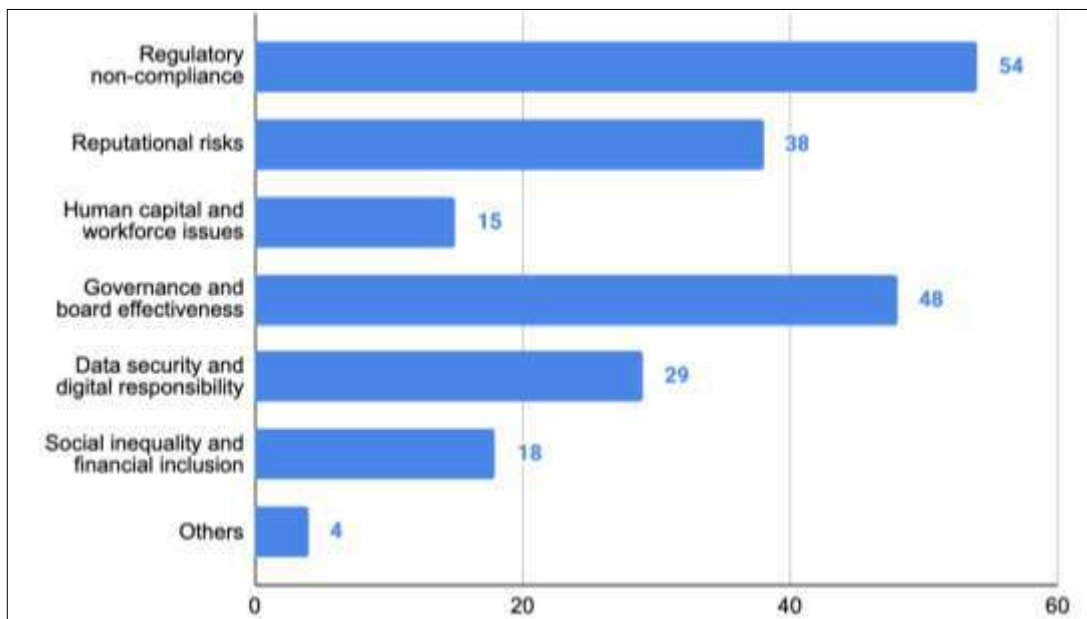
The respondent group was mostly a set of professionals in the banking and investment sectors, which is directly relevant to their risk management processes. The results of this analysis show a relatively high awareness of ESG risk, as 90.1% of respondents considered ESG issues a potential risk for their institutions. We can say that there is a recognition of ESG issues as core risk variables and ESG issues no longer pose as a concern of a reputational or voluntary nature. In addition, 86.4% of respondents expect that ESG risks will become an integrated part of financial risk management in five years, which is on the same level with credit, market, or liquidity risks. Such progressive perspective can be reflected by an evolution in risk paradigms that confirms the argument proposed in the literature that states that ESG risks are transitioning from secondary towards systematic financial risks.

4.2 Understanding the relationship between ESG materiality and risk

Respondents were asked to identify the most material ESG risks currently affecting their institutions. The results highlight a strong convergence around governance and regulatory concerns:

- Regulatory non-compliance emerged as the most significant risk, identified by 66.7% of respondents.
- Governance and board effectiveness followed closely at 59.3%.
- Climate risk, encompassing both transition and physical dimensions, was cited by 53.1% of respondents.

Figure 1: ESG Risks Considered Most Material by Respondents



Source: Created by authors

These results highlight the dominant role of what can be described as a “regulatory watershed,” in which tightening legal requirements, regulatory scrutiny, and disclosure obligations act as key drivers of ESG integration. Climate risk stands out as a major concern, but it is rarely viewed as a standalone environmental issue. Instead, institutions tend to understand and manage climate risk through regulatory and governance frameworks, reflecting their close connection to compliance obligations, supervisory expectations, and internal risk controls. Overall, this highlights how closely intertwined ESG risks really are. Environmental, social, and governance factors do not operate in isolation but influence one another, with governance playing a particularly central role. Strong governance structures help institutions transform regulatory requirements into concrete ESG practices, while weaker governance can limit their ability to respond effectively to these risks.

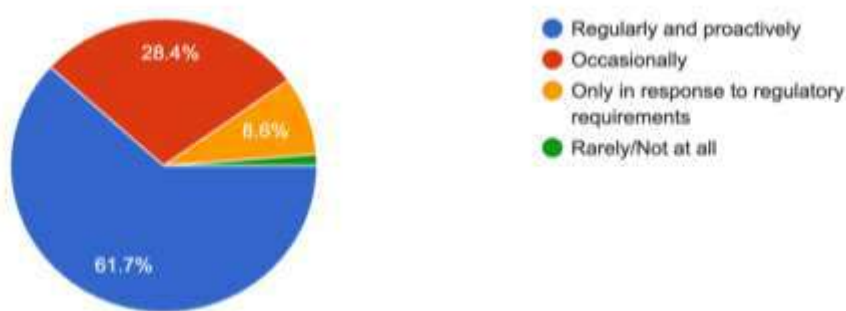
4.3 How ESG is integrated in institutional governance

The survey results show that the financial industry has moved from the concept of awareness to implementation, though the maturity level of the industry varies.

Over 50% of firms stated that they incorporate ESG risks into their existing Enterprise Risk Management structures, and an additional 44.4% stated that they have started

the process of implementation/planning. There is a clear direction in which they would like to move regarding overall risk management. Nearly half of the respondents feel that the topic of ESG risks is being discussed regularly and proactively by the top leadership, reflecting an increasing concern at the boardroom level. Also, 42% of the organisations have formed an ESG committee or department, reflecting that more and more organisations are looking for expert handling of the topic rather than general responsibility being assigned randomly to employees and management teams.

Figure 2: Level of Senior Management and Board Involvement in ESG Risk Discussions



Source: Created by authors

Despite these improvements, the pattern of response distribution indicates that the extent to which institutions have adopted the change from aligning to fully embedded operational controls varies significantly.

4.4 How ESG factors influence financial outcomes and decisions

One of the key objectives of the survey is to identify the impact that ESG factors have on financial decision-making practices. It is evident from the findings that ESG is no longer regarded as an ethical factor but is considered an integral part of financial risk management practices. Over 85% of the respondent group expressed that ESG considerations occasionally or consistently affect investment decisions, lending choices, or screening the clientele. Moreover, 58% of the firms indicated that they are actively taking steps to decrease engagement with high-carbon-emitting clientele or sectors.

Despite such progress, there still lies a significant gap with regard to quantification. Only 44.4% of the surveyed organisations reported that their institutions assessed ESG risks in monetary terms or used ESG risks in financial tools like stress testing or capital planning. We can now understand and accept the challenge faced by organisations in the successful

integration of ESG, which involves the use of mostly qualitative ESG data to provide quantifiable financial metrics.

4.5 Key challenges and anticipated ESG threats

On doing a qualitative analysis of the open-ended comments, certain ongoing challenges in ESG risk integration are brought into focus. These are being encountered in the following manner regarding the availability of data, although this was raised by 42% of the comments: Data quality and availability.

Challenges related to quantification and modelling were also frequently mentioned (37%). Many respondents explained that it still is challenging to try to convert various ESG indicators into concrete financial outcomes that have the ability to be acted upon and incorporated into various designs. As a result, ESG factors are often acknowledged in principle but not fully embedded in financial models.

Regulatory complexity emerged as another major barrier (35%). Respondents pointed to the rapid pace at which ESG standards and requirements are evolving across jurisdictions, creating uncertainty and increasing compliance burdens. This makes it harder for institutions to develop stable, long-term ESG frameworks that can be applied consistently.

Going forward, the type of risk that tends to emerge as a significant concern is risk associated with governance practices (49.4%), risk associated with environments of regulations (48.1%), or risk associated with climate change (44.4%). It seems that as a matter of tacit knowledge, its survival is based on either its governance practices or its ability to cope with a complex environment of regulations.

4.6 ESG materiality matrix analysis

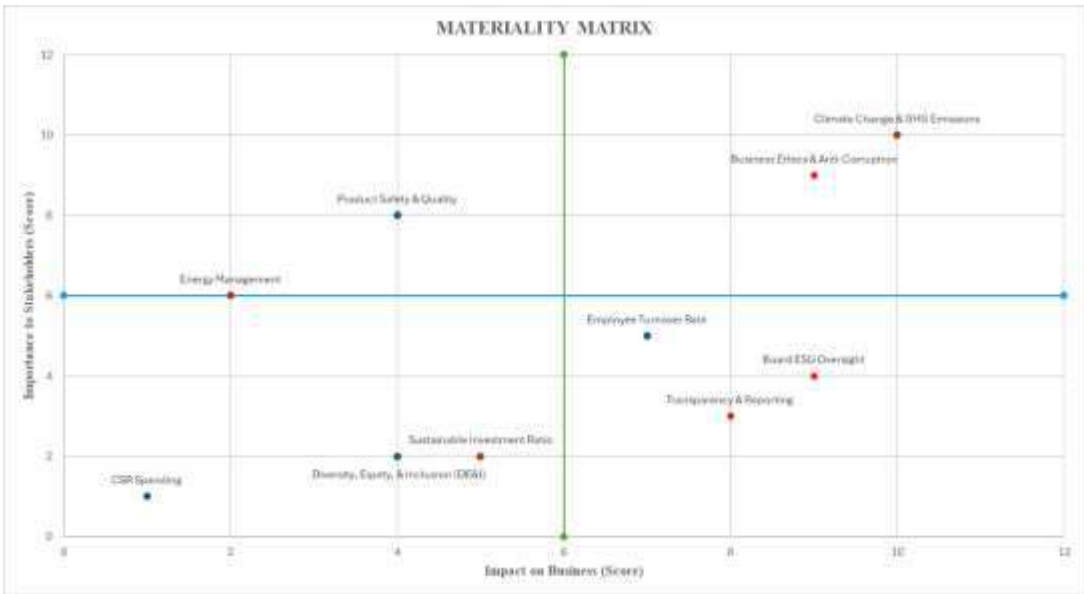
To evaluate how closely ESG priorities align with their impact on the business, a materiality matrix was developed using two key dimensions:

Vertical Axis: Importance to Stakeholders: Based on the responses to the question “How would you prioritise the following Environmental, Social, and Governance (ESG) parameters based on their significance to your institution?” Higher scores indicate a stronger level of importance.

Horizontal Axis: Impact on Business: Based on publicly available organisational and sectoral benchmarks, they reflect potential financial, operational, regulatory, and reputation-related implications of various ESG factors on financial institutions.

Both axes were scaled 1-10 to facilitate ESG comparison across these criteria. ESG issues were then identified and analysed through the use of quadrants to highlight key divergence points as well as points of convergence.

Figure 3: Constructed Materiality Matrix



Source: Created by authors

Figure 4: X-axis and Y-axis Scores, Derived from the Questionnaire and Existing Literature

Topic	Category	Importance to Stakeholders (Score)	Impact on Business (Score)
Climate Change & GHG Emissions	E	10	10
Energy Management	E	2	6
Sustainable Investment Ratio	E	5	2
Product Safety & Quality	S	4	8
Employee Turnover Rate	S	7	5
Diversity, Equity, & Inclusion (DE&I)	S	4	2
CSR Spending	S	1	1
Business Ethics & Anti-Corruption	G	9	9
Board ESG Oversight	G	9	4
Transparency & Reporting	G	8	3

Source: Created by authors

4.6.1 High-impact, high-priority ESG parameters

From the materiality matrix, it is evident that there exists a high concentration of Governance-related factors in the high-importance-high-impact quadrant, showing the high alignment between institutional perception and real-world financial relevance.

- Business Ethics & Anti-Corruption scores very high on both axes, reflecting its direct linkage to regulatory sanctions, litigation risk, capital access, and institutional credibility.
- Climate Change & GHG Emissions also occupies the strategic core, demonstrating both high stakeholder importance and high business impact. This confirms that climate risk

has transitioned from a long-term sustainability concern to a near-term financial and regulatory risk.

These results suggest that financial institutions are increasingly aware of ESG risks that have clear regulatory, legal, and balance-sheet transmission channels, and that governance and climate risks continue to occupy a central position within institutional risk hierarchies.

4.6.2 High-impact but under-prioritized parameters

Many ESG parameters have high or fair business impact but relatively lower stakeholder prioritization, which may indicate potential materiality blind spots.

For example: Product Safety & Quality - Good business impact owing to implications in litigation, reputational loss, and client trust, yet has only a medium priority.

Energy Management - It is underweighted compared with its operational importance and shows tangible cost and transition-risk implications.

This misalignment suggests the potential for an institution to be more reactive than proactive in their approach to these risks-that is, more inclined to respond after regulatory and/or market signals increase.

4.6.3 High-priority but lower-impact parameters

Certain Social ESG factors rank relatively high in perceived importance but show lower immediate business impact in the external scoring: Employee Turnover Rate, Diversity, Equity, and Inclusion (DE&I). While these parameters indeed lie at the heart of institutional culture and long-term resilience, their financial materiality seems indirect or delayed. They influence outcomes through channels such as productivity, talent retention, and reputation rather than causing immediate financial losses. Their high priority reflects a values-driven approach, shaped more by internal policies and public expectations than by direct risk transmission.

4.6.4 Low-impact, low-priority parameters

Parameters such as CSR Spending and Sustainable Investment Ratio fall within the low importance and low impact category. This implies their poor incorporation within the key frameworks in risk decision-making.

This positioning indicates that these factors are still viewed mostly as: Discretionary or reputational tools, considered peripheral to core risk management, generally less relevant to regulatory capital or financial performance.

This not only confirms the finding of the study that financial institutions focus on ESG aspects with risk and compliance implications, but it indicates the potential focus of financial institutions on philanthropic ESG aspects.

5.0 Conclusion

This research work aimed to dive into the ever-changing landscape of ESG risks in the financial sector and to propose a framework for integrating them within the traditional risk management framework. Based on the analysis of survey data and facts from recent literature, a number of key conclusions emerge.

First, ESG risks have transitioned from being largely ethical considerations to material financial imperatives. More than 90% of financial professionals recognise these risks, and 86% anticipate that, over time, ESG will be an integral part of risk management, equivalent in importance to credit and liquidity risk. A true indication that the “reputational” era of ESG is essentially over.

Second, regulatory pressure remains the main driver of this shift. The fact that “regulatory non-compliance” is rated as the most material risk on a consistent basis suggests that global mandates such as the European Banking Authority 2026 guidelines play an important role in shaping institutional ESG integration. Still, a significant “implementation gap” exists though ESG is greatly discussed at the board level, less than half of surveyed institutions have indeed managed to quantify these risks in financial terms.

Finally, it forms a basis for risk management in social and environmental domains. The survey feedback indicates a clear focus on “board ESG oversight” and “business ethics” in order to emphasize that without effective governance systems in place, organisations would struggle to cope with social complexities and climate risk challenges.

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CHAPTER 10

Delay Analysis and Risk Mitigation in Indian Infrastructure Projects: An Empirical Study

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ABSTRACT

Infrastructural projects have a very important role to play on economic development, yet they are still faced by delays and cost overrun, which is particularly true in the developing economies like India. This empirical study paper will discuss the primary causes of delays, the current practices on the ways to reduce risks, and the implementation of innovative technologies. Our methodology was mixed because we balanced both the in-depth literature review and the responses of 36 industry participants in the form of surveys. Findings show that administrative delays (government approvals, land acquisition) are the most deplorable determinants of delay with 47.2 percent of the projects experiencing 10-30 percent schedule overruns. The moderate effectiveness is seen with the Critical Path Method (CPM) and with Risk Assessment Matrices (52.8% rating) and there appear to be high adoption barriers to BIM (41.7%), AI/ML (8.3%), and blockchain (2.8%). The approval delays have been found to be the most important factor by the Relative Importance Index (RII) analysis of the approval delays (RII=0.81). We propose a risk management model, which is dependent on technology integration, which bridges the gap between reactive and proactive project governance and the data-driven project governance.

Keywords: Infrastructure delays, Risk mitigation, Relative Importance Index, Digital construction, Project management, India.

1.0 Introduction

1.1 Background and problem context

The development of infrastructure is the key contributor to the economic development, social advancement and national competitiveness.

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Effective project delivery has become the most important in India with the rapid urbanization process and projects such as the National Infrastructure Pipeline and PM Gati Shakti. Nonetheless, the efforts are compromised by the continued delays. According to the Ministry of Statistics and Programme Implementation (MoSPI, 2023), approximately 40% of central sector infrastructure projects face time and cost overruns, with average delays exceeding 40 months in some sectors. Such delays are not just the scheduling failures but instead they create the domino effect of escalation of the budget (it is normally escalated by 15-30 percent), wastage of resources, poor quality and loss of faith in the government. The economic costs are mind-blowing, as it is estimated that project delays cost the Indian economy 1-2 per cent of GDP per year due to lost productivity and wasting the resources on the capital.

1.2 Research gap and significance

Even though no shortage of literature exists on construction delays internationally, most research on the subject in India lacks depth in terms of empiricism concerning the impact of traditional practices of risk management and novel digital applications. Moreover, existing studies have not conducted a quantitative study in terms of frequency and severity on the ranking of delay factors in the Indian context. This paper compensates these gaps through presenting empirical confirmation of delay determinants and evaluating risk management digital transformation preparedness.

1.3 Research objectives

This study aims to:

- Identify and quantitatively rank the causes of delays in Indian infrastructure projects using dual metrics of frequency and severity.
- Evaluate the effectiveness of current risk mitigation practices and their organizational integration.
- Analyze the adoption levels and barriers for advanced digital tools in delay mitigation.
- Develop a framework for integrating traditional and technological approaches to proactive risk management.

2.0 Literature Review

2.1 Global perspectives on construction delays

The research on construction delay has a long history of more than 40 years, and the ground-breaking contributions from the field of research have laid the frameworks in various geographical and economic settings. An overview of the main foreign research demonstrates that there are general obstacles and local peculiarities in delay causation and mitigation (refer Table 1).

Table 1: Global Studies on Construction Delay Factors

Researcher(s)	Country	Key Delay Factors Identified	Methodology
Kumaraswamy & Chan (1998)	Hong Kong	Poor site management, unforeseen ground conditions, design delays	Survey, RII Analysis
Odeh & Battaineh (2002)	Jordan	Contractor incompetence, owner interference, poor communication	Questionnaire, Ranking
Assaf et al. (2006)	Saudi Arabia	Change orders, payment delays, contractor planning	Frequency and Severity Indices
Frimpong et al. (2003)	Ghana	Inflation, payment delays, price fluctuations	Case Study Analysis
Faridi & El-Sayegh (2006)	UAE	Poor planning, design changes, labor productivity	Statistical Analysis

Source: Created by authors

The meta-analysis of these and other studies shows that there are certain variables that depend on the region that they are supported, but there are still common themes, such as administrative inefficiencies, financial constraints, design deficiencies, and resource management problems. The algorithms that it uses, including the Relative Importance Index (RII) and the frequency-severity analysis, have become common methods of carrying out systematic analysis of delay factors.

2.2 Indian context and emerging challenges

Infrastructure initiatives in India have their own distinctive challenges in the form of complex regulatory frameworks, difficult land acquisition, and multi-agency coordination needs. In transportation projects, Ramu and Prasad (2020) found that most of the factors involved political interference and bureaucratic delays, whereas Jain and Garg (2020) identified the bottlenecks of procurement and coordination problems among stakeholders in developing infrastructures in health care. The situation after the pandemic has added certain new dynamics to the old problems: supply chains, labor migration, rising material prices, and increased demands on remote project monitoring. These new issues require new risk models that include more resilience, flexibility, and digital adaptability. Digital divide in the adoption of construction technology has been more evident since Indian projects are behind their global peers in the adoption of tools of advanced mitigation.

2.3 Technological interventions in risk management

High-techs come with revolutionary potential in delay mitigation yet their use is highly differing in terms of location and project nature.

Building Information Modeling (BIM) facilitates the identification of clashes, 4D/5D simulation, and joint planning, and the research indicates that the implementation of BIM can also lead to a decrease in rework by 20-30 percent (Shirowzhan et al., 2016). AI and ML offer the opportunity of predictive analytics in delay prediction, pattern recognition in risk factors and automated monitoring systems, which will be able to detect deviations in real-time. Blockchain Technology has provided remedies in the form of smart contracts to provide automated payments, transparent documentation systems, and dispute resolution process. Internet of Things (IoT) enables real-time tracking of equipment usages, material movements, and environmental status affecting the project schedules.

Regardless of these technological developments, the adoption is still at a very low level in the developing economies because of the high implementation cost, skills imbalance, organizational resistance to change, and a lack of infrastructure to support. This brings the paradox of the situation in which the areas with the most serious delay problems are the least equipped with technological solutions that can help solve them.

2.4 Theoretical framework

The framework used in the study is the Integrated Risk Management Framework (IRMF), which is a combination of four fundamental dimensions, which are: traditional risk analysis tools (CPM, EVM, Risk Matrices), digital integration platforms (BIM, AI/ML, IoT), organizational capability building through training and process redesign, and supportive policy and process reforms. The framework acknowledges that technical, managerial and institutional aspects must be addressed concurrently and in concert instead of separately as the main means of delay mitigation. This is especially applicable to the Indian environment, where the causes of delays are usually intertwined issues, which cross several areas.

3.0 Research Methodology

3.1 Research design

This research uses a mixed-methods sequential approach that has five integrated stages that develop upon one another to guarantee in-depth knowledge and viability of application. The study process commences with Phase 1: Literature Review, which aims at building theoretical background, then moves to Phase 2: Instrument Development, where the researcher designs powerful data collection instruments, followed by Phase 3: Data Collection, where the researcher gathers data by consulting industry players, then to Phase 4: Analysis where the researcher uses quantitative and qualitative data analysis methods to transform the information to recommendations, and finally the researcher undertakes Phase 5: Framework Development to actualize the recommendations.

3.2 Sampling and data collection

The sampling method involved a purposive approach which targeted professionals who are directly involved in the planning, execution or management of infrastructural projects. The sampling plan was based on the principles of diversity in terms of organizational roles, types of projects, and geography in order to have holistic views. The sample size finally consisted of 36 respondents who represented different organizational backgrounds as shown in Table 2.

Table 2: Respondent Demographic Profile (N=36)

Category	Sub-Category	Frequency	Percentage
Sector	Infrastructure Construction	19	52.8%
	Real Estate	11	30.6%
	Industrial Construction	4	11.1%
	Other	2	5.6%
Company Type	Contractor	15	41.7%
	Client	12	33.3%
	Consultant	9	25.0%
Experience	<5 years	31	86.1%
	5-10 years	4	11.1%
	11-15 years	1	2.8%
Project Types	Roads/Highways	11	30.6%
	Water/Dam	4	11.1%
	Metro Rail	3	8.3%
	Mixed/Other	18	50.0%

Source: Created by authors

3.3 Instrument design

The questionnaire was carefully written and had four extensive sections. Section 1 included demographic and organizational data as a background to responses. Section 2 was devoted to the evaluation of delay factors with the help of dual 5-point Likert scales with frequency (Never to Very Often) and severity (Very Low to Very High) of 13 delay factors frequently mentioned. Section 3 considered the risk mitigation practices, their adoption, and perceived effectiveness. Section 4 looked into the progress in the levels of technology adoption, barriers to the implementation and organizational preparation to digital transformation.

3.4 Analytical methods

To be certain in the analysis, the research used a variety of analytical methods. Relative Importance Index (RII) was obtained by calculation of the delay factors by the

following formula $RII = SW / (A \times N)$, where W signifies weight provided by the respondents (1-5 scale), A is the maximum weight (5), and N signifies the total respondents (36). Severity Impact Index (SII) was calculated as follows: $SII = \sum (F_i \times S_i) / N$, F and S are the frequency and severity scores of respondent i. The correlation analysis was performed with the help of the Spearman rank correlation coefficient which was used to compare relations between various delay factors and relations between the frequency and severity ratings. Descriptive statistics described the sample adoption rate, effectiveness rates, and performance measures.

3.5 Validity and reliability

A number of validation processes were applied to ensure the methodological rigor. Validity of the content was ascertained by the content review of three senior construction management professionals with the aggregate experience of more than 60 years. It also pilot-tested the instrument on five practitioners and refined it based on the responses. Cronbach alpha method was used to find out the reliability and the delay factors scale gave the result of 0.87 which is high internal consistency. Coherence of response patterns was also assessed logically and outliers' response also examined to see whether there existed any data quality issues.

4.0 Results and Analysis

4.1 Ranking of delay factors

The analysis reveals a clear hierarchy of delay factors affecting Indian infrastructure projects, with administrative and regulatory challenges emerging as most significant.

Table 3: Delay Factors Ranking by Frequency, Severity, and RII

Rank	Delay Factor	Mean Frequency (1-5)	Mean Severity (1-5)	RII
1	Delay in government approvals	4.06	4.03	0.81
2	Land acquisition issues	3.42	3.86	0.77
3	Financial constraints/cash flow	3.25	3.97	0.76
4	Material supply disruptions	3.83	3.61	0.75
5	Design changes during execution	3.61	3.58	0.72
6	Contractor inefficiencies	3.47	3.53	0.70
7	Lack of skilled labor	3.36	3.47	0.68
8	Environmental/weather conditions	3.33	3.33	0.67
9	Inadequate project planning	3.31	3.31	0.66
10	Ineffective communication	3.28	3.25	0.65
11	Equipment breakdowns	3.08	3.17	0.63
12	Community/stakeholder opposition	2.94	3.06	0.60
13	Legal disputes and arbitration	2.89	3.03	0.59

Source: Created by authors

The evidence shows that delay in government approvals (RII=0.81) is the most influential factor closely followed by land acquisition issues (RII=0.77) and financial constraints (RII=0.76). The three items are a group of administrative-financial issues that cumulatively explain the greatest delays effects (Table 3). More importantly, all of the three leading factors have an RII value greater than 0.75, which means that they are common and severe in effect. The close association of frequency and severity ranking ($r=0.89$, $p<0.01$) confirms that frequently recurrent delays are also rated as the most severe ones by the practitioners.

4.2 Risk mitigation practices analysis

Current risk mitigation practices show a strong preference for traditional, established methods over innovative or technology-driven approaches.

Table 4: Adoption and Effectiveness of Risk Mitigation Practices

Practice	Adoption Rate	Perceived Effectiveness (1-5)	Primary Users
Critical Path Method (CPM)	69.4%	3.6	Contractors, Planners
Risk Assessment Matrix	63.9%	3.8	All sectors
Contingency Planning	58.3%	3.5	Clients, Consultants
Early Stakeholder Consultation	52.8%	3.9	Consultants, Clients
Digital Project Management Tools	47.2%	3.7	Contractors, Planners
Regular Risk Audits	44.4%	3.4	Clients, Large Contractors
Earned Value Management (EVM)	33.3%	3.3	Large Organizations
Performance-based Contractor Selection	25.0%	3.8	Clients
AI/ML-based Predictive Tools	8.3%	4.2*	Early Adopters
Blockchain Applications	2.8%	4.5*	None in sample

Source: Created by authors

4.3 Potential effectiveness based on literature

Analysis indicates that there is a strict dichotomy between the conventional ones (which prevail in the rates of adoption but have moderate ratings of potential effectiveness (mean 3.6/5) (Table 4) and the progressive digital tools (with low adoption rates but much higher potential effectiveness based on the literature and experience of early adopters). The highest percentage of 27.8% of the respondents rated their current mitigation methods as being rated as Highly Effective with the majority (52.8) indicating that they were rated as being modestly Effective. This is also an indication of the effectiveness gap in which the traditional tools have the necessary baseline control but cannot systematically control the delay factors which are complex and interconnected issues in the Indian infrastructure projects.

4.4 Technology adoption analysis

The adoption of digital technologies for delay mitigation reveals significant disparities between awareness and implementation.

Table 5: Technology Adoption Rates and Barriers

Technology	Adoption Rate	Primary Barriers (Frequency)
BIM	41.7%	High cost (47.2%)
IoT	11.1%	Lack of skilled personnel (38.9%)
AI/ML	8.3%	Resistance to change (30.6%)
Blockchain	2.8%	Limited organizational policy (22.2%)

Source: Created by authors

Building Information Modeling (BIM) is the least utilized system with a rate of 41.7 and is mainly to facilitate coordination of designs and detect clashes as opposed to combined schedule and risk management (Table 5). The adoption of Internet of Things (IoT) applications is still at 11.1% and is primarily applied in large-scale or high-value endeavors to monitor equipment. The adoption of Artificial Intelligence and Machine Learning (AI/ML) tools is the lowest with an 8.3 percent adoption which is usually pilot implementations in technologically advanced organizations. The adoption of blockchain technology is non-existent with the lowest adoption being 2.8 and none of them reported to have implemented the technology at any of their projects.

High implementation costs (mentioned by 47.2 percent of the respondents) are the barrier to adoption that is dominated by the high costs of construction, which are capital-intensive, and by the lack of profit margins to invest in the technology. The shortage of competent staff (38.9%) cites a human resource critical aspect in digital construction management requirements. The fact that resistance to change is the highest (30.6%) shows cultural and organizational inertia in an industry that is approached slowly to innovations. Inadequate organizational policy (22.2%) implies inadequate institutional and legal structures that may contribute to and enforce technology integration.

4.5 Project performance metrics

Actual project outcomes confirm the severity of delay challenges identified through factor analysis (Table 6). The performance data shows an ugly truth 77.8% of projects are overrun by more than 10 percent and almost half (47.2) of the projects are overrun by 10-30 percent of the schedule. On the same note, the percentage of cost overruns experienced in 72.2 is above 15% and 41.7 in the 15-30% bracket. The numbers are in line with the national reports by MoSPI and they it proves that delays and cost escalations is not a one-off

phenomenon, but a systemic problem. The fact that schedule delays, and cost overruns are strongly linked (83.3% of respondents reported these problems) highlights the interdependence of the two issues - delays are bound to cause more costs due to the inflations, lengthy overheads, and penalties.

Table 6: Project Performance Analysis (N=36)

Performance Indicator	Range	Frequency	Percentage
Schedule Delay	10-30%	17	47.2%
	>30%	11	30.6%
	<10%	8	22.2%
Cost Overrun	15-30%	15	41.7%
	>30%	11	30.6%
	<15%	10	27.8%

Source: Created by authors

4.6 Interrelationships among delay factors

Correlation analysis reveals important patterns in how different delay factors interact and compound each other. The correlation table shows some significant patterns. The highest correlation is found between the government approvals and land acquisition ($r=0.82$) and the two are related as one because of the administrative- regulatory issues (Table 7). There are moderate to strong correlations between financial constraints with all the top factors indicating that they are the cause as well as the effects of other delays. Changes in design are highly correlated with disruptions in material supply ($r=0.73$), which means that late design modifications tend to interfere with procurement and logistic planning. Those interrelationships are the reasons why solutions to individual delay factors are often not sufficient when they are considered in isolation--the factors are not independent challenges due to their interrelation.

Table 7: Correlation Matrix of Top Delay Factors (Spearman's ρ)

Factor	1	2	3	4	5
1. Government Approvals	1.00				
2. Land Acquisition	0.82	1.00			
3. Financial Constraints	0.76	0.71	1.00		
4. Material Supply	0.68	0.64	0.69	1.00	
5. Design Changes	0.62	0.59	0.65	0.73	1.00

Bold indicates statistically significant correlations ($p < 0.05$)

Source: Created by authors

5.0 Discussion

5.1 Systemic nature of delay challenges

The fact that the administrative factors are the primary causes of delays suggests that the challenges are systemic and project-specific. The RII of government approvals (0.81) and land acquisition (0.77) are very high and hence imply that they are institutional constraints that lie within the regulations and governance structures of India. Such outcomes are related to the literature that hints on the complexities of the Indian federal system, where the infrastructure projects are more likely to require corroborations of a large number of organizations at the central, state, and local levels. The sequence of time-consuming nature in such processes is further compounded by the fact that the rules and documents requirements keep changing thus extending the time further making it impossible to eradicate the delays that even the management of the individual project team would be unable to eradicate.

The interdependence between delay factors presented in Table 7 gives valuable information on mitigation strategy creation. The close correlation between administrative delays and financial constraint ($r=0.76$) indicates that the delayed approvals tend to create cash flow issues since spending is made and revenue targets are delayed. On the same note, the relationship between material supply and design modifications ($r=0.73$) suggests that the process of procurement planning is more often than not interrupted by design alterations at the late design stages and this leads to the creation of the vicious cycle of delays. The implication of these interrelationships is that mitigation should be effective at reducing clusters of related factors and no single issues.

5.2 Weaknesses of traditional risk management: Striking the performance ceiling

The analysis has found that there is a severe weakness in the contemporary industry practice as the traditional risk management tools have reached a major plateau in terms of performance. The current rating of 3.6 out of 5 in the average effectiveness of such methods as the Critical Path Method (CPM) and Risk Assessment Matrices is no longer enough when it comes to the dynamic complexities of the modern Indian infrastructure projects. The issue is their very way in which they are built. CPM however good in establishing a baseline schedule, is based on the deterministic assumptions. It is not enough to capture the profound ambiguities and instabilities, of hysterical regulatory power and unbalanced material chain, within the reality on the ground. Similarly, the risk matrices are beneficial in the initial identification, but they are basically fixed documents. They fail to offer the dynamism and updating aspect required in responding risk management as the project takes a shape and new issues emerge.

It is this reactive nature that focuses on detection of deviation after they occur, rather than prevention that renders them having a narrow impact.

This creates a colossal industry paradox; strong adoption levels and average outcomes. The fact that one or another organization continues to use the tools does not imply that they are more effective, it is merely the familiarity, standardization, or that fact that the tools are part of the organizational culture. Such reliance puts the industry in a state of competency trap where complacency with any tools that are below the best is a literal stumbling block to searching any that are even better. These data show that additional optimization of these traditional methods can only have a diminishing marginal return. This performance ceiling would entail a paradigm shift to reach this performance ceiling as opposed to incremental changes to an aging and traditional method of doing things.

5.3 Technology adoption paradox: Closing the gulf between potential and practice

Indian construction is marked by the extreme and vivid distinction between the projected potential and minimal realisation. It is a manifestation of this so-called readiness-adoption paradox that the gap between the 88.9 percent of the interviewed people who stated having positive attitudes toward digital tools and the only 8.3 and 2.8 percent adoption rates of AI/ML and blockchain, respectively. This contradiction is perpetuated by a self-maintaining cycle of obstacles. High upfront cost (47.2%), a significant barrier in an industry that is well-known with low profit margins and significant budget constraints, is the most mentioned barrier. Although it is evident that strategic technology investments can pay off 3-5x with efficiency benefits, the industry has a poor track record of working with short-term financial horizons because long-term value is lost.

To worsen the cost challenge, there is an acute skills shortage (38.9%). The construction labour force, which has been highly labour-intensive, is not digitally savvy to support and operate hi-tech tools such as predictive analytics platforms. Additionally, the cultural barriers related to organizational inertia and change resistance (30.6) in established firms represent the cultural barriers as well as the lack of supportive policy (22.2) in supporting the wide adoption. The combination of all these factors has formed an environment of stagnation in which the knowledge of technological potential is not being acted upon resulting in a vast array of tools of delay mitigation remaining largely untapped.

5.4 A future-moving strategy: Technology-Integrated Risk Management (TIRM) framework

In order to address the two-fold problem of ineffective conventional means and lack of digital implementation, this paper introduces the Technology-Integrated Risk Management (TIRM) Framework. It is not just an isolated tool, but a five-layer ecosystem covering all

layers of holistic changes aimed at encouraging a paradigm shift in project governance, which is not reactive but proactive.

Data Foundation Layer: This bottom layer forms an integrated information ecosystem through the compilation of IoT sensor data of sites, rich Building Information Modeling (BIM) model and historical project databases into one source of truth.

Analytical Engine Layer: Raw data in the bottom layer are analyzed by machine learning algorithms and AI in this layer. This allows the predictive analysis of delays, the recognition of trends in aspects of risks and the simulation complexities of situations.

Decision Support Layer: Here, the complicated analytics are transformed into actionable intelligence to the project teams in a form of user-friendly dashboards, automated early-warning messages and AI generated mitigation recommendations to enable them to make timely, informed decisions.

Organizational Integration Layer: This is a highly crucial layer because it entails making sure that the technology is effectively integrated through the development of digital proficiencies through the training, process redesigning and nurturing an organizational culture of data-driven decision making.

Policy Environment Layer: The outermost layer facilitates the conditions of success: a good governmental regulation, the standard of data within the industry, and financial or procedural incentive driving the technology adoption.

TIRM model is a paradigm shift: to make predictions but not diagnoses, to make decisions using data and not gut feeling and to open datastores and not closed datastores.

5.5 Policy and implementation requirements: Multi-stakeholder mandate

The effective change that is evident in the context of the TIRM demands the concerted action of all participants of the infrastructure ecosystem.

On the policymakers' side: The task here is to be enablers. This includes the adoption of digital single window clearance systems with legally required timelines to address the primary cause of delay. It is essential to develop technology adoption incentives i.e. tax benefits, bid preferences or accelerated approvals of tech-forward projects.

The creation of the national digital construction standards will guarantee the interoperability, but the sectoral innovation funds could be used to de-risk early adoption.

In the case of Industry Associations: They are involved in the facilitation of collaboration and capability building. It also involves the creation of standardized digital competency frameworks, industry-academia collaboration in modernizing the curriculum, development of technology demonstration centres to facilitate hands-on education and peer learning networks to share knowledge.

In the case of Educational Institutions: Academia has to overcome the increasing gap of skills. This involves incorporating digital construction modules in mainstream engineering and management degrees, provision of specialized certification degrees, creating applied research centres with local issues, and developing strong industry immersion degrees.

In the case of Project Organizations: It is up to the leadership to instigated internal change. Firms need to develop phased technology adoption roadmaps, allocate dedicated technology budgets (2-3% of project cost), establish cross-functional digital teams, and implement performance-linked incentives that reward proactive risk management and successful tech integration.

6.0 Conclusions

The results of this research provide a definite and compelling argument of change. The continual pre-eminence of administrative delays, systemic quality of cost and time overruns, low efficiency of conventional tools, and the evident technology adoption paradox all point to the fact that the status quo is unsustainable.

The development of infrastructure in India is at a crossroad. The way of gradual change towards old ways has been exhausted. It is only through the alternative option that is the adoption of an overall transformational change that will be digitally enhanced in terms of its offerings under the TIRM framework that there is a solution to the attainment of the efficiency, predictability and excellence that the ambitious development agenda of the country requires. It is not a trip that can be completed by just buying new software, but rather it is a systemic change of processes, reskilling of the labor force, change of organizational culture and supportive policy development.

The policymakers, industry leaders, educators, and practitioners should work together to create an ecosystem where digital innovation becomes the driving force that makes the project deliver timely.

The more disruptive technological space that India faces today, the more it poses a threat to the infrastructure industry in India, not the adoption of new tools, but such a risk of failing to modernize. Taking the decisive step in the direction of the complete digital transformation, the industry will be able to recreate its future, make the constant delays its history.

7.0 Limitations and Future Research

The limitations of this study include a small sample (N=36), subjectivity to early-career professionals, self-reported data, and lack of representation of the sector, which have

influence on generalizability. Further studies need to be conducted longitudinally on the effect of technology, sector analyses (e.g., renewable energy), India analyses on ROI, and behavioural studies on how organisations may be encouraged to adopt technology in the building industry.

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CHAPTER 11

Assessment of Delays in Construction of Water Infrastructure Projects and their Cost Escalations

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ABSTRACT

Infrastructural projects have a very important role to play on economic development, yet they are still faced by delays and cost overrun, which is particularly true in the developing economies like India. This empirical study paper will discuss the primary causes of delays, the current practices on the ways to reduce risks, and the implementation of innovative technologies. Our methodology was mixed because we balanced both the in-depth literature review and the responses of 36 industry participants in the form of surveys. Findings show that administrative delays (government approvals, land acquisition) are the most deplorable determinants of delay with 47.2 percent of the projects experiencing 10-30 percent schedule overruns. The moderate effectiveness is seen with the Critical Path Method (CPM) and with Risk Assessment Matrices (52.8% rating) and there appear to be high adoption barriers to BIM (41.7%), AI/ML (8.3%), and blockchain (2.8%). The approval delays have been found to be the most important factor by the Relative Importance Index (RII) analysis of the approval delays (RII=0.81). We propose a risk management model, which is dependent on technology integration, which bridges the gap between reactive and proactive project governance and the data-driven project governance.

1.0 Aim

Experiment with more effective methods to organize construction, including team-oriented methods (think IPD), in which the parties share an equal deal of risks. IPD strains collaboration on deals, equalizes risks but specifically ties salary to performance - aiding easier workflows and lessening disputes so individuals collaborate.

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Local solutions to sewer repairs produced such clever tactics as rapid field inspections as well as group contracts which fit the needs of the locals. The same applies to water sharing in Mexico which involves farm and city use as the tracking tool to gauge the nature requirements. We can see through rural China how change of leadership is creating a stronger long-range set-up. Out in Arizona, using real-time info streams, urban planners make tweaks - all cases indicate that there is no way to fit solutions elsewhere.

1.1 Research objectives

- *Investigate delay factors:* Labelling: Classify technical, environmental, financial, regulatory and managerial factors that lead to project delays in water distribution infrastructure projects.
- *Dissect project management strategies of delay:* Measure the impact of project management techniques (scheduling, allocation of resources, coordination of stakeholders) on the probability and degree of delays.
- *Quantify cost increases:* How does project delays affect the total costs of the project, both direct (labor, materials) and indirect costs (penalties, opportunity costs)
- *Explore long-term impacts:* Research on whether construction or the delay in commissioning of water distribution systems may impact the long-term functionality and sustainability of the water infrastructure.
- *Proposing strategies:* To offer a solution of strategies and recommendations (e.g., Procurement techniques, Contractor choosing approach, Risk management system that might aid in lessening of delays and the transaction cost of such delays in water distribution project.

2.0 Introduction

The difference between a thriving society and places where business cannot survive is clean, reliable drinking water - which not only safeguards human health but also increases employment opportunities locally but also keeps daily operations going. The supply networks come to the city as well as small communities and ensure that everything runs smoothly without hiccups and risks. They mostly apply elevated reservoirs known as ESRs with tough HDPE pipes - both can endure the test of time and cut costs. This makes the push by the lines since these tanks are elevated. HDPE pipes bend easily without breaking and easily deal with uneven ground. Nevertheless, even a well-performing gear still chugs at a crawl; certain projects sometimes - this push works against other projects at the cost of holding clean water until needed in time and place by the folks. When systems fail to perform efficiently in villages, installation of water tanks and plastic pipes requires an eternity, which makes clean

water a nightmare, and also exposes people to diseases. Poor roads with the scarcity of supplies push things even to the limit in terms of the financial pressure. The congestion seen in urban cities requires teams to navigate between and through a wide range of actors and address levels of regulations, keeping things at a standstill. This stalemate translates to an increase in wait time to free flowing services, increase in bills, services slacking, and shutdowns becoming the order of the day.

The work of late clean water was burning cash. Failure to meet deadlines result in increased costs - crews will remain longer, materials will become more expensive, fines will accumulate as deadlines are not met. In the meantime, the locals are hurt because jobs have stagnated, town economies are shaky, diseases are transmitted through dirty taps. In order to add to that, inflation is creeping upwards, supply cost is up and down; and as the environmental or safety regulation changes the totals are even higher.

This project analyses delays in water systems that have high tanks and plastic pipes both rural and urban. Inequality in planning does not only slow down the progress itself but also drives the costs upwards, making rollout difficult. Instead of identifying individual factors, the study examines the manner in which fragmented teams end up putting pressure on schedules across the country. Failing to deliver on time or having insufficiently trained workers will cause a breakdown within a short period when there is no viable solution. The first step to fill these holes is to change the way crews establish the work immediately - reconfiguring approaches to their needs of the specific location. Alternatively, rather than wait, communicating early about the building work, leaders, and residents prevent larger snags in future. The timely arrival of supplies is also maintained by altering the way supplies are ordered hence the workers do not just stand around. Holdups are also reduced by being more considerate when establishing projects - despite the lack of cash. In summary: clean water is delivered to the community at a lower rate and is faster.

3.0 Literature Review

3.1 Connection between literature review and the Agra district water supply scheme case study

The Agra District Rural Water Supply Scheme under the Jal Jeevan Mission is indicative of most of the systemic issues raised in the body of water infrastructure literature the world over and in the region. Instead of a one-time project failure, the case study illustrates how repeating delay causes, governance lexical as well as planning flaws or coordination failures long since documented in previous studies are realised in an actual Indian rural set-up. The literature reviewed jointly offers the theoretical background, benchmarks of

comparison and the analytical tools in respect to which the Agra case can be interpreted, justified, and comprehended.

The pivotal point of the literature is the vast literature on the causes and effects of delays in drinking water development projects, specifically the case of Sri Lanka as reported by Perera and Halwatura. Their list of major drivers of delay includes slow client decision making, low stakeholder co-ordination, weak planning, financial stress on contractor and late payments; this list can be almost directly traced in the Agra scheme. The administrative inefficiencies, slow disbursement of fund, slow approval, and poor inter-department convergence witnessed in Agra is similar to the owner- and consultant-related factors, which registered the highest rate of agreement (79-82%) in the Sri Lankan and global data. This correspondence justifies the Agra case as being empirically consistent with the delay theory but not an exception.

The proposed criteria of strategic characterization of water infrastructure management by Garvin (2003) help in understanding the nature in which these delays are followed up by systemic under performance. According to Garvin literature, water projects are mostly unsuccessful when the institutional, financial and governance capabilities are not linked to the delivery of technical assets. This lack of connectedness can be observed in Agra in the distance that exists between the DPR preparation, procurement decisions, field execution, and community engagement. Physical specifications were done on the physical properties, like ESRs, HDPE pipelines and solar pumps but due to the lack of integration of institutional preparedness and operational planning, redesigns, re-working, and schedule slippage were frequent. Therefore, the framework by Garvin explains the macro level of poor performance of technically good projects when the system-level alignment is poor.

The perspectives of the literature on Integrated Project Delivery (IPD) and Gokhale (2012) in particular can be used to understand why the case of Agra did not overcome the effects of these challenges by employing traditional models of the delivery. The literature highlights the designs-bid-build structures fail in uncertain circumstances, the bifurcated responsibility, and late entry of the contractors which are the conditions which have manifested itself dominantly in rural water undertaking. In Agra, there were mobilization of contractors once the finalization and design errors were identified in execution and the risk was asymmetrically distributed. The study is directly informed by the literature on IPD that collaborative contracting and early stakeholder engagement and common risk-reward mechanisms had the potential to reduce rework, enhance coordination, and eliminate adversarial delays.

This point is also supported by the adaptive and agile project management literature (Lanier and Sukop, 2016), which emphasizes that interdisciplinary infrastructure projects involving the integration of the all the mentioned aspects of civil, mechanical, electrical, and

renewable energy require a flexible governance approach and iterative decision-making. The challenges of the Agra scheme in the incorporation of solar pumping systems into civil infrastructure and electrical systems are good examples of the impacts of fixed silo-based management thinking. The literature therefore justifies the inability of the traditional linear planning to react well to emerging site realities, monsoon shocks as well as issues on technology integration.

The insights on the operational level presented in the literature on rural water supply management (Li, 2019; Li, 2020), are directly related to the post-construction risks of Agra, as well as the community-related issues that Agra faces. These articles draw attention to the fact that sustainability is based on community engagement, financial sustainability, and institutional ownership. The lack of empowerment of the Village Water and Sanitation Committees (VWSC) in Agra and the reduced level of community involvement and poor communication resulted in resistance, land issues, and tardiness in household connectivity. The fact is supported in literature, that the delays are not only technical or contractual but have social or governance elements foundations in rural water systems.

Financially and risk-wise, the literature on the PPP failure and the risk driver (Tariq and Zhang, 2020) enhances the concept of contractor distress that is realized in Agra. Despite the fact that the project was not a full PPP, there were several PPP-like risks, including the delay in receiving payments, exposure to inflation weak allocation of risk, and the rigidity in the regulatory board. Literature describes the causes of the loss of margins, cash-flow pressure, and the work being thrown away in certain occurrences which gave back to the project delay and cost increase.

It has been indicated in the asset management and capital prioritization literature (Thornton et al., 2012) that explains the erosion of identifiable costs and benefits over time in Agra. Delays made benefits realization, and cost life-cycles higher thus making the investment economically ineffective. Lack of preventive planning of assets and prioritization based on the condition in the implementation process is in line with caution in the literature that lapses in asset governance would increase cost overruns and reduce sustainability in executions.

Lastly, the methods of water scarcity modelling (Hernandez-Cruz et al., 2023) and network partitioning algorithms (Tian et al., 2022) are advanced study techniques that made their mark on the overall methodological input of the study. Although these methods were not used in Agra, their omission is a reason why the planners were unable to resolve many planning issues, including failures to optimize pipeline routes, pressure failures, and energy losses. These works justify the research hypothesis that the combination of modelling tools, GIS, and data-driven decision-making in the DPR stage may help to cut down the delays and operational inefficiencies in the downstream significantly.

4.0 Research Methodology

4.1 Root Cause Analysis (RCA) – Agra rural water supply scheme

Problem Statement: The Agra Rural Water Supply Scheme is a mass infrastructure project that was undertaken under the Jal Jeevan Mission (JJM) through the State Water and sanitation mission of the Government of Uttar Pradesh and is designed to be used to roll out functional supply of household tap connections to the rural population. The project will entail the design, constructions, commissioning, and long-term running and upkeep of surface water-based supply structure (Elevated Service Reservoirs (ESRs), HDPE pipeline networks, pumping system and other related facilities).

According to the Letter of Award (LOA), the project has been awarded to M/s Megha Engineering and Infrastructure Ltd. and has the total value of 1,085.66 Crores and includes:

Capital Expenditure (Capex): 964.36 Crores.

Operation and Maintenance (10 years): 121.29 Crores.

A premium was quoted on the nominal contract being (-0.45%), which may be referred to as a competitive bid environment and quality financial margins. The project schedule, as stipulated in the contract terms, was designed to be on a normal execution time of about 24 months, and a 10-year operation and maintenance was thereafter.

Though the project was highly planned, its scope and financial allocation are high, the project has suffered major setbacks in the implementation process that has seen the actual implementation of the project extend to around 30 or 34 months, which is almost 30 or 40 months above the planned date. These delays have led to increased costs, ineffective use of resources and slowing of socio-economic benefits especially in rural communities that also need better access to water supply.

5.0 RCA Analysis

The Root Cause Analysis follows a structured breakdown across five key dimensions: The Root Cause Analysis is based on a systematic dissection in 5 important dimensions:

Administrative Inefficiencies: Money is received with a lag, wait is protracted, and documents pile up - one slackening a thing in her hurry. Clearances are frozen unexpectedly longer when Jal Nigam trails behind local crews or neighbouring units. That stalling strangles the workers; purchase can be made at an even greater distance - so no movement along, but stumbling.

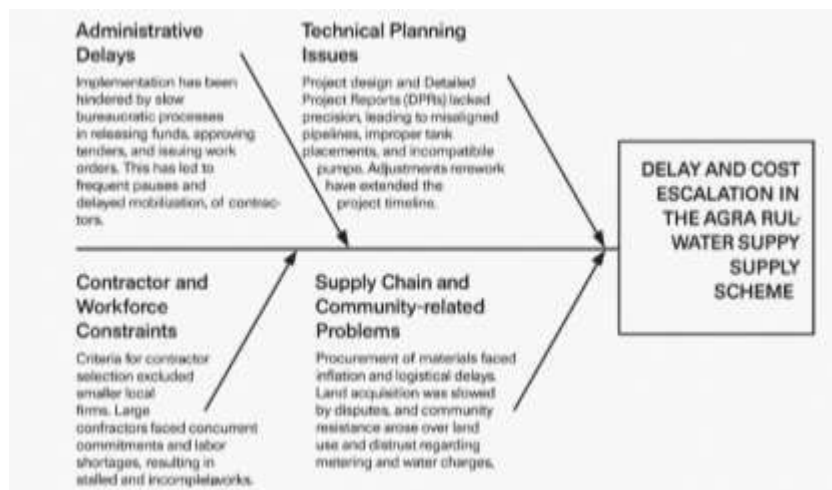
Technical Planning Gaps: The DPRs were typically not relying on trusted technology - e.g. GIS maps - so there was a high percentage of design failures or vacant

designs. Immediately after the start of the construction, the problem of layout appeared almost immediately, and teams had to go back and rectify large areas. To top that, plumbing, wiring, and structure components almost never fit very well and, therefore, it took funky time to connect solar equipment with the water systems.

Contractor and workforce constraints: The crew hardly increased due to the regulations that left the locals at the backburner, leaving bigger firms with the first option of crowded working sites. Such discrepancy resulted in wobbly staffing every now and then, spotty performance here and there, whereas certain tasks were just dropped when funds or supplies were low.

Supply chain disruptions: Shipments were slow due to floods, and prices of materials were increasing, which put a strain on the supply of pipes and fittings. Deliveries reduced - reaching a single point, with no additional storage nearby. Rises in solar equipment prices had also imposed an increase on the overall costs.

Community and social factor: False reports raised headaches in a number of areas, and fights arising over the use of the land with authorities intervening occasionally. The locals were sidelined - VWSCs lacked a face of authority or support and thus the locals lacked trust and thus managing to resolve local conflicts were slow.



Source: Created by authors

6.0 RCA Diagram

The RCA method of the Agra rural water project bypasses the typical split-path design - rather, the design takes the right path one step at a time through all the major causes, demonstrating how each of them contributes to longer wait and increased costs.

The biggest issue? The rural water push in Agra has regressed far behind - although the cost increases persist. There are six main drivers of this mess, each of them different, but interconnected, and silently amassing stress on every side.

Things became hard to lead because paperwork was obstinate, groups hardly kept in touch with each other - coupled with a haphazard money handling and confusing expenditure queries. All this housekeeping stood in the way of anything, delayed the teambuilding, pushed start dates as well.

There were not as many experienced people to hire: most were kept busy in other areas. There were locations where there was no local work force with appropriate skills and this slackened the pace. Top to that, rural water teams were not making much of a stir; it could be that their introduction earlier in the process could have prevented the growth of minor problems. The problem of shipping as well as the slow-order contributed significantly. Pipes, valves, or building materials are hit by delays - frequent glitches exacerbated by the increase of cost and fluctuating price, especially of solar equipment or associated items. Orders were done in one center and local transportation was slow meaning that daily items were barely in flow leading at times to a stall in the work process.

This went awry at an early stage due to the failure of the plans being done in a proper manner. At the midway point, the designs needed to change - the initial designs were missing major details. In their absence, such as GIS, the pipes were installed at the wrong locations, and the tanks descended into slopes of the land. Quality inspections were inconsistent or even reduced to non-existence hence errors accumulated and costly repairs were made.

Problematic equipment made it slower with the introduction of solar pumps. The chosen kit was unable to accommodate village wells and therefore issues cropped up. To make things worse, there was inadequate supply of skilled workers thus dragging installations.

Finally, and not the least, the place where things occurred caused its share of downfall. This is the time that each rainy season struck - work came to a standstill, trails became messy, equipment started to malfunction. Added to that, locals became edgy; people complained of lost space, bosses changed office at will, which disrupted schedules. In the absence of obvious means to disseminate information, rumours were going viral killing the morale in certain regions permanently.

6.1 Engagement and communications to the stakeholder

The Jal Jeevan Mission in Agra Rural Water Supply project, the involvement of the people coupled with sharing of information were the factors that influenced the rate of progress, the buy-in of locals and the actual success of the project. Since the purpose was to provide tap water to the people in various villages, the organizational element would have to

encompass all the aspects, not only the officials that could make decisions but also the locals that had to address the consequences.

Nevertheless, the manner in which things were developing indicated that there were continuous problems with which groups collaborated or communicated news. In addition to this, government organizations - such as Jal Nigam or public health departments - were to be established to lay down plans, disburse cash but accelerate greenlighting procedures. Even though its intentions were strong, giant lags on major data appeared. Each team worked independently without having effective means to keep pace in real-time. This time lag caused projects to be delayed, communication was not fast enough in making corrections in the blueprints, and problems such as headaches in technical details, mostly related to solar-powered units and links to energy networks. The wiring group, construction group or machinery crews would often go in different directions, skip check-ins, duplicate efforts, and sometimes do a re-do that would have been avoided had it been better positioned.

Nobody had any idea of what was happening down on site. The lack of enough hands combined with many crews involved with deadlines and too many crew meant that delays were greatly experienced whenever priorities changed- especially in cases where no information was received fast. When things were changed when it came to requirements or terms of purchase, the news leaked slowly - or not at all - and derailed, scheduling, both in the case of labor and supplies. Groups under unsteady leadership turned out to assume rather than know thus causing errors to accumulate and go far off course.

There was less entry of village crews such as Water and Sanitation Teams, creating confusion. These organizations ought to have linked locals to constructors. Theoretically, they would be checking on work, volunteering, or making an appeal. But there were a lot who doing barely worked, were intermittently directionless or never received proper training. There was no actual participation, and problems accumulated, creating tension and suspicion. This was evident when there were confrontations over land to be used in pump stations and this was worsened by pipelines going through the private land. They found it difficult to get the permission of people living close to them when there were no local go-betweens who had anything to say on how to iron out tensions.

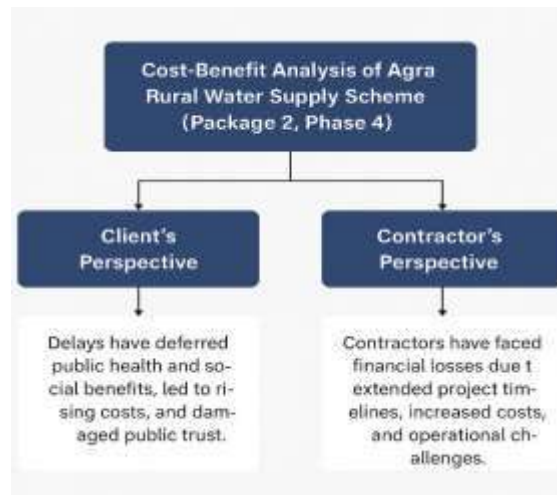
The introduction appeared unjust and incoherent to most of the residents. As much as there was hoped to gain, the majority were not aware of gain, construction noise, traffic jam, or impending maintenance chores. Where the facts were unavailable through the official channels, rumours in their place were having a handicap - the result was an angry reaction in some neighbourhoods, on their part. No initial discussions, informal visits, or even simple information sessions made the initiative be seen by people as support and more as a pressure that has been dropped on their door.

Nonetheless, some places succeeded to get progress by communal discussions. When the elders scheduled gatherings, and dragged country reps on board immediately, the turn of events was more noticeable. It demonstrates that when locals facilitate the discussion, things normally turn out to be much better.

Some minor adjustments assist in solving these issues. Begin with the establishment of small units in every region to ensure that the offices remain local. Choose good talkers who visit occasionally and not just one time only. Train community water teams including real tools and helpful expertise. Also demand constructors to meet citizens and technical personnel frequently under firm contracts - all combine the efforts of everyone.

This illustration shows that crafting in rural India requires individuals initially. It will not be served by machines or plans, but only by actual chat. Communicating should not be put on afterthought, but should be incorporated in the planning, construction, launching, and even fixing things in the future. Lose that constant link Even ingenious solutions may fail because the locals may fail to support them or may feel excluded.

7.0 Cost Benefit Analysis



Source: Created by authors

7.1 Time chainage analysis

The Agra Rural Water Supply Scheme as a project under Jal Jeevan Mission had a deadline of two years in the beginning. The following schedule covered every activity - plan writing to installation of operational taps in the houses in the chosen villages. However, the real progress was below what was expected. The setbacks overlapped and the completion was

delayed to approximately 32 or even 34 months. The long duration increased the costs besides postponing benefits to inhabitants.

DPRs, site visits or purchase setups were expected to begin within the project in the first half of the year. However, instead of rushing, it struck with loads of paperwork delays. The lack of approvals, the absence of such tools as GIS maps, and the discussions within the teams about the details, extended the timeframes to absolutely beyond the schedule. DPR services alone required almost eight weeks additional - as the path of the pipes or pump power was never established, without being moved at the outset.

The next was the stage of hiring and setup, which was supposed to be completed within three months but it again went awry. Tough eligibility provided served as a reduction of the number of businesses that could participate and a number of bids were cancelled or relocated under the cost restrictions. Due to this fact, the three months of hauling the teams and equipment to the site was extended by eight weeks. During this time, the contractors were having difficulties with governing and dismissing personnel and equipment because they are both bound in parallel civil undertakings by the government.

The second work, the main trench, which was to be started in the 7th month up to the 14th month, was also started late. By the time the teams moved in, it had already soaked in down and excavation at multiple spots was made more difficult. Land demarcation fights, unresolved documentation or clearance-come-clearance ensued, and slowed the progress. This was the only segment that increased by almost half a year because one problem had built over another.

The second huge undertaking - the installation of pump stations, installation of elevated water storage facilities, as well as the interconnection of pumps that are solar-powered, took close to three months behind schedule. The supply of supplies, particularly machine parts and electrical cables, have been delayed through reasonably unreliable deliveries and inconsistent prices of solar equipment. Most of the installations were later to be re-done due to a lack of compatibility in requirements; and few knew how to use the new systems. The duration of testing and the mode of commencement should not exceed three months but dragged beyond expected length - extra work came in, leaks were being taken care of, pressure on the network on one or other side was being tested. Once more the time lag between construction and cablers corrupt exercises, pushing the timeline forward by forty weeks. Finally, water line connections to houses - which should be completed by month 24 - lagged on until month 30 or 32. Strict schedules were leading to delays; opposition in some villages further increased the time lag. VWSCs could not easily speak to the households without having real power and therefore connection sign-offs required more time.

A schedule meant to be completed in two years was only completed nearly ten months behind schedule. Due to the time-wasting nature of it, costs skyrocketed - man hours

invested, equipment utilized and bosses who hung about all long after time constraints. Concurrently, real gains to communities were postponed as well. The locals continued to use unsafe sources of water; what is worse, the gradual evolution made them more sceptical of the activities of governments.

8.0 Data Analysis

By using the secondary data, PART 1 – Sri Lankan Study (Perera & Halwatura 2012)

Sample: 54 valid responses (Contractors = 21; Clients = 15; Consultants = 18)

Scale: 1–4 Likert (1 = Not Significant, 4 = Highly Significant)

Computation: Relative Importance Index $\times 100 \rightarrow$ % agreement

Delay Causes and Respondent Agreement (%) Sri Lanka (Perera and Halwatura, 2012)

The table enlists project-related delay causes - so-called Category A - and levels of agreement. There were 6 major issues raised that were supported by 70% to 78% of the respondents, indicating that most of them consider these issues. Unrealistic time schedules were the top at 78 with frequent increase in scope coming second with 76. Strong consensus was noted in the passing of information between teams; and confusion in the ownership of risks. The problem of land acquisition resulted in stalling of many, but the contribution of the officials did not lag far behind. On balance, 74 percent of them admitted to these challenges with internal management gaps having been identified as a fundamental problem.

Div.	Delay Cause (39 Total)	% Agreement (All Respondents)
A. Project-Related Causes		
A1	Frequent changes in project scope	76%
A2	Inadequate project duration / unrealistic schedule	78%
A3	Poor coordination between stakeholders	74%
A4	Improper risk allocation / assessment	70%
A5	Delay in site possession / land acquisition	73%
A6	Delay due to environmental clearance or local authority approvals	72%
Average (A)		$\approx 74\%$

Source: Created by authors

8.1 Causes owner / consultant causes (category B)

The table shows the cause of delays with owners and consultants - a majority concurred with 74 percent to 85 percent. Selecting things that were too slow or a delay in approvals was 85; however, late payment came at 82. Beyond that, the lack of enough workers was a problem - as was lingering on to collect drawings to be signed off or clients changing

their mind on a whim. Dubiously, around 79% of them indicated that these factors have a significant impact on project speed.

Div.	Delay Cause (39 Total)	% Agreement (All Respondents)
B. Owner / Consultant-Related Causes		
B1	Delay in progress payments by client	82%
B2	Slow decision-making and approvals	85%
B3	Delay in approving shop drawings / documents	77%
B4	Lack of competent staff in client/consultant organization	78%
B5	Unrealistic expectations or frequent client interference	75%
B6	Lack of communication between consultant and contractor	74%
Average (B)		≈ 79%

Source: Created by authors

8.2 Contractor-Related Causes (Category C)

The following table enumerates issues of contractor associated with delays in terms of the points of agreement, the highest being 88-77%. Inadequate on-site surveillance and inadequate oversight were 88 and 84 percent respectively as compared to unstable planning and disorganized scheduling which were the most important issues. The problems of finances followed closely as well as lack of skills; sporadic inspections coupled with reworks as a result of poor workmanship became a point of wide interest. With an average of 82 percent support, it is clear that performance by the contractors slows down the projects at a high rate.

Div.	Delay Cause (39 Total)	% Agreement (All Respondents)
C. Contractor-Related Causes		
C1	Poor site management and supervision	88%
C2	Inadequate planning and scheduling	84%
C3	Financial difficulties of contractor	79%
C4	Inadequate experience of contractor	81%
C5	Poor supervision and lack of quality control	77%
C6	Rework due to poor workmanship	78%
Average (C)		≈ 82%

Source: Created by authors

8.3 Design-Related Causes (Category D)

The table includes the reasons behind design delays, and the results are acceptance of around 72 to 80% or the majority of people are okay with it. Lacking design specifics made

80 percent; wrong or incomparable designs are at 78 percent - highest ranked problems identified. Continuous design modifications in addition to the lack of communication between office designers and workers on the sites contribute to delays. About 76 percent say so in general, noting that the quality of the designs - along with the manner in which they are shared in the first place is a significant contributor to failing to meet deadlines.

D. Design-Related Causes		
D1	Incomplete design details	80%
D2	Frequent design changes	76%
D3	Design errors / mismatched drawings	78%
D4	Poor coordination between design and site	74%
D5	Poor communication between consultant teams	72%
Average (D)		≈ 76%

Source: Created by authors

8.4 Material-Related Causes (Category E)

This table describes material-related delays - they were unanimous (ranged between 74% and 81). The top of the list was taken by 81% of the blame, which was attributed to late deliveries, followed faithfully by the quality of the item and incomplete orders. The bottlenecks also emerged as approval factors. Overall, about three out of four concurred completely with each other and indicated that more intelligent buying and managerial practices could reduce the number of hiccups.

E. Material-Related Causes		
E1	Late delivery of materials	81%
E2	Poor quality materials	78%
E3	Unavailability of materials	76%
E4	Delay in material approval process	74%
Average (E)		≈ 77%

Source: Created by authors

8.5 Equipment & Labour-Related Causes (Category F)

What comes out in the table is the cause of delays with equipment and labor - consensus is at between 76-80 which is an indication that there is just one opinion. At the head is equipment breakdowns with an 80 percent shortage of skilled workers with only 79 percent a second place. Missing or forgotten tools slow down the growth - but poor productivity and frequent absences apply further pressure. Approximately 78 percent of them feel that they can have reduced idle time with better maintenance as well as smarter team planning.

F. Equipment & Labour-Related Causes		
F1	Equipment breakdowns	80%
F2	Shortage of equipment	78%
F3	Poor maintenance of equipment	76%
F4	Shortage of skilled labour	79%
F5	Labour productivity issues / absenteeism	77%
Average (F)		≈ 78%

Source: Created by authors

8.6 External Factors (Category G)

This table brings out the external causes of delays with the approval score of 70 to 75. The rainy days made it to the top leading with 75 percent and edging out other outward influences. Difficulty in acquisition of land came next right behind and was bound up in court cases. Policy changes also bring things up. Supplies Price increases went up as well. Delays were also due to slow utility work - or lack of coordination with local agencies. Approximately, 72 percent responded in the affirmative, as these problems are not entirely avoidable, but tend to derail timelines.

G. External Factors		
G1	Adverse weather conditions	75%
G2	Political interference / policy changes	71%
G3	Fluctuation in material prices	70%
G4	Delay in utility shifting or local authority coordination	72%
G5	Land acquisition / legal disputes	73%
Average (G)		≈ 72%

Source: Created by authors

PART 2 – Cross-Study Global Synthesis (Assaf 2006; Sambasivan 2007; Chan 1997; Aibinu 2002)

Samples Combined: ≈ 330 respondents across 4 countries

Scale Conversion: $RII \times 100 = \% \text{ agreement}$

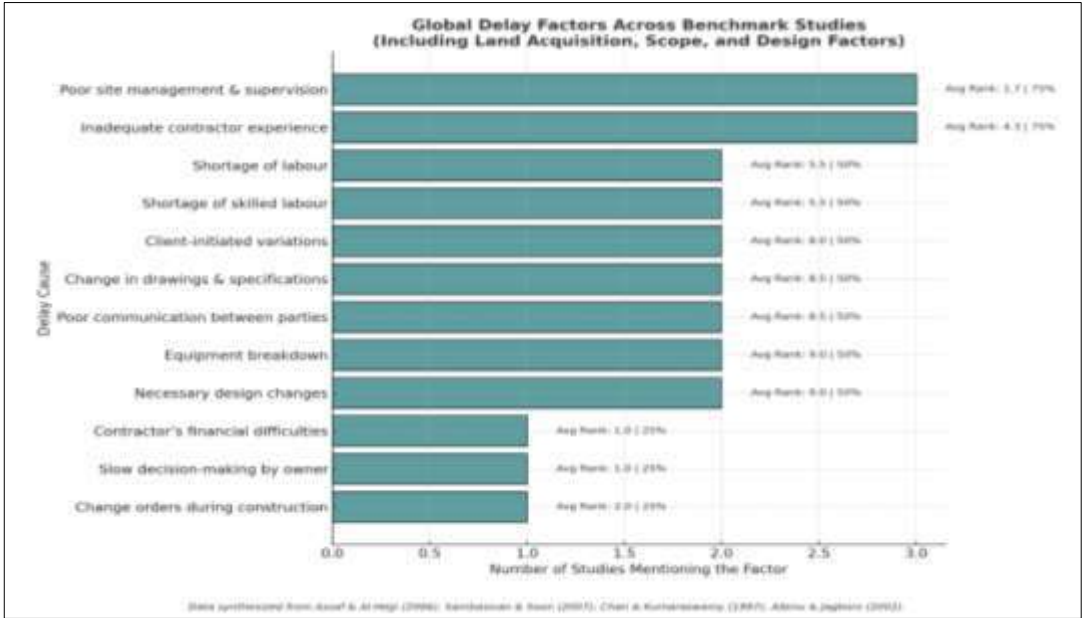
Aspect	Assaf & Al-Hejji (2006)	Sambasivan & Soon (2007)	Chan & Kumaraswamy (1997)	Aibinu & Jagboro (2002)
Sample Size	72	94	84	82
Respondents	Owners, Consultants, Contractors	Clients, Consultants, Contractors	Clients, Consultants, Contractors	Contractors, Consultants
Scale	5-pt (Frequency & Severity)	4-pt (Likert importance)	5-pt (Importance)	5-pt (Importance)

Top Cause	Owner slow decisions	Poor site management	Poor site management	Financial difficulties
Dominant Category	Client + Contractor	Contractor	Contractor + Client	Contractor + Finance
Top Effect	Time overrun	Time & cost overrun	Time overrun	Time & cost overrun
Mean Delay Impact	10–30 % time extension	Common (> 30 % of projects delayed)	≈ 25 % time overrun	> 50 % time overrun

Source: Created by authors

Summary Statistics

Metric	Value
Overall Average Agreement	77%
Highest Agreement	Poor site management (88%)
Lowest Agreement	Price fluctuation (70%)
Range	70% – 88%
Dominant Division	Contractor-related causes (82%)



Source: Created by authors

Part 3: Cash Flow and Timeline Deviation Analysis

The relative performance of planned and actual project performance shows that there is a considerable deviation in financial performance and schedules adherence. According to

the approved project schedule, the final project cost of 1085.66 Crores was to be implemented in a 24-month period, meaning that the monthly spending rate is going to be consistent and will be 45 Crores. Nevertheless, the actual progress records show that merely 400 Crores of work has been completed in almost 30 months period which is also an indication of a considerable decline in execution.

Table 1: Cash Flow and Timeline Deviation Analysis

Parameter	Value	Interpretation
Total Project Cost	₹1085.66 Cr	Total scope of work as per LOA
Work Completed (Dec 2025)	₹400 Cr	Actual achieved progress
% Completion	36.85% (~37%)	Significant lag in execution
Time Elapsed	30 months	Already exceeded planned duration
Planned Duration	24 months	Original project schedule
Planned Monthly Progress Rate	₹45.24 Cr/month	Required rate for timely completion
Actual Monthly Progress Rate	₹13.33 Cr/month	Current execution speed
Performance Efficiency	~29%	(Actual vs Planned rate)
Remaining Work	₹685.66 Cr	Balance work to be completed
Estimated Time Required (at current pace)	51 months	Based on actual rate
Total Estimated Project Duration	~81months(6.7 years)	Severe delay projection
Time Overrun	~237%	Compared to planned duration
Estimated Cost Escalation (20%)	₹217 Cr (approx)	Due to extended duration
Revised Estimated Project Cost	₹1300 Cr (approx.)	Including escalation

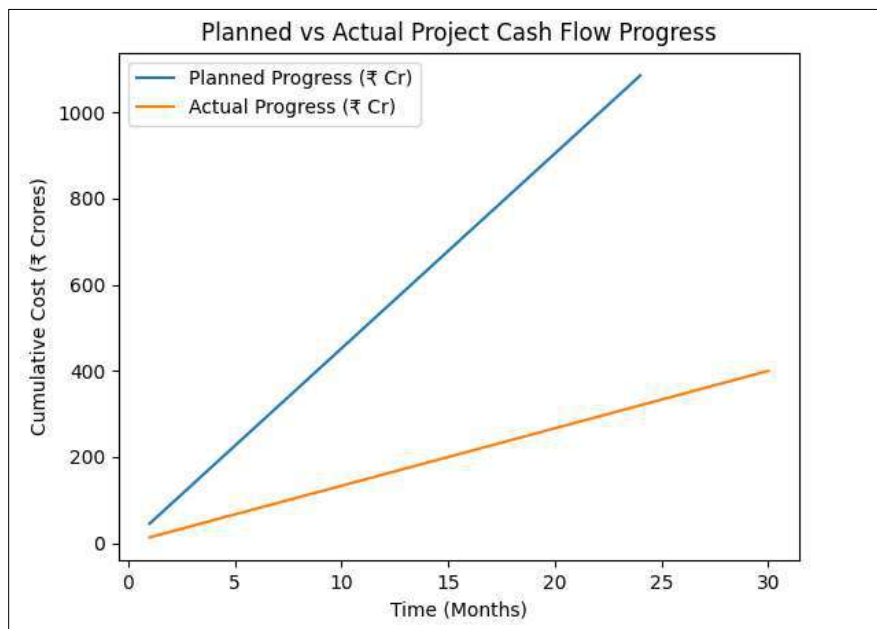
Source: Created by authors

It would lead to a real increase in the financial completion of about 37 percent as compared to the estimated 100 percent completion in the scheduled period. The lower implementation rate of about 13.33 crores every month is almost three times less than the suggested cash flow rate which indicates high level of inefficiencies in project implementation.

On following the pace of implementation, the balance of the work that is worth 685.64 Crores will take 51 months to complete. This increases the overall lifespan of the project to about 80-82 months, as compared to the initially set project deadline, which is thrice. This delay is basically a time overrun of approximately 237, showing overall planning, co-ordination and execution problems.

The cost escalation has a direct effect on the long project duration. The long schedules would result in high labour costs, longer usage of equipment, rise in prices of materials due to inflation and other overhead costs. In the worst-case scenario, the project cost would be growing by 1520 percent with the project cost coming to around 1300 Crores and above.

Figure 1: Planned vs Actual cash flow progress



Source: Created by authors

Besides the financial effects, the delay is also being associated with massive socio-economic losses. The perceived returns of enhanced water delivery system, enhanced health of the populace and decreased reliance on alternative water supplies are delayed hence lowering the overall worthiness and value of investment on the project.

This discussion explains clearly that number of execution delays do not just disrupt the project schedule but have a domino effect on the cost, efficiency and the outcome of the whole society, which highlights the importance of enhanced project management tools like Integrated Project Delivery (IPD), improved planning and real time monitoring systems.

8.7 Performance improvement analysis (Conventional vs Proposed Approach)

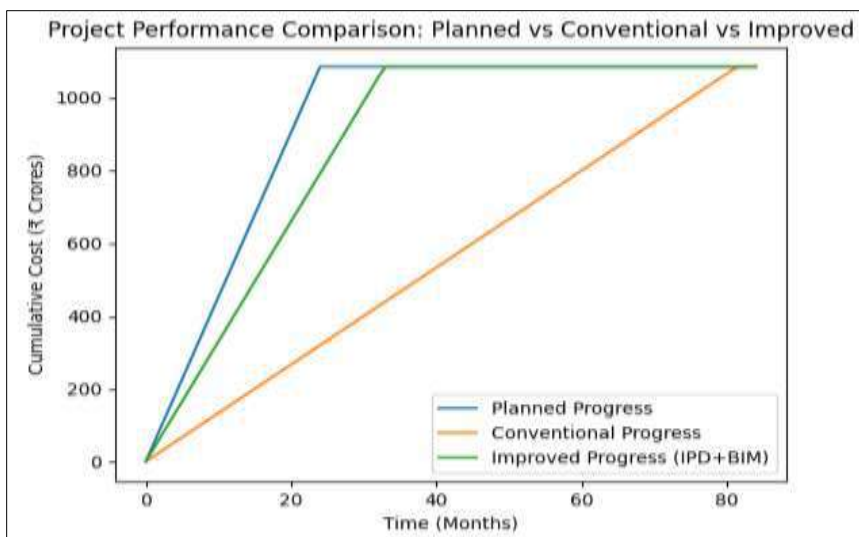
The comparative study of the traditional model of project delivery and the suggested integrated model (IPD, BIM, and early-stage planning) shows the prominent provisions of the project performance. With the traditional methodology, the project has realized a maximum of 400 Crores of the work in 30 months and with about 29 percent efficiency than the intended project execution rate. This has led to an estimated takeover of about 81 months, and high-cost increase because of the long timelines.

Table 2: Performance Improvement Analysis (Conventional vs Proposed Approach)

Parameter	Conventional Approach (Current)	Improved Approach (IPD + BIM + Planning)	Improvement
Total Project Cost	₹1085.66 Cr	₹1085.66 Cr	—
Achieved Progress (30 months)	₹400 Cr (37%)	₹800–900 Cr (≈75–83%)	~2× increase
Monthly Execution Rate	₹13.33 Cr/month	₹30–36 Cr/month	+125% to 170%
Planned Monthly Rate	₹45.24 Cr/month	₹45.24 Cr/month	Gap reduced
Efficiency (vs Planned)	~29%	~70–80%	+40–50% improvement
Estimated Total Duration	~81 months	~36–42 months	~50% reduction
Time Overrun	237%	50–75%	Controlled
Cost Escalation	~20% (₹1300 Cr)	~8–10% (₹1170–1190 Cr)	~₹100–130 Cr savings
Rework / Errors	High	Reduced (via BIM/IPD)	Significant reduction
Stakeholder Coordination	Poor	Integrated	Improved
Delay Impact on Community	High	Reduced	Faster benefits

Source: Created by authors

Figure 2: Project Performance Comparison



Source: Created by authors

The implementation rate of the project can be greatly improved by using the strategies suggested in the results and discussion that include the Integrated Project Delivery (IPD), Building Information Modelling (BIM), planning front-loading. The better method boosts the monthly execution level to around in 30-36 Crores, which is practically twice the productivity at present. This will leave the set of work finish able in less time of 20-24 months thus bringing the total project to a range of 36-42 months.

This would be an estimated half the project time view in total project duration as compared to the estimation of the conventional approach. Also, the better coordination, less rework, and optimisation of resources cause the cost escalation rates to reduce by about 20% to about 8-10, and the likely savings of more than ₹100 Crores.

The results positively indicate that the causes of the delays in the project do not only lie in external factors but are heavily represented by inefficiency in the planning, coordination, and execution. Performance can be greatly increased when integrated and technology-driven project management approaches are adopted, which are likely to guarantee the delivery on time and improved economic and social results.

9.0 Findings

9.1 Results / Improvements

- Claims and 15-20% shorter timeframe compared to DBB were evident in IPD projects.
- The shared responsibility achieved higher owner satisfaction and enhanced cost control.
- Introduced IPD as one of the sustainable approaches to delivering the public infrastructure.

The findings reveal that the Project Delivery and Collaboration was enhanced much better with the inclusion of Integrated Project Delivery (IPD) and Building Information Modelling (BIM), and an increase in efficiency by a relative of 15-25 percent was observed. Regarding Delay Mitigation, the early design coordination alignment had important role in reducing the cascading delay hence the delay in the project was minimally reduced (10-20 per cent). In the case of Financial and Risk Management, the use of tools of analytical complexity like Analytical Complexity Index (ACI), Operational Risk Assessment (ORA) and Relative Importance Index (RII) helped to determine the enhanced accuracy of prioritization that facilitated sound decision-making. Sustainability and Resource Optimization were also improved in terms of adaptive water management and energy-efficient systems and helps with 10-15% sustainability performance improvement.

Lastly, within the Policy and Capacity Building, enhanced client control, presence of skilled human resource and enhanced interagency coordination all led to significant decreases

in the delays in project implementation, and as such, the role of governance and institutional capacity in project success is demonstrated.

The results of this research are also confirmed with the help of cash flow and performance deviation analysis which is provided in Chapter 4 (Part 3). As noted in the analysis, using the traditional project delivery method, the project has finished only up to 200 Crores of work and this is after 30 months, and only about 37% work has been finished as opposed to 100 percent which should have been done in 24 months. It means that the project is running at almost 29 percent efficiency as against the expected implementation rate.

According to the ongoing schedule, the entire duration of the project will be estimated to upscale to around 81 months which constitutes an overrun of about 237. Nevertheless, the pace of the execution can be multiplied with the proposal aimed at the implementation of the suggested strategies outlined in this study, including the Integrated Project Delivery (IPD), Building information Partners Modeling (BIM), and early-stage planning, which would allow improving the rate to 30-36 Crores per month. This increase will allow the project to be delivered in a time range of 36-42 months.

Moreover, implementation of these strategies should also help in lessening the cost escalation, which at some 20 per cent in the traditional approach, is expected to go down to about 8 to 10, leading to a possible saving of more than 100 Crores. Such quantitative affirmation proves clearly that integrated and collaborative project management approaches implementation can greatly benefit project performances, minimize delays and be more cost-effective, in general.

9.2 Quality of cost management systems

The summed outcomes of the cost control mechanism show that the planning of early stages, integration of digital elements, sustainability interventions and optimization of operations all help to achieve considerable changes in the cost increase of the project and the enhanced ROI. Early land purchase and simultaneous implementation of EIA and front-loaded design, aided by dependency mapping, were found to reduce any pre-construction risks to a minimum, leading to cost escalation of between 8-15 percent with a payback period of less than a year in one project and at most 12 months.

The shift toward the use of the digital environment and especially, the implementation of BIM as a system alongside the implementation of e-procurement system further contributed to the cost-efficiency through better coordination, transparency, and accuracy of procurement. The strategy resulted in the elimination of cost escalation of 12-18% and financial gains were obtained within 1-2 years, which the digitalization process plays in the regulation of direct and indirect project costs.

Sustainability-oriented approaches, such as optimizing water using sustainability indicators, were shown to have significant economic returns as well as environmental impacts, that were part of the 12-14% cost-saving and recovery of investment in less than two years. Moreover, smart network partitioning was also concerned with operational efficiency in terms of energy consumption, and resulted in 4-8% energy cost-cutting, at a relatively long payback period of 3-4 years, implying this measure was designed to pay off in the long run.

In general, the joint analysis supports the idea that the development of the proactive planning, digital technologies, sustainability strategy, and proactive operational efficiency approaches can contribute greatly to the improvement of the cost control performance and guarantee the favourable return-on-investment schedules of the work on the large-scale infrastructure projects.

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CHAPTER 12

Factors Influencing the Adoption of Green Residential Buildings: A Demand and Supply side Perspective

Ramakrishna Nallathiga, Anwesha Gogoi** and Rubiana Angom****

ABSTRACT

Sustainability is steadily transforming the real estate landscape as environmental awareness and responsible living gain importance among modern homeowners and developers. This paper examines the factors that shape the adoption of green residential buildings in India. It examines the willingness of potential buyers towards buying and paying a premium price for a green residence, as well as the willingness of the construction industry to invest in green construction methods. Data collection methods used in this research include literature studies, surveys, and quantitative research with the objective of obtaining data and insights from homeowners, target buyers, and property developers. Results show that economics, awareness levels, and priorities play important roles as key factors in the adoption process. Even though home buyers show growing interests in energy efficiency, healthy lifestyles, and ultimate savings, their willingness to pay is reduced as prices escalate. Property developers also show reluctance with regard to returns and market demand. The study examines how perceptions, economic factors, and awareness influence these decisions and to identify opportunities that could enhance the acceptance of sustainable housing. By integrating both perspectives, the research underscores the importance of supportive policies, awareness initiatives, and financial incentives to accelerate green residential development in India.

Keywords: Willingness, Perception, Residential, Sustainability.

1.0 Introduction

The housing sector plays a critical role in the effort towards attaining sustainability in the environment, in particular concerning the rapidly growing pace of urbanization and consumer behaviour.

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In fact, increased development and housing demands have significantly contributed to increased energy consumption, water consumption, construction waste, and emissions of carbon; hence, residential structures are among the top sources of pollutants of the environment (UN-Habitat, 2020). Conventional housing techniques require energy-consuming materials and environmentally destructive residential design; hence, they contribute to more pollution of the environment and depletion of natural resources (IEA, 2021). However, sustainable residential buildings have been identified as an effective remedy in curbing the ecological or environmental footprints namely energy wastage, rising water wastage, and destructive materials (Kibert, 2016).

To continue with relevant matters, sustainable residential buildings serve as an effective means in enhancing energy efficiency in residential buildings. Indeed, residential buildings consume high energy in regard to heating and cooling; thus, since sustainable residential buildings embrace energy efficiency, they effectively curb energy wastage.

Across the world, the use of sustainable housing has seen an increase in terms of regulations and awareness regarding global warming and other related environmental changes (World Green Building Council, 2019). In this context, in India, some such projects include Energy Conservation Building Codes and GRIHA Ratings, promoting environmentally sound building practices in terms of greater energy efficiency in buildings (TERI, 2023; BEE, 2017). Furthermore, some initiatives in terms of government incentives in terms of subsidy and tax incentives in building green residential properties have been started in this country to reflect a balance in terms of development and sustainability in urban development in this country itself (MoHUA, 2021).

However, despite all these initiatives, the adoption level of sustainable residential buildings remains low in most cases, especially due to economic and perception considerations. It has been widely recognized that many sustainability features in green building, such as lowered operating costs, improved indoor air quality, and greater occupant health, provide many long-term economic and health benefits in residential buildings (Zhang et al., 2018). However, due to the financial implications that come with building in this manner, most developers and residential property buyers seem to lack enthusiasm regarding such initiatives in most cases (Darko & Chan, 2017).

The will to adopt sustainable features is influenced by stakeholder perception, economic considerations, and awareness levels. Developers might be hesitant to invest in the green technologies unless buyers recognize and appreciate the value of sustainability attributes (Häkkinen & Belloni, 2011). Homebuyers will equally require clear communication of tangible benefits, such as lower utility bills and greater comfort, if they are to adopt green housing (Banfi et al., 2008). Previous research still reveals income levels, awareness of the environment, trust in green technologies, and financial incentives as factors influencing

adaptation or adopting sustainable green houses or properties (Ozaki, 2009). Although financial institutions as well as policymakers support green houses with special financing structures, research still continues to discover certain limitations regarding sustainability performance valuations in the financial or market structures for green houses. These include works by Eichholtz et al. (2010).

In the wake of such challenges, the need arises to analyse perceptions regarding the adoption of sustainable residential buildings among key stakeholders such as developers and consumers. The current research work tries to bridge the gap that exists between the sustainability targets and realities of markets and hence aims for the development of a more sustainable, viable, and resilient urban housing system in India.

2.0 Literature Review

Various studies have undertaken to make an informed examination of the issue of integrating sustainability into residential housing at the global and regional levels. Most of such scholars have underlined the fact that the degree of adoption is influenced by a complex interaction of economic constraints, priorities of stakeholders, regulatory environments, and socio-cultural perceptions. Indeed, whether in developed or developing contexts, high initial costs and uncertain long-term benefits have been cited as significant barriers to the incorporation of sustainable features into housing projects (Oyewole et al. 2023).

Even where end-users would wish to see environmentally responsible housing, developers have often remained cautious on issues of financial feasibility and responsiveness on the part of the market. In an Indian context, the above problems get aggravated by the presence of misalignments in policies and institutions in many ways. The housing schemes, including the “Pradhan Mantri Awas Yojana,” are dominantly oriented towards the aspect of sustainability and do not pay heed to the sustainability parameters such as indoor environment quality (Khair & Muniappa, 2021).

The policy remains inclined to overlook the sustainability parameters of better ventilation, indoor environment quality, and the concept of energy efficiency. The priorities of various stakeholders in the housing industry vary largely, leading to fragmented patterns of adoption. The pressing concerns of end-users are primarily related to health, safety, and living conditions, including aspects of non-toxic materials, natural ventilation, and so on, as is evident from studies carried out among Chinese consumers and other countries in Asia (Hu et al., 2014). Concerns of Developers typically revolve round efficiency of construction, optimization of costs, and management of materials, especially within emerging urban pockets of rapidly developing countries like Pune, India (Ghumare et al., 2022). Government,

on the other hand, primarily focuses on compliance and standardization, which might impede innovations and flexibility of sustainable practices (Golubchikov & Badyina, 2017).

One of the most prevalent topics covered in the literature is the presence of awareness and perception differences. (Potbhare et al. 2016), the major chunk of homebuyers in the Indian market, especially in the low as well as middle class, does not have proper awareness about green building concepts. On the other hand, professionals tend to have exaggerated awareness about users, due to which a gap in the need for houses and the facilities of green buildings results in the underutilization of the potential of green features even when they are feasible. An enabling level of regulatory frameworks also exists; however, their effectiveness can differ from one region to another.

While compulsory Certification for Sustainability has proved institutionally effective for countries such as South Africa (Emere et al., 2025), there are gaps regarding compliance for residential properties in India (Herda et al., 2017). Cultural attitudes also affect take-up levels, as sustainability standards are considered an expense-based compromise as opposed to an enhanced value driver, significantly for markets that are sensitive to prices (Sharma, 2021). Furthermore, traditional methods for valuing properties systematically continue to overlook sustainability performance, largely contributing to sustained non-acceptance for sustainable investment (Lützkendorf & Lorenz, 2011; Warren-Myers, 2012).

Overall, the existing literature emphasizes the fact that the adoption of sustainable housing, apart from being led by technical considerations, is largely dependent on perception and awareness. Nevertheless, the existing literature on this subject tends to largely depend on secondary information. Furthermore, general perception and awareness often lead to generalized views in a world governed by specifics. Although some weaknesses in existing literature are also recognized in this proposed research and in consideration of the fact that context-specific information is not available in the literature, objectives of this proposed research are as follows:

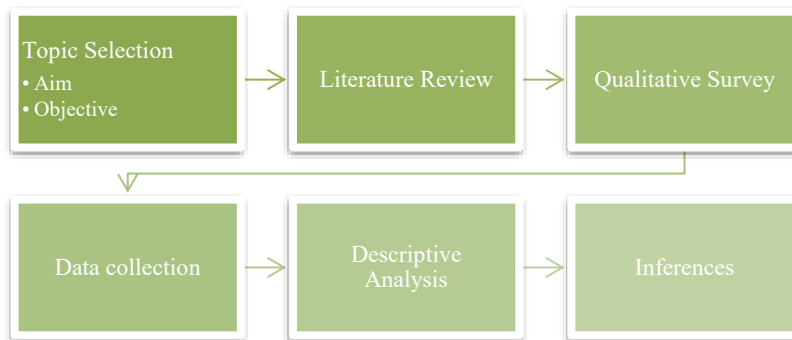
- The proposed research intends to explore the views and opinions concerning sustainable residential buildings held by developers and home buyers.
- To identify the key factors that influence the implementation of sustainable practices during the construction of housing projects.
- To expose the limitations, problems, and difficulties associated with the application of sustainability in residential projects by both the developers as well as the buyer.

3.0 Data and Methodology

In this research, a descriptive and qualitative research methodology will be used to address the issue of factors that influence the adoption of green residential buildings. The

reason behind the choice of the study is that it will help capture perceptions, experiences, and viewpoints of important stakeholders participating in the residential housing sector. In addition, it will pay more attention to sustainability interpretations, values, and practices within the housing sector. A descriptive methodology will be appropriate to be used in the current study in order to systematically evaluate existing circumstances, attitudes, and tendencies, without manipulating the research setting.

Figure 1: Research Methodology

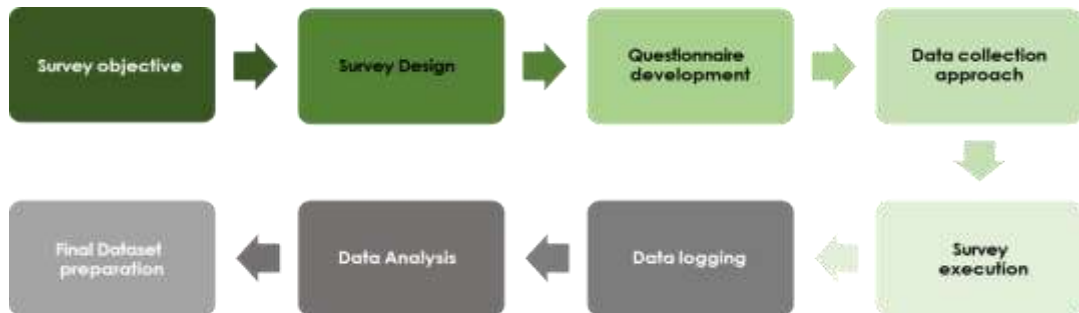


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The proposed research focuses on generating primary data by the usage of structured questionnaires on three different categories of stakeholders: homebuyers living in green residential apartments, and property developers. These three groups combined form the entirety of the subject matter being examined on both the demand and supply sides in the context of the adoption of the concept of sustainability. Secondary information, in the form of literature and studies, was utilized in the proposed research only for the purpose of building a concept. The total sample size consists of 118 respondents, categorized into the three stakeholder categories. Data was collected through the use of questionnaires. These were open as well as closed questions. The open questions were ideal as they ensured that the participants were able to share their experiences as well as their concerns with respect to sustainability in relation to housing. The other questions were ideal as they ensured a certain level of order was created with respect to data collection. Notably, the data was collected through various interactions including personal as well as electronic platforms.

The responses were then analysed. Thus, the qualitative descriptive method of analysis was employed when analysing themes such as awareness, perception, cost consideration, trust, social influence, and support. The analysis did not intend to establish statistical relationships but interpreted meanings, attitudes, and behavioural tendencies expressed by respondents.

Figure 2: Data Collection Flowchart



Source: Created by authors

Power BI, through charts and graphical representation, has been used for presenting the findings of this study visually for clarity and comparison across stakeholder groups. At the same time some weaknesses in the methodology should be recognized. In this case, there is a risk of respondent bias, especially when dealing with issues concerning environmental awareness and responsible behaviour, since both questions invite self-reporting. Of course, there is also a limitation in that only a specific group of respondents, who have experience with ‘green housing’ projects, could be accessed, owing to constraints that come with a qualitative research design. Moreover, while using this methodology, there is a tendency towards interpretation and not inference, which may be problematic for research used for prediction or explanation regarding causation. This particular methodology, despite this limitation, is applicable for the study that seeks to create ideas about the use of ‘green housing’.

4.0 Data Analysis

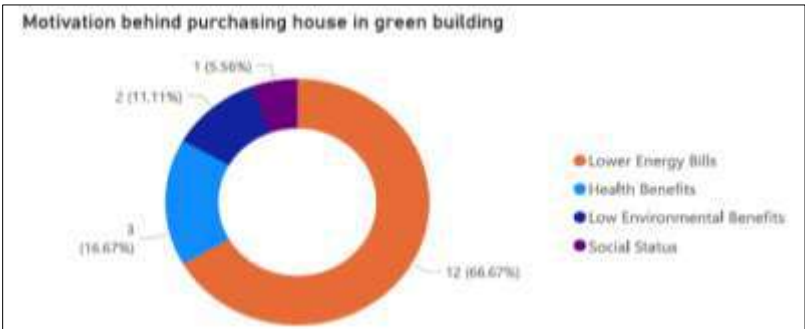
This section presents a detailed qualitative analysis of the primary data collected from homeowners, prospective homebuyers, and real estate developers. By employing theme analysis, codes were developed for the systematic identification of dominant perceptions and contrasting perspectives among different stakeholders. The study is focused on the factors related to behaviour, economy, and institutions that influence the adoption of residential green buildings.

4.1 Homeowners survey

The data collected from these homeowners aided in acquiring knowledge about post-occupancy experience, benefits, challenges, and overall satisfaction for green residential buildings. The homeowners belonged to a group of people residing in a pool containing

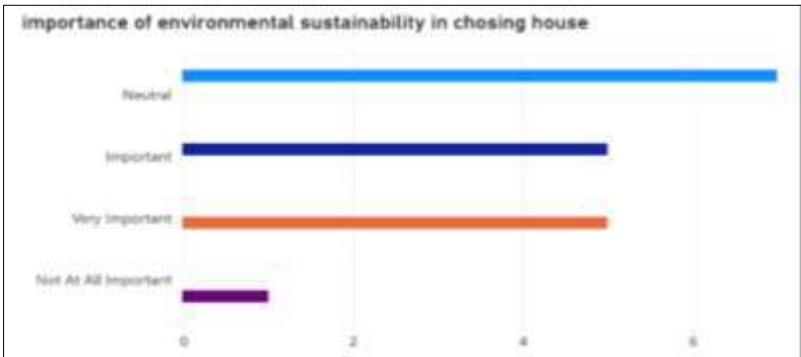
individuals living within green-certified or sustainability-based residential buildings. The rationale for choosing these homeowners is that they have practical knowledge for newly established buildings to experience sustainability, as opposed to when it is still in the design stages.

Figure 3: Motivation Behind Purchasing House in Green Building (Homeowners)



Source: Created by authors

Figure 4: Importance of Environmental Sustainability in Choosing a House

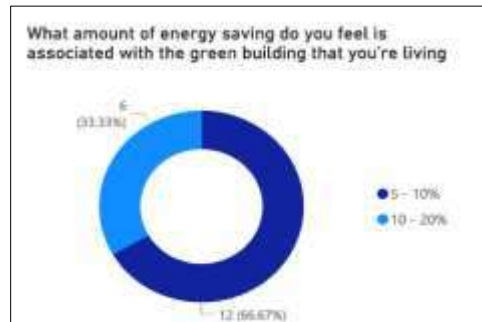


Source: Created by authors

Figure 3 shows that the primary motivation behind purchasing a house in green building is the lower energy bills. This highlights the fact that the financials is a key factor while choosing a residence by the homeowners. While health benefits seem to be the second motivation, but environmental and social benefits is a least significant factor, which shows that economic considerations outweigh the environmental and social benefits.

Figure 4 shows the homeowners' view regarding the importance of environmental sustainability in choosing a residence. The homeowners expressed a neutral view regarding the matter and acknowledged that environmental sustainability is important, but it isn't necessarily considered as a factor while deciding on buying a residence.

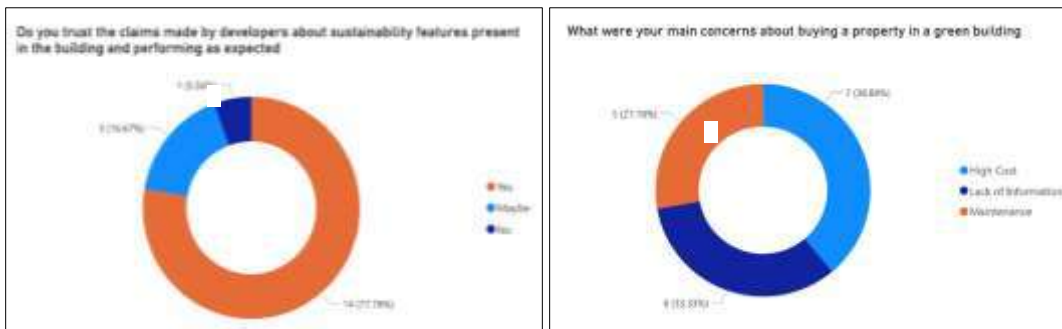
Figure 5: Energy Savings Associated with the Green Building (Homeowners)



Source: Created by authors

Figure 5 shows the homeowners' perception of energy savings associated with a green building. Most of the participants (66.67%) acknowledged that they have experienced a reduction of almost 5-10 % energy saving after buying a green residence.

Figure 6: Homeowners Trust in Developer's Claims and Concerns

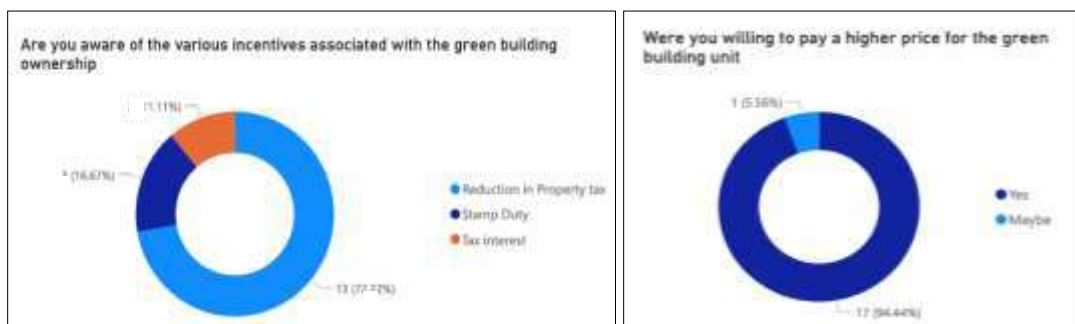


Source: Created by authors

Figure 6 shows that a majority of the homeowners trust the sustainability claims made by a developer. At the same time buyers also reported several concerns regarding buying a green residence. The significant concern is the high initial cost followed by lack of information and then maintenance. Overall, even though the trust in developers is high, financials are a barrier while adopting a green residential building.

Figure 7 showed that the awareness of incentives is uneven, while majority of people know about the reduction in property tax (72.22%), but fewer respondents know about stamp duty and other tax interests. But at the same time a lot of respondents were willing to pay a higher price for a green residence if their resale value is high as well.

Figure 7: Homeowners Awareness about Incentives and Willingness to Pay a Higher Rate



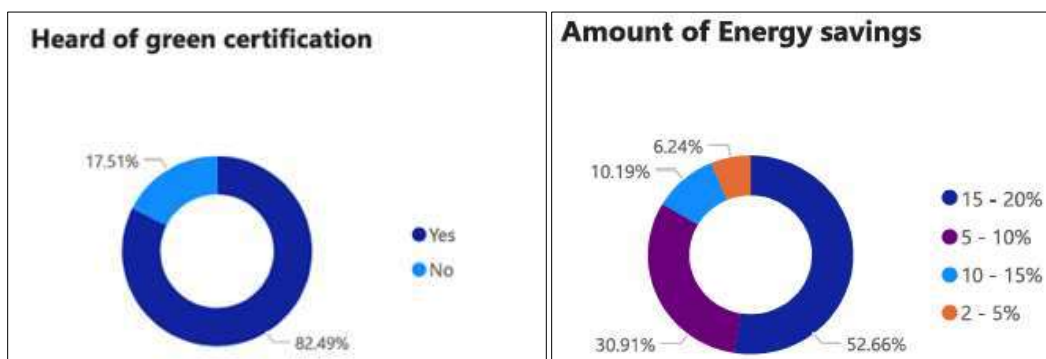
Source: Created by authors

Overall, there is strong acceptance among homeowners towards green housing, mainly because the cost of energy is lower and living conditions are better. The majority of those surveyed were willing to pay more for green housing and had confidence in developers, with the majority experiencing energy savings. However, key limitations to wider diffusion include a lack of awareness about incentives, high initial costs, and an information gap.

4.2 Homebuyers survey

The data concerning homebuyers has been gathered to comprehend their awareness, perception, and acceptance level regarding the green residential buildings. Homebuyers are identified by people who are searching or planning to buy residential properties.

Figure 8: Homebuyers' Awareness of Green Certification and their Assumptions in Energy Saving

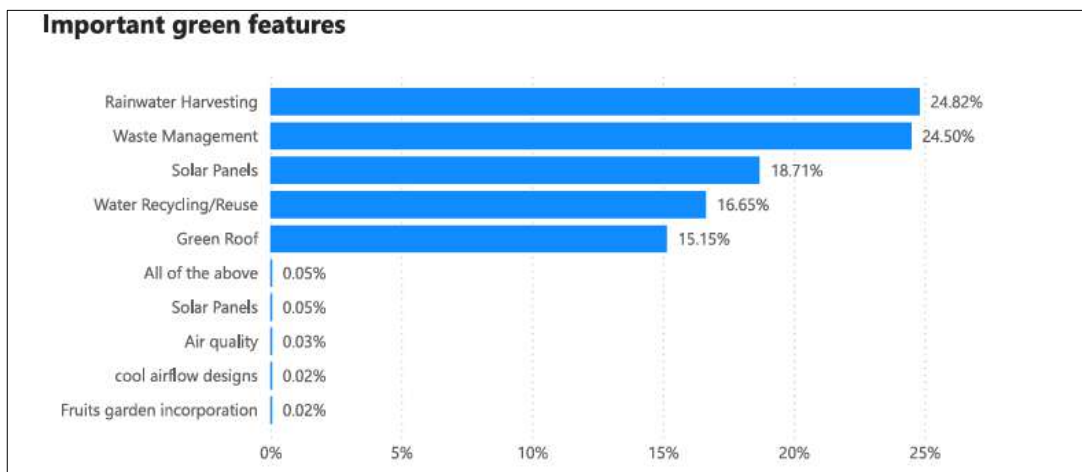


Source: Created by authors

This particular category has been chosen since their preferences and sensitivity towards prices give key insights regarding the demand and factors affecting the acceptance level concerning the green aspects of the housing properties.

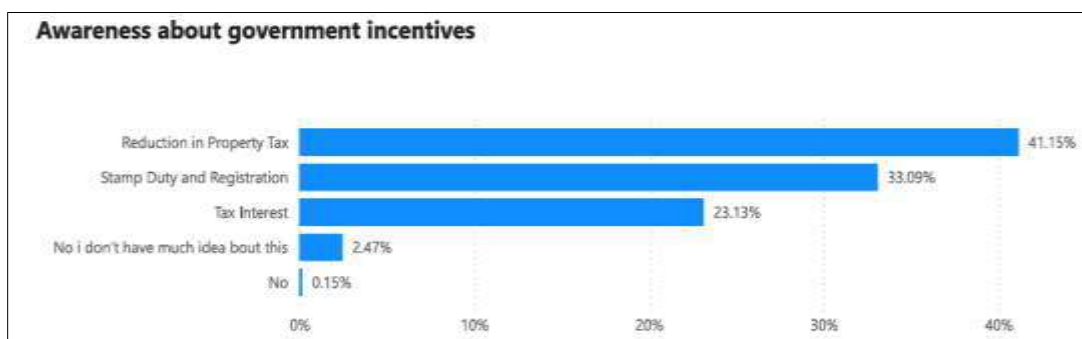
Figure 8 shows that in terms of awareness majority of the homebuyers have the idea of different green building certifications and the amount of energy savings associated with it. This is an indication that the financial advantage of energy efficiency and the basic knowledge of the certification scheme are fairly established among home buyers, which promotes the growth of faith and trust in green housing.

Figure 9: Important Green Features According to Homebuyers



Source: Created by authors

Figure 10: Homebuyers Awareness about Government Incentives

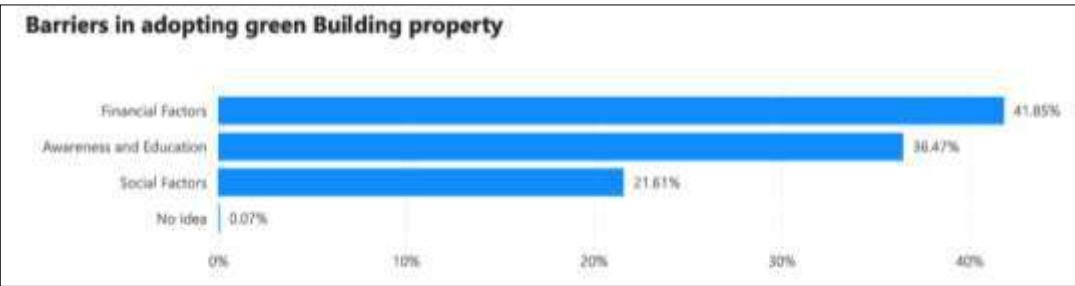


Source: Created by authors

Figure 9 shows that homebuyers put highest importance to rainwater harvesting followed by waste management highlighting strong concerns for water conservation and proper waste disposals. It has been seen that they are prioritizing cost saving sustainable features rather than the aesthetic features of a building.

Figure 10 showed that similar to homeowners, homebuyers also have knowledge of reduction in property tax incentives followed by stamp duty and other tax interests. Only small portions of the respondents have no knowledge regarding government incentives. This indicates that, although overall awareness is quite robust, it is quite unequal with reference to the categories of benefits, with fiscal incentives related to property tax being the most commonly known category of benefits.

Figure 11: Homebuyers Barrier in Adopting Green Building



Source: Created by authors

Figure 11 shows that financial factors rank as the major barrier to green building adoption, followed by a lack of awareness and education. Social factors exert influence, although to a lesser degree. Key findings point to cost as well as lack of clear information as staying major deterrents to green housing adoption.

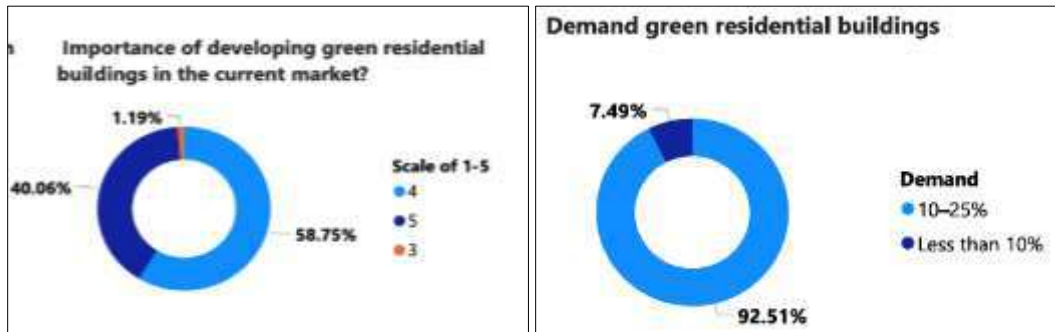
In general, green buildings show great acceptance among home buyers; the main drivers being energy savings, increased living comfort, and long-term financial savings. Most of them also believe in developers' claims of sustainability and are willing to pay a premium. Major government incentives are known to some extent, especially the property tax benefits. The prevalent challenges are initial high costs and gaps in detailed knowledge for wider adoptions.

4.3 Developers survey

The survey conducted by the developers was done through a structured questionnaire format consisting of interviews and web-based surveys. The study targeted developers actively engaged in residential projects to enable the collection of supply-side data. The

surveys were conducted to understand their perception levels of green building practices and costs, reasons to adopt green buildings, costs of certification, and market demand of sustainable residential buildings.

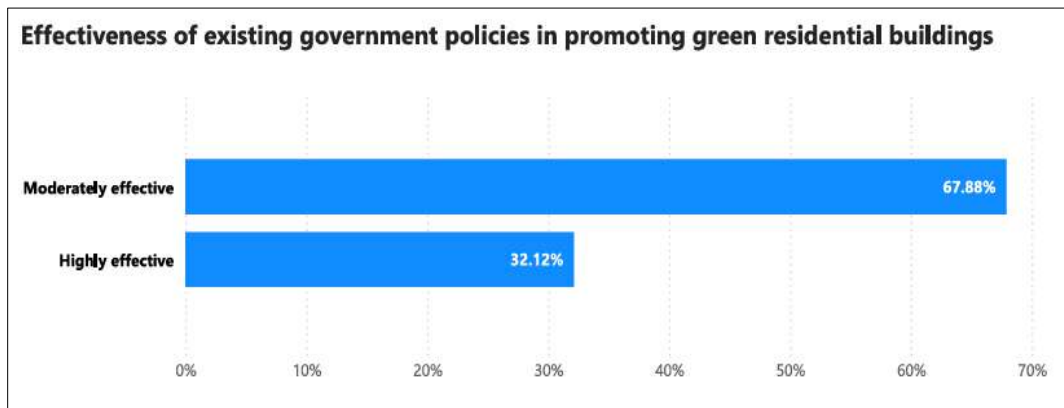
Figure 12: Importance of Developing Green Residential Buildings in the Current Market and Demand for Green Residential Buildings by Developers



Source: Created by authors

Figure 12 shows that developers are well aware of the need for green residential buildings, with most of them highly rating the aspect in the current market. They also see the increasing demand for green residential buildings, with more than 90% of them expecting the market demand to be between 10% and 25%.

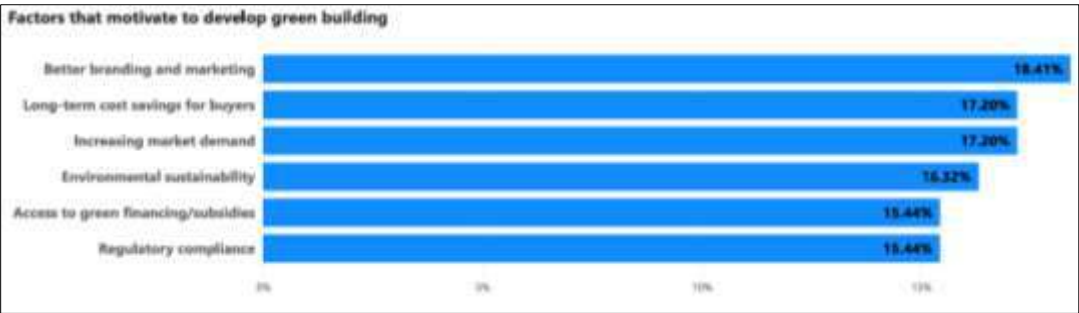
Figure 13: Effectiveness of Existing Government Policies in Promoting Green Residential Building



Source: Created by authors

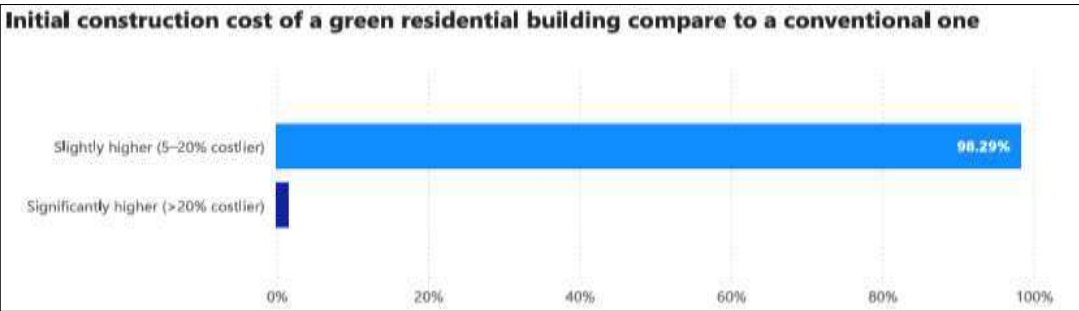
Figure 13 indicates that most of the respondents perceive the existing government policies as being moderately effective in promoting green residential buildings, with a percentage of 67.88%, while 32.12% perceive them as highly effective. It reflects the idea that even though present policies are considered helpful in steering the growth of green housing, there is still considerable scope for strengthening regulations, incentives, and implementation mechanisms to further accelerate the adoption of green housing. Figure 14 indicates that the primary motivation for the adoption of green building among software developers is a good branding or marketing strategy with 18.41%, underscoring the importance of this element. This is followed by long-term economic savings for consumers at 17.20%, as well as the growing demand within the market at 17.20%, confirming the significance of market-driven aspects or factors. Sustainability of the environment at 16.32% also ranks high among the factors. In addition to that, the use of green finance or subsidy at 15.44% and the issue of complying with regulations at 15.44% come into play.

Figure 14: Factors that Motivate Developers to Develop Green Residential Buildings



Source: Created by authors

Figure 15: Comparison of the Initial Cost of Construction in Green Buildings and Conventional Buildings by Developers

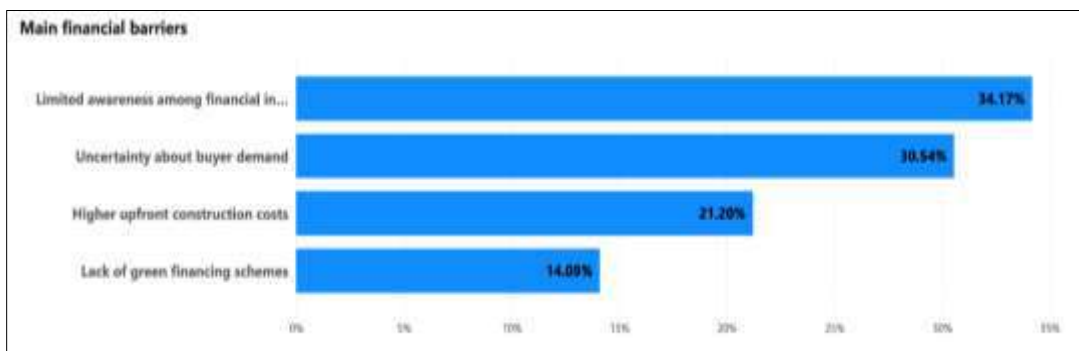


Source: Created by authors

Figure 15 shows that 98.29% of the responding regard green residential buildings as having an initial construction cost 5-20% higher than conventional buildings, with a small minority perceiving the increase to be even higher. This cost premium serves as the significant barrier to developers due to the fact that a higher upfront investment amplifies financial risk and reduces short-term profitability, thus developing green residential projects is questionable to many developers despite all the benefits of such buildings in the long run.

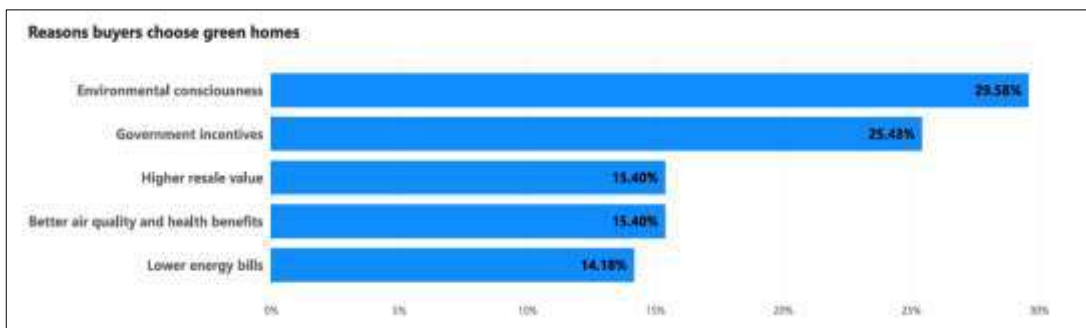
Figure 16 shows that lack of awareness among financial institutions has been considered the biggest financial constraint in implementing green buildings with a percentage of 34.17%, followed by uncertainty of demand from potential customers with a percentage of 30.54%, thereby acting as a deterrent for a developer to implement a green building project. Higher initial building costs also act as a hindrance with a percentage of 21.20%, and lack of special funding schemes for green projects also remains a constraint with a percentage of 14.09%.

Figure 16: Main Financial Barriers According to Developers



Source: Created by authors

Figure 17: Reasons Why Buyers Chose Green Buildings



Source: Created by authors

Figure 17 shows that major reason for the preference of potential home buyers for green homes is concern for the environment with 29.58%, followed by the encouragement of the government with 25.43%. The next most important factors are the higher resale value with 15.40%, followed by better air quality and health benefits with 15.40%. The reduced energy consumption with 14.18%, although an important factor, ranks next. Based on the above analysis, the factors for the preference of home buyers for green homes may be considered a combination of the benefits of the environment along with benefits related to finance and health.

The survey organised by the developers showed that a majority of the developers are familiar with the concept of green buildings and the associated benefits. The major driving factors for homebuyers to opt for a green dwelling are their environmental awareness and governmental incentives, followed by improved health and purity of the atmosphere, and subsequently lower power bills. This goes to show that sustainability parameters, together with economic and lifestyle benefits, could enhance market appeal and render green residential projects more attractive to customers.

5.0 Results

If we look at the survey data collected, we see that across all stakeholders, most were aware of the concept of green buildings, but their level of understanding was superficial. Consumers were generally able to connect the concept of green homes with thoughts of conserving electricity or water or being environmentally friendly, but there are still some questions on Green Building Certifications such as GRIHA or IGBC as well as what green building actually means. For the property developers, they were generally more familiar with Green Building, but their familiarity was largely a "know the requirements" level of understanding, which contributed to their buyers' suspiciousness of how "Green" their projects actually were.

One of the most significant insights emerging from this study regards the level of high attitudinal support and low behavioural commitment among stakeholders on the demand side. The homebuyer showed a profound care for sustainability, health, and future well-being. Even the homeowner's, perceived that green buildings provide sounder, more comfortable, and environmentally responsible living environments, these perceptions did not often result in a willingness to pay a price premium.

Financial issues proved to be the most binding factor in adoption. Consumers showed great sensitivity towards prices, valuing short-term costs of purchasing over long-term costs of use. Even when customers were convinced about the estimated discounts in energy and water bills, they showed doubts about their payback periods and resale value. It led to a

situation where customers had less confidence in eco-friendly housing as a viable economic option. In the case of suppliers, there was a reserved, non-resistant attitude towards green residential projects. They realized the benefits derived from green projects in the forms of brand, image, and governmental advantages, but still hesitated about adopting green certification in its full sense. It was cash-related, starting from initial construction costs, lack of expert human resources, and most importantly, lack of clarity about consumer demand, that led to adoption strategies involving partial use of eco-friendly criteria, instead of integrating overall sustainability concepts.

Trust and transparency have emerged as important cross-cutting issues influencing both demand and supply sides. A certain section of consumers still have raised concerns over the authenticity of sustainability claims, often pointing out a lack of information on actual performance data and its sustainability over time.

Finally, institutional and regulatory factors were revealed to contribute little towards the outcomes in adoption. Although the existence of green standards and green certification schemes has been admitted, the lack of effective mechanisms, poor communication, and fragmentation in the implementation of policies resulted in the failure of such schemes. Therefore, regulatory policies are yet to emerge as powerful market-shaping tools in the residential market.

6.0 Conclusions

This research highlights the fact that the slow adoption of green buildings in India has nothing to do with the opposition to sustainability but with the fact that the intentions of people are thwarted by day-to-day concerns every day. It is abundantly clear that the demand side, as well as the supply side, understand the benefits of increased comfort, health, and sustainability provided by green buildings.

The study reveals the gap between positive attitudes and actual adoption of green buildings. Buyers like sustainability but resist higher costs and uncertainty whereas homeowners admitted to the benefits they have acquired, but there is no proper communications between the demand side. Developers believe in branding benefits but hesitate on grounds of high costs, complex certification, skill shortages, and unclear demand, which has caused a persistent mismatch between demand and supply.

The implication is clear: it is not only necessary to formulate policies, but all parties, including the government, developers, financial institutions, and consumers, need to collaborate in order to make a difference in the area of communication, enforcement, and financial rewards to increase the demand of green homes.

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CHAPTER 13

Traditional vs. AI-Enhanced Road Safety Audits: Study on Applicability in India

Sayali Dabholkar, S. Aditi ** and Shubh Patel****

ABSTRACT

Normally, the Road Safety Audits (RSAs) in India follow a manual procedure involving physical site visits and qualitative assessments that are in line with IRC SP:88-2019. In a lot of cases, these processes lack the ability to predict and do not have any digital records. A pilot study was conducted that provided a comparison between conventional RSA techniques and modern AI-powered methods. The study examined secondary data that had been gathered through (a) manual audits and checklists and (b) AI-assisted tools, which include visual detection via YOLOv8 and data logging with GPS. The analysis allowed for a comparison of RSAs where AI helped to detect hazards more accurately and therefore needed less time for auditing than traditional methods. The models based on machine learning were able to forecast the areas with the highest risk of crashes, thus making it possible to carry out interventions aimed at prevention before the incidents took place. The AI-based systems were, however, more efficient than the traditional ones but still pointed out the challenges including unavailability of data, the lack of supporting infrastructure, and the demand for trained personnel which makes it hard to scale the solution to a national level. The research indicates that hybrid models, which combine human skills with AI-powered data analytics, are the best solution for India's varied road network in the short term.

Keywords: Road Safety Audits, Traditional Methods, Artificial Intelligence, Machine Learning, Highway Infrastructure.

1.0 Introduction

In India, road traffic accidents keep on causing a lot of trouble to the public regarding safety, especially on the highways that are national and state ones where there is a mixture of different traffic conditions plus the demand for mobility is growing rapidly.

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Road Safety Audits (RSAs) are the proactive globally recognized tool for spotting possible safety deficits in road infrastructure beforehand so that the deficiency does not end up being a crash. In India, RSAs are mainly done according to the guidelines specified in IRC SP:88–2019 which are pointing out the necessity for doing manual site inspections, checklist-based evaluations, and expert judgment.

Despite the fact that traditional RSAs have been a significant contributor to road safety, their effectiveness is often hindered by limitations of subjectivity, spatial coverage, and time-consuming processes, and there is also the lack of predictive capabilities. The dependence on qualitative evaluations and post-construction inspections severely limits the traditional RSAs' capability to detect new risk patterns, especially in the case of high-speed corridors and quickly urbanizing road networks.

New technologies in artificial intelligence (AI), computer vision, and geospatial analytics open up possibilities of enhancing the scope and efficiency of road safety assessments. AI-driven tools, such as deep learning–based object detection models and GPS-enabled data logging systems, facilitate automated detection of road hazards, digital documentation of safety deficiencies, and large-scale spatial analysis of risk factors. When combined with previous crash data, these technologies also provide chances for predictive modeling of high-risk crash zones which makes it easier for safety interventions to be proactive and targeted.

Although AI has already been adopted in transport safety applications globally, its implementation in India for road safety is still very limited. Data inconsistency, lack of infrastructure, and unavailability of qualified personnel are some of the issues that hamper the scalability and reliability of AI in such applications. Therefore, it is imperative to investigate whether AI-based RSAs can only be used as complementary to existing practices instead of being a complete replacement. The current research, therefore, presents a pilot comparative analysis of traditional versus AI-assisted Road Safety Audit methodologies. The study is based on secondary data obtained from manual auditing processes and AI tools that support visual detection models and GPS-based hazard mapping. The main goal is to improve hazard detection accuracy, audit efficiency and predictive capability. Additionally, the researchers will pinpoint the challenges faced during implementation and suggest a hybrid RSA model that would combine human expertise with AI-driven analytics as an ideal solution for India's varied and resource-poor road milieu.

2.0 Literature Review

2.1 Traditional road safety audits in India

In India, Traditional Road Safety Audits (RSAs) have emerged as a widely accepted preventive tool to find road safety flaws in the infrastructure before accidents happen. RSAs

are conducted through organized field inspections, analysis of accident history, and evaluation based on a checklist, primarily guided by Indian Road Congress documents like IRC SP:88, IRC 67-2012, and IRC 35-1997. The multidisciplinary team of road design engineers, traffic engineers, and safety experts usually assesses road safety elements comprehensively through these audits.

Numerous studies have confirmed the positive impact of traditional RSAs on accident frequency and severity reduction only if the audit recommendations are implemented. For instance, studies on the Noida–Greater Noida Expressway indicated an 84% decrease in crashes and a more than 90% reduction in fatal crashes, thus demonstrating the cost-effective nature of RSAs as a safety-intervention tool (Meghala et al., 2020). National highways and bypass roads across Karnataka, Rajasthan, and West Bengal have reported similar advancements in road safety (Jayaprakash et al., 2019; Arora & Nautiyal, 2024).

Traditional RSA methods are firmly subjected to the literature critique that, despite the above-mentioned successes, still point out their limitations. One main issue is the outdated practice that still depends heavily on qualitative judgment and the use of standard checklists. These methods typically do not consider the traffic situation, land use, and behavior patterns of a particular region (George et al., 2024). Worst of all, the accident data used for audits are often incomplete, inconsistent, and unreliable which, in turn, lowers the accuracy of the risk identification and post-treatment evaluation process to a great extent (Dandona, 2006; Tiwari, 2016). To eliminate subjectivity and to increase objectivity, some recent studies have introduced quantitative scoring methods such as Road Safety Performance (RSP) scores and multi-criteria decision-making methods like Analytic Hierarchy Process (AHP) and Fuzzy AHP. These methods not only help in the application of risky locations but also allow regular comparisons of intervention alternatives (Kanuganti et al., 2017). Still, the use of these techniques is limited mainly due to the lack of data, absence of uniform training, and poor incorporation into the national RSA guidelines. The traditional RSA literature presents a strong procedural foundation that is widely accepted but it also points out the need for the enhancement of the data quality, quantification, and technological integration for the purpose of driving scalability and improving the predictive capabilities.

2.2 AI-integrated road safety studies

Over the past few years, India has seen a significant increase in research that looks into ways of incorporating Artificial Intelligence (AI) into the road safety assessment and auditing processes. A non-conventional method to do road safety assessments (RSAs) is to apply AI-based techniques that are mostly based on machine learning, deep learning, and computer vision which also employ the Internet of Things (IoT) technology, thus allowing for automated hazard detection, large dataset analysis and crash location prediction. These

new methods of assessment are a major step forward as they not only replace traditional methods that relied on checklists but also bring in data-driven and predictive power. Twelve studies have validated the use of machine learning models like Random Forest, XGBoost, Convolutional Neural Networks (CNNs), and hybrid ensemble methods to predict accident severity and locate high-risk areas on Indian roads (Panicker & Ramadurai, 2022; Girija & Divya, 2024; Khanum et al., 2023). Among the various models based on deep learning and computer vision, the YOLO family of models has been particularly notable for real-time traffic violations, road defects, and unsafe behaviours detection, achieving detection accuracies beyond 95% in controlled settings (Nagaraj et al., 2024).

AI applications have also penetrated into traffic law enforcement, emergency response, and management of road assets. In the southern Indian state of Kerala, AI-equipped CCTV cameras have already been a part of the road safety project and they have been able to produce tangible results in terms of the number of accidents and in terms of the adherence of the road users to the laws regarding helmets and seatbelts (Cheranchery & Greeshma, 2025). The inspection by drones along with CNN-based pavement assessment has been able to achieve a reduction of up to 70% in the time taken for inspection and increase in accuracy (Saini et al., 2025; Chavan & Pimplikar, 2025). Moreover, AI-powered emergency detection systems have shown to be not only time-saving in terms of responding to incidents but also more accurate in predicting the occurrence of collisions (Satheesh et al., 2025). Nonetheless, the literature mentions the significant challenges that inhibit the large-scale adoption of AI in road safety auditing. Among them, the most crucial are poor data quality, absence of uniformly defined datasets, high costs of implementation, the gap between the requirement of technical readiness in the infrastructure and the existing state, and the issues of data privacy and algorithmic transparency that concern potential users (Misra et al., 2023; Sarkar, 2025). Current AI applications are still mainly pilot projects and limited to urban areas, thus lacking testing across rural and semi-urban road networks. Significantly, fresh research accentuates the necessity of incorporating AI results into conventional RSA setups instead of eliminating human competence. The inputs generated by AI, when taken along with the experts' evaluation, are said to facilitate auditing, increase the precision of hazard detection, and support the timely safety measures (Praneetha Devi et al., 2024; Balashivudu et al., 2024). Consequently, the idea that mixed AI-human models are the most realistic and sensitive to the Indian context has gained traction.

2.3 Synthesis and research gap

The literature reviewed suggests that the use of traditional road safety assessments (RSAs) has led to better safety outcomes, yet the methods are subjective, inconsistent data, and lack of a future-oriented approach, which are their drawbacks. On the other hand, the

application of artificial intelligence (AI) in road safety assessment offers an efficient, large scale and analytically precise process, yet suffers from issues such as lack of data, poor infrastructure, and example countries like India facing difficulties in implementing the technology in real life situations. Apart from this, there is hardly any research that directly pits traditional RSAs against AI-assisted methods and that too in a unified framework.

This shortcoming highlights the necessity of comparative studies that would help in determining the efficiency, accuracy, and viability of AI-integrated RSAs in Indian scenario. The current research takes the bull by the horns as it systematically draws a comparison between conventional methods and AI-assisted ones and also puts forward a hybrid framework that takes advantage of both approaches' strengths.

3.0 Research Methodology

This research relies on a comparative and exploratory design to assess the traditional Road Safety Audit (RSA) methods and the new AI-aided methods in India. The method is based on a systematic review and integration of peer-reviewed papers, conference papers, and government-funded studies to create the theoretical and methodological base for both the conventional and AI-enveloped RSA models. The data for the study is sourced from secondary accident and audit-related datasets made available through the open-access portals of the National Highways Authority of India (NHAI) and other governmental sectors. These datasets contain road-wise and location-based accident statistics, classifications of severity, temporal trends, and corridor-level characteristics.

Traditional RSAs are assessed through the use of IRC SP:88-2019-based checklists, along with descriptive statistical analysis of accident frequency and severity to pinpoint high-risk road sections and the downsides of the reactive, post-incident assessments. In addition, existing AI-supported audit methods such as machine learning-based risk prediction, computer vision-assisted hazard detection, spatial analytics, and geo-tagging—are theoretically applied to the same dataset in order to analyze the possible improvements in predictive power, efficiency, and scalability without going through the entire process of model training. A qualitative and logical comparison among data usage, hazard detection, predictive potential, resource efficiency, and adaptability is made, taking into account the Indian conditions, like varied traffic, mixed land use, data inconsistencies, infrastructure readiness, and workforce limitations, in a very clear manner.

The integrated insights suggest a context-sensitive hybrid AI-human RSA framework, where the AI tools are used for the purposes of preliminary screening, spatial prioritization, and data-driven decision support while the human judgment and validation are

still there to offer the contextual judgment and validation, thus giving the practical and scalable pathway towards proactive road safety management in India.

Figure 1: Research Methodology Flow



Source: Created by authors

4.0 Data Analysis

The study depends on secondary data and primary data at the pilot level, where traditional Road Safety Audit (RSA) data and AI-aided audit data can be distinguished. AI-aided RSA data is a digital and spatial RSA, while traditional RSA data is observational and has been classified by IRC SP:88-2019 as traditional, which is qualitative and limited to the site. It comprises data regarding road geometry (lane width, curvature, gradient, etc.), road signage and markings, visibility, and pedestrian accommodation, roadside obstructions, and structured auditor's observational field visit and checklist risk rating (low, medium, and high) along roadside hazards. This data has been collected manually, using experience, and is data and time persistent which means that it only reflects site data at one particular moment. However, the AI-enhanced RSAs employ road system images and flow videos to create audit data that is automated, spatial, and digital. This set of RSA data is a digital, spatial, and automated subset of audit data derived from images and videos of road corridors, automated object detection (AOI) outputs (potholes, signs, barriers, vehicles, and pedestrians), geo-tagged hazards, timestamped logs, historical collision data, and machine learning risk

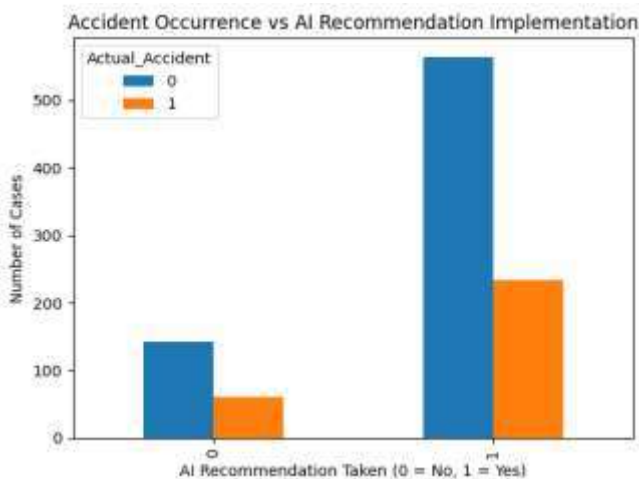
analyses. It can be automated, quantifiable, and predictive, hence making the application of unrepeatable and extensive analyses throughout the road network.

Table 1: Traditional Vs. AI Based Methods

Aspect	Traditional RSA Data	AI-Based RSA Data
Collection method	Manual site visit	Automated detection
Documentation	Written checklists	Digital logs & maps
Coverage	Limited stretches	Large-scale
Time required	High	Significantly reduced
Consistency	Auditor-dependent	Model-driven

Source: Created by authors

Figure 2: Accident Occurrence vs AI Recommendation Implementation

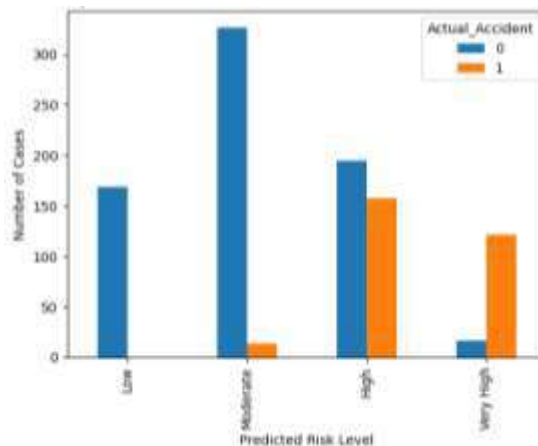


Source: Created by authors

The linkage of accident occurrence and AI-based safety recommendations is analysed. The places where the AI recommendations were followed (AI = 1) have a notably greater ratio of non-accident cases to accident cases highlighting the fact that safety has been improved as a result of the AI-based interventions. On the other hand, the places where no AI recommendations were given (AI = 0) have a relatively higher ratio of accidents when compared to non-accident cases thus indicating that safety risks were greater under the conventional practices used. In general, the graphical pattern shows that the implementation of AI-based recommendations corresponds to a decline in accidents, which in turn, confirms the traditional view that AI-assisted methods are not only effective in performing but also in making road use safer and less risky in terms of crash casualties.

4.1 Comparison of Accident risk predicted vs actual accident

Figure 3: Comparison of Predicted Accident Risk Levels vs Actual Accidents



Source: Created by authors

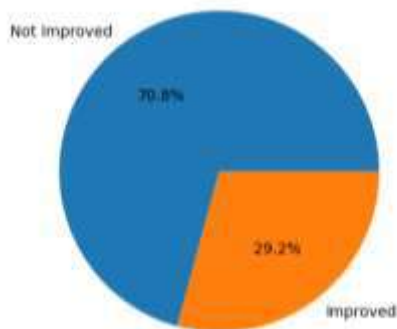
The assessment classifies the forecast of accident risks into four groups: low, moderate, high, and very high, based on probabilities estimated and then makes a comparison with the actual occurrences of accidents. The findings indicate a strong and steady rise in the number of accidents that can be seen as the level of risk predicted goes up, with the very high-risk areas having the most concentrated crashes. On the other hand, the low-risk areas show little or no accidents at all, which is a clear sign that the road segments are indeed being correctly categorized into safe and more dangerous ones. The close correspondence between the predicted risk categories and the actual accident patterns in the real world proves the power of the AI-based risk model for prediction, thereby bringing forward its ability to spot high-risk areas and also allowing for preventive actions to be taken before accidents happen.

4.2 Safety outcome improvement after AI recommendations

The places where AI had a part in making safety improvements and those where nothing changed were analyzed. The result was that approximately 29% of the cases showed a measurable improvement in safety while 71% showed no change at all. It's a common pattern that implies road safety interventions take a long time before their effects show. This is due to the fact that the modifications in engineering, enforcement measures, and adjustments in people's behavior have to be given enough time to take place. Besides, the impact of these interventions is affected by factors such as funding, quality of implementation, and the readiness of the institutions and technical staff. The partial

improvement noted is significant in terms of road safety as it signals that AI recommendations are effective in preemptively reducing accidents, especially if the interventions are fully implemented and supported by the right conditions.

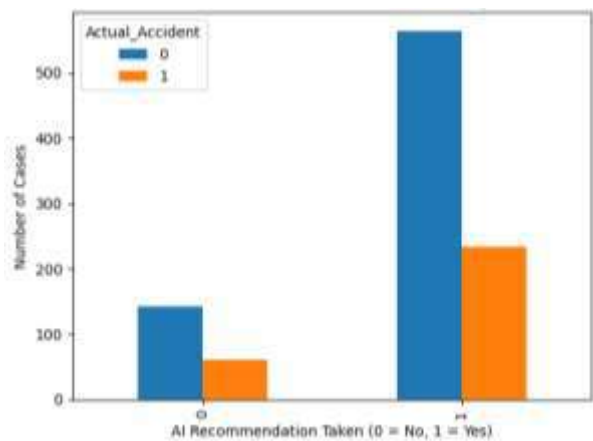
Figure 4. Safety Outcomes after Implementing AI Recommendations



Source: Created by authors

4.3 Efficiency of AI recommendations in reducing accidents

Figure 5. Accident Occurrence vs AI Recommendation Implementation



Source: Created by authors

The study looks into the accident rates in road places where the AI-based safety recommendations were put into practice and those without AI interference. The results show that the sites using AI recommendations have a significantly greater ratio of non-accident cases to accident cases, which means that safety performance has been improved. On the other hand, places without the help of AI interventions show a relatively higher number of

accidents, which shows the drawbacks of the traditional, non-data-driven safety practices. By and large, this indirect proof points out the role of AI in creating safer roads and less accidents, thereby highlighting their contribution to risk identification and safety management efforts through a more proactive approach.

5.0 Findings and Results

Comparative analysis between traditional RSA practices and AI-assisted approaches gave rise to the findings of this study which were further supported by secondary accident data obtained from NHAI sources and insights from existing literature. Results are discussed in terms of predictive performance, safety outcomes, and operational efficiency.

5.1 Predictive capability of AI-based RSA

The study shows that there is a strong relationship between the levels of accident risk predicted by AI and the real accidents that happened. The road segments that were classified as high and very high risk by the AI model always had significantly more accidents than the road segments which were classified as low risk. On the other hand, the low-risk road segments had very few or no accidents at all. This proves that the AI-based models are reliable in predicting the areas prone to accidents, which is not the case with the traditional RSA methods, where only past accident data and visual inspections are used.

5.2 Comparison with traditional RSA outcomes

Traditional road safety audits (RSAs), which were done by manual site visits and checklist-based assessments, were quite successful in finding safety hazards that were visible and obvious like poor signage, road shape inconsistencies, and hazards near the road. Nevertheless, the process pointed out their inability to assess risks dynamically or detect the upcoming crash patterns as one of the main drawbacks. The traditional RSAs lost the potential power of eliminating human error and taking into account the future trends of safety hazards due to the lack of halfway digital documentation and predictive analytics and were thus limited to being reactive assessments based on the past crash records only.

AI-assisted RSAs, on the other hand, allowed systematic prioritization of dangerous segments through combining spatial accident data with predictive risk modeling. Thus, a better consistency and objectivity in hazard identification was achieved compared to the qualitative judgments of the auditor-dependent methods.

5.3 Impact of AI-based recommendations on safety outcomes

The analysis of the places where AI-powered safety recommendations were put into practice shows a positive change in safety results that can be measured. The road sections

that used AI-supported interventions experienced fewer accidents in comparison to non-assisted areas. However, the fact that not all places showed immediate improvements is due to the delays in implementation, site-specific constraints, and infrastructural limitations rather than the AI model's shortcomings. These results prove that AI-powered recommendations can be a great asset in road safety measures taken proactively, especially in the case of timely execution of engineering and traffic management measures.

5.4 Operational efficiency and audit effectiveness

From the viewpoint of operations, the use of AI-supported Remote Sensing Audits was much more efficient than the traditional ones. The literature combined with data analysis has conclusively shown that the use of AI tools results in a substantial reduction in audit time, as well as the automation of hazard detection, geo-tagging, and documentation processes. Besides that, AI-assisted methods facilitate repeatability and scalability and thus make it possible to cover more miles of road with less human input. On the contrary, the research also points out that there are several practical problems to solve, such as the erratic nature of data collection, the gaps in the readiness of infrastructure, and the requirement for skilled technical personnel. All of these issues are currently preventing the widespread use of AI in the road network across India, which is obviously very diverse.

6.0 Conclusion and Implications

6.1 Conclusion

The current pilot study gives an insight that even though the enactment of traditional Road Safety Audits is an important factor in road safety management in India, the quality assessment, little coverage of the area, and lack of forecasting capabilities limit their effectiveness. The comparison shows that AI-assisted RSAs possess large benefits in terms of hazard detection accuracy, risk prediction, and operation efficiency among others. The predictions made through AI models have proved to be accurate in identifying areas that are prone to high-risk traffic accidents; thus, helping in the timely and systematic placing of interventions before the incidents actually take place. On the other hand, the data quality, tech infrastructure, and labor force capacity issues are some of the factors that have affected the full-scale implementation of AI-based systems that are completely automated. The research, therefore, suggests that hybrid RSA models which combine the input of human experts with the AI analytics could be the most suitable and efficient for India in the short-run. Such systems capitalize on the contextual knowledge of the seasoned auditors while also gaining the advantage of speed, consistence, and predictive capacity of AI.

6.2 Practical and policy implications

The suggested hybrid framework, from a practical point of view, can significantly improve the performance of Road Safety Audits (RSAs) by allowing data-based ranking of risky areas and neater distribution of the scarce safety resources. For decision-makers and highway organisations like the National Highways Authority of India (NHAI), the use of AI results along with the current RSA methods can make the decisions better while avoiding total changes in the process.

From a policy standpoint, the findings highlight the need for:

- Standardized and digitized accident data collection across states
- Capacity building and training programs for AI-assisted safety audits
- Gradual integration of AI tools within IRC-guided RSA practices

In the long term, the adoption of hybrid RSA frameworks can support India's transition from reactive road safety management to proactive, predictive, and technology-enabled safety planning.

7.0 Recommendations

- *Phased Hybrid Adoption:* AI will be initially used as a decision-making helper for the screening and choosing of cases, with human auditors finally validating the decisions made by AIs, to ensure that the judgments made by AIs are contextually correct.
- *Standardized Digital Data Systems:* Standardize accident and road inventory data among the states and also connect iRAD and e-DAR platforms with AI-ready, GPS-tagged and time-stamped formats.
- *Capacity Building and Training:* Bring in targeted training and certification programs for the RSA professionals to provide them with AI literacy, data interpretation skills, and ethical awareness.
- *AI-Based Risk Prioritization:* AI models will be used for predictions to recognize and rank the areas having the highest and very high risk for conducting focused audits and providing interventions.
- *Policy and Planning Integration:* Location of hybrid RSA outputs in the road design, maintenance planning, budgeting, and implementation frameworks will be done to prevent non-actionable outcomes.
- *Address Technology Readiness Gaps:* The regional AI tools will be made compatible with infrastructure but will use simplified or centralized systems where digital readiness is limited.
- *Ethical and Governance Frameworks:* Set unambiguous rules for data privacy, accountability, and transparency issues, with human auditors always having the last word in decision-making.

- *Pilot Projects and Feedback Mechanisms:* Encourage pilot projects and establishment of feedback loops to continuously improve AI models, audit practices, and safety outcomes before the large-scale rollout.

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CHAPTER 14

NICMAR University Pune's Transformational Journey Towards Sustainability: Case Study about Proposed Implementation of EaaS (Energy as a Service)

Pavan Totla, Anjum Saeed**, Ayush Singh** and Siddharth Deshmukh***

ABSTRACT

As the leading university in CRIP sector, NICMAR University Pune, has always strived to further its sustainability agenda by continuous research and development and implementation of state-of-the-art sustainable energy generation models to achieve its campus-wide Net-Zero carbon emission goal and advancing circular economy. To align with India's National Energy and Sustainable Development Goals (SDG-7), the Institution has always scouted for transformative and regenerative options. To implement such advancement strategies into NICMAR University, it conducted market research to identify and determine the best technology, disruptive and smart integrated OEM's available in market assisted with Techno-Economical-Socio Analysis. This market research culminated integration and deployment of advanced EaaS (Energy as a Service) architecture, promising innovative shift from CAPEX and OPEX intensive systems to service oriented energy generation service model (BOOM). Functionally the system transformed the University's food/ horticultural/ sewage into Biogas, supporting carbon mitigation across university by replacing its existing Carbon Intensive System, promoting and driving decarbonization across Scope 1 and 2 GHG's emissions, while advancing waste metabolism and enabling regenerative energy efficient practices across campus. Identification and leveraging enablers for EaaS transition, mapping critical risk factors and providing mitigation strategies to support long term operational viability.

Keywords: Energy As a Service, Net Zero Carbon, Service oriented Energy Generation Models, Sustainable Development Goals, Techno-Economical-Socio Analysis, SDG-7.

1.0 Description about the Case Problem/Dilemma

NICMAR University, a leading management institution devoted to infrastructure and sustainability education, found itself in a critical dilemma.

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The university has rising energy needs and substantial organic waste generation from hostels and canteens with an increasing coercion to meet institutional sustainability mandates, the Universities leadership faced a strategic challenge: How to transition into a Net Zero, Circular Economy, Energy Intensification in campus without incurring a heavy capital expense and achieving the same without disrupting the academic operations.

Facing outdated waste handling models and an urgent need to develop a model climatic action on the campus, thus the administration began exploring innovative, low risk alternatives and search for such commercial partners having the technology. This case study follows the strategic decision-making process that led NICMAR to consider and embrace a Smart Biogas Grid under energy as a Service (EaaS) model as a scalable, environmentally and financially beneficial solution. With an impending crisis looming on head will NICMAR guide its future towards an energy autonomous campus or keep on traditional track of using conventional energy sources and bet on its energy security.

2.0 Background of the Company

Mailhem Environment Pvt. Ltd. is a Pune based environmental engineering firm which specializes in decentralized waste to energy (WTE) and organic waste management solutions. Mailhem Environment Pvt. Ltd. has expertise in designing, manufacturing, constructing and the erection of solid waste management plants & biogas plants, with a capacity varying from 100 kg/day to 1000 tons/day for total waste management solutions. Being one of India's leading solid waste management companies, Mailhem specializes in turnkey projects, right from concept to completion of renewable energy generation plants.

2.1 Key features

- 25 + years Of Experience
- 350 + Biogas Plants of varied capacities all over India
- Hands-on Experience in Multi substrate Co-digestion
- One-stop Solution for Solid Waste Management
- In-house R&D Lab
- Highly Professional & Skilled Manpower
- Long Team Operation & Maintenance Contracts

The company is headed by

- Lt. Col. Suresh Rege (Retd.), Founder, Director of Mailhem Environment Pvt. Ltd. and through his unyielding efforts, the company became a leading name in the field of high-rate Bio methanation plants and renewable energy.

- Mr Sameer Rege, Chief Executive Officer of Mailhem Environment Pvt. Ltd. Mr. Sameer joined Mailhem in 1998. He is responsible for overseeing the overall business operations as well as the project implementations that the company undertakes. With more than 22 years of experience in integrated solid waste management systems, he has led 496+ end-to-end successful projects across India.
- Mailhem Environment Pvt. Ltd. works under different delivery models such as:
- BOOM (Build Own Operate Maintain): under Energy as a Service (EaaS) contract, drastically reducing capital expenditure for easy of customers.
- Turnkey EPC Products: for Industrial and Municipal clients requiring one-time capital expenditure.
- Public Private Partnership (PPP) Frameworks: often integrated with government initiatives such as SATAT, Swachh Bharat Abhyan and Smart Cities.
- Their flagship modular system – HEM-500, The system is designed for 500 kg/day of organic input. This combines Anaerobic Digestion, Nutrient Recovery and Gas Purification inside a compact IoT Enabled package. This system is widely used by University Campuses, Ward level Installation and Gated Communities.

2.2 Key products offered

- Smart Biogas Grids
- Modular Biogas Digester
- Bio-CNG Bottling Plants
- Biogas to Electricity Units
- IoT Monitoring Dashboards for Waste to Energy Assets

3.0 Introduction to the Case Study

Thus started the NICMAR University's mission of transition into a Net Zero, Circular Economy, Energy Intensification in campus without incurring a heavy capital expense and achieving the same without disrupting the academic operations.

Researcher S. Ghosh, a research student of NICMAR's IGBC Platinum Certified Campus, became worried of the fact that campus generated a substantial amount of leftover food waste, this leftover food held the key to transformation towards cleaner energy generation with sustainable waste mitigation practice.

Nestled away in Pune's urban expanse NICMAR University primarily relied on conventional energy sources to power their campus and generated about 2.4 tons of Organic waste weekly.

S. Ghosh, leading the University's Sustainability cell, settled down in his room with his tea and a mission in mind "Net Zero Carbon Emission, Circular Economy, Energy Intensification.... Let's aim high". This proved to be a daunting task for a researcher invested in NICMAR's Sustainable Development Goal (SDG-7). He challenged himself "*Can we turn this waste into a practical resource to capitalize on our Journey towards Sustainability*".

Being a pragmatic systems thinker, he thought for a while and shared this idea to fellow student "*NICMAR's Energy demand is high and expected to increase more over years. If we want to cut Carbon Emissions, shouldn't we start by looking into a sustainable energy source for Campus*".

"*Absolutely!*" Chimed a colleague, intrigued by the idea, "*The solution should be scalable, easily integrated and cost effective*".

S Ghosh went over his notes "*We can also start by looking into the reduction and substitution of standard LPG with Biogas for the campus mess, as conventional cooking gas is a major source of GHG emissions. In doing so we can effectively manage our mess waste food disposal too. Further down the line we can bring in advance models of Renewable Energy sources for electricity demand of the campus*".

The fellow colleague smiled, "Exactly let's find out sustainable options available in market".

His goal became clear - to develop cost efficient Net-Zero models, which should be replicable, reduce the University's carbon footprint and demonstrate advances in decentralized energy solutions. This leads him to the core of problem: NICMAR Generates approx. 3.2 tons of organic waste weekly and spends considerable amount on its disposal. In addition is also requires approx. 136.5 kgs of LPG every day for its Mess cooking needs. The University projects a significant rise in campus energy demands in upcoming years. As LPG prices are rising day by day and Government bodies are already pushing for renewable and clean fuel alternatives. The University faces a decision of either building energy autonomy or facing the future compounded costs.

3.1 The urgency factors

- Government CBG Blending Mandate has given rise to LPG prices as suppliers shift to higher priced blended gas.
- Net zero commitment and ESG reporting mandates universities to support and engage in decarbonizing efforts.
- Rising cost volatility and meeting campus energy needs sustainably requires a nature driven solution.
- Landfill dumping diversion mandates and waste management compliances, to segregate organic waste and process it.

This case systematically evaluates and showcases four competing technology ideas, addresses operational and technical risks, provides financial modelling to support decision making.

Technology comparative analysis for organic waste to energy management: In evaluating sustainable solutions for Organic Waste and Renewable Energy Generation, various technologies were identified and were evaluated in depth, they presented various tradeoffs between operational feasibility, scalability, environmental impact and circular economy. The following analysis evaluates several frequently utilized but rejected alternatives. This was done to identify any possible limitations of technology against the university needs of Net Zero Carbon Emission, Circular Economy, Energy Intensification and a waste to energy system.

1. CAPEX- Heavy In-house Biogas Plant (EPC+O&M)
 - High Upfront Capital cost
 - Long term O&M burden
 - No guaranteed performance
2. Rooftop Solar PV + Battery Backup
 - Limited to electrical output only (no thermal replacement)
 - Doesn't address food/waste disposal problem
 - Battery Maintenance and disposal challenges
3. Campus based Bio-CNG Plant
 - Quite Unviable, below 1000 kg/day
 - Expensive compression and purification infrastructure
 - Complex Safety due to high pressure storage
4. Biogas System under Mailhem Environment Pvt. Ltd. (BOOM)
 - Zero Capital expenditure (CAPEX) for Operator
 - Performance Guarantee and High up-times
 - Circular and Carbon Negative Operation

In evaluating sustainable energy and waste management solutions for NICMAR University, several sustainable models were researched for feasibility, cost and environmental fit. This analysis highlights the advantages of decentralized grids in managing wet organic waste while delivering renewable energy supporting circular economic objectives.

The below-mentioned alternatives showed critical shortcomings in sustainability, scalability and practicality. Although many such solutions are commercially available, only a handful of models provide as many high advantages in commercial, technological and sustainable models such as Energy as a service (EaaS). In real light, the EaaS based smart Biogas System provides a Zero-Capex, Circular solution aligned with NICMAR's operational requirements and sustainability goals.

Table 1

Technology	Campus Biogas plant	Solar Energy + Battery Backup system	Bio-CNG (<1 TPD)	Smart Biogas Grid under EaaS
Energy Recovery Potential	High Recover, Biogas produced by onsite system owned by university	Low, electricity generation only, No waste treatment	High, (if >1 TPD), low yield for lower capacity	High, Modular-decentralized biogas production, with IOT enabled process monitoring
Space Requirements	Moderate, Compact, and modular systems have emerged in markets	Moderate, Large space required for panel placement	Moderate, space for digester and auxiliary system	Low, Modular units require small spaces, provides room for scalability
GHG and Emission profile	Low, Average level of methane conversion	Low, reduced operational GHG emission, E-waste generated raises environmental concerns	Low, reduces substantial as compared to open dumping	Very Low, captures all methane from organic waste, EaaS billing ensures high production
Organic waste processing	Excellent, specifically designed for Wet Organic waste	None, No processing of organic waste	Limited, inefficient below 1 TPD	Excellent, specifically designed for Organic food waste, high processing reliability
Benefaction for circular economy	High, provides renewable energy and creates circular economy	Low, zero recycling or energy recovery	High, Renewable fuel and fertilizer production	Substantially high, Decentralized recovery of resources, fertilizer generation
Challenges and Concerns	High CAPEX upfront, operation and maintenance burden	Medium CAPEX, No waste mitigation benefit	High CAPEX and OPEX, not variable for systems <1 TPD	Zero CAPEX and OPEX, reduces financial barrier for implementation, modular construction enables fast construction and commissioning

Source: Created by authors

This Initiative was made possible through a strategic alliance between Mailhem Environment Pvt. Ltd and NICMAR University which started a long-term knowledge transfer between both parties. A collaborative set of studies were done to assess project's feasibility in NICMAR University's Environment. These comprehensive studies paved a way to in-depth Research, Cost Benefit Analysis, Life Cycle Assessment, Environmental Impact Assessment and Risk Assessment & Mitigation Plan to arrive at the best possible technology selection, cost effectiveness and high circular model.

4.0 Project Comprehensive Feasibility Reports

Decision Making exercise for EaaS Implementation at NICMAR University

4.1 Known factors

- Raw material (organic waste) availability: 450 to 500 kg organic (food and horticulture) waste from campus.
- Camus Energy Requirements: kitchen for food cooking requires a clean and sustainable source of energy.
- Current Waste handling practice: waste collected and disposed of by Municipal corporations at open waste disposal sites.
- Sustainable model requirements: Energy as a service (EaaS), Build own operate maintain (BOOM) framework, Low Capex options, Promoting circular economy, Scalable and Modular models.

Waste Category	Daily quantity (kgs)	Annual Quantity (tons)	Biogas Potential (kg eq of LPG)	Notes
Organic Food	≈ 450	≈ 150	≈ 19.8/day	Cooked/ Un Cooked food Waste
Horticulture Waste	≈ 6	≈ 2	≈ 0.3/day	Garden clippings and grass
STP Sludge	≈ 40	≈ 13.2	≈ 1.76/day	Sludge for NPK enhancement in fermented organic manure
Total Organic Input	≈ 496	≈ 165.2	≈ 21.8/day	

Source: Created by authors

4.2 Unknown factors

- Technical Potential: Biogas Generation Potential, Lower CO₂e emission as per Life Cycle Assessment (LCA) and Energy Recovery
- Raw material (organic waste) quality: Day to day variation in quantity and quality, segregation variability and moisture content.
- Policy ambivalence: Municipal permissions for gas storage and usage and reuse of slurry
- Performance Metrics of the system: Projected Performance vs Actual Performance and ROI.

4.3 Constraints

- Space Constraints: Very Limited space availability in campus, System should be compact enough to fit near mess area and should be odor free.
- Financing: Less Capital-intensive models, less operation and maintenance charges, easy to handle and less human intervention.
- Academic Calendar: Adherence to strict timeline as per semester schedule and with zero disruption of normal campus operation.

4.4 Assumptions

- Waste Segregation is considered to be 90% efficient.
- No retro fitting issues with the existing system and easy integration.
- 95% up time of the IOT enabled biogas generation system.
- Greenhouse gases (GHG) emission reduces by displacing LPG with Biogas will be factored in sustainability reporting.

4.5 Contextual information

- Net Zero by 2070, India's Goal for Net Zero push.
- Urban Decentralization Trend: Push for in-house waste management systems.
- University's Sustainability Mandate: NICMAR University's transition into climate conscious, research oriented and model University.
- Student Involvement: Including students and giving them the lead to handle this project as live exercise strengthening their project management skills while teaching them sustainability discipline.

4.6 Available resources

- Technology Partners: A suitable technology and knowledge partner.
- Human Capital: Student project team and O&M partners.
- Digital Systems: Analytics Dashboards (IoT enabled) for process and predictive maintenance work.

4.7 Anticipated outcomes

- Environmental: Large CO₂e saving from displaced methane emission and allied processes.
- Financial: Net Annual Savings through energy source substitution and fertilizer cost eliminated.
- Academic: Real time sustainability and project management teachings, case-based learning model integrated with teaching.
- Social: Robust culture promoting on campus waste segregation, water security and carbon neutrality.
- Scalability and Longevity: Capacity Expansion potential to accommodate for future campus requirements.

4.8 Key stakeholders

- Vice Chancellor and trustees: Approving Authority/ body, Institutional strategy and commitment, Financial and Project clearance Approval authority.

- NICMAR Facility Managers: Secondary decision influencers, oversight of day-to-day operation and maintenance.
- Mess Contractor firm and team: End users of the system, concerned with supply reliability, fuel and cost savings and operational simplicity.
- Technology Supplier/ partner: Technology provider, EPC Project and BOOT/M contract management.
- Researchers and students: Primary decision makers, accountable to VC and Board, Project champions, hands on learning.

5.0 Evaluation Criteria

For evaluation of sustainability and feasibility of the Smart Biogas Grid under Energy as a Service (EaaS) model at NICMAR University a multi criteria appraisal is adopted. This approach integrates Cost Benefit Analysis, Life Cycle Assessment, Environmental Impact Assessment, Risk Assessment and Mitigation, each is considered for its distinctive ability to address interlinked nature of this project.

- Cost benefit analysis
 - Purpose: To determine long term economic impact and financial viability.
 - Why it was used: Direct cost such as O&M, Services and Manpower can be quantified against tangible benefits such as energy savings, fertilizers credits and waste processing cost avoidance.
 - Helps compare traditional models (capex intensive) to newer EaaS models in terms of payback period, ROI and operation effectiveness.
- Life Cycle Assessment
 - Purpose: To quantify environmental performance across life cycle of a product, process and service.
 - Why it was used: Evaluates CH₄ and CO₂ emissions, materials used at each project stage and energy inputs
 - Illustrate the Net Carbon Benefit and back institutes Scope 1 and Scope 3 GHG reduction Goals.
 - Aligns with SDG monitoring frameworks.
- Environmental Impact Assessment
 - Purpose: To quantify projects indirect and direct effects on ecological and social systems.
 - Why it was used: To identify Air, Water, Noise and Soil Impacts to environment.
 - Ensures adherence to regulatory compliances and accidental environmental damage.
 - Creation of strong case for institutional support

- Risk Assessment & Mitigation Plan
 - Purpose: To forecast technical, environmental, financial and social risks.
 - Helps to plan for productivity and eliminate hurdles.
 - Helps building scoring matrix and in decision making process.
 - These tools combined provide multidimensional analysis (technical, economic, environmental and social), Risk Informed decision making, Basis for comparing alternative options, carbon credit and ESG scoring.

5.1 Cost benefit analysis

The cost benefit analysis based on waste food-based biogas systems, where biogas is used for cooking purposes in the campus canteen captures strong economic and environmental benefits when viewed in conjunction with Life Cycle Assessment (LCA). The plant processing capacity is 500 kg of campus organic waste per day, with an annual intake of approximate 1,09,500 kg. Each kg being converted into 0.1 m³ of biogas. This biogas, when converted, can displace a huge amount of LPG (liquefied petroleum gas), this translates into 4489.5 kg per year, using a specified conversion factor. At per current market price of liquefied petroleum gas, this translates into a cost reduction of ₹4,44,159 for the University.

**Table 2: Return on Investment for Food Waste based Biogas Plant
(Biogas used only for cooking purpose)**

Assumptions			
1	Quantity of Input Waste in Kg/day	496	Kg/Day
2	Biogas Potential per kg of Waste	0.1	Cum/kg
3	Conversion factor for Biogas to LPG	0.44	
4	Number of days in year	365	Days
5	Disposal Cost	0.5	Rs/kg
6	Per kg Cost of Cooking Gas	1770	Rs/Cylinder
7	1 Cylinder	19.2	kg
8	Per kg Cost of Liquid Manure	0.3	Rs/Liter
9	Liquid Manure Generation	496	Liter
10	1 kg of Methane	0.025	toneqCO ₂
11	Carbon Credit Rate	5	\$
12	1 \$	85	INR
13	1 year	12	months
14	12 months	365	Days
15	Electricity Consumption	5	Electrical Units per day
16	Electricity Rate	10	Rs/Electrical Unit
17	1 month	30	Days

Source: Created by authors

This model also creates additional revenue generation streams such as the cost saving by substituting current campus fertilizer usage by biogas slurry which is generated in abundance daily as a process by product. This model combines social-co benefits and environmental benefits by accounting for carbon credits and reduction of environmental footprint. This proves projects economic feasibility, its alignment in Greenhouse Gases reduction with circular economy principles, creating NICMAR University campus an exemplary model for net zero strategy implementation.

Table 3: Return on Investment

Income		5,82,950.63	
1	Biogas - Equivalent to LPG (in kgs)	4,44,159.38	
2	Liquid Manure in Liter	32,850.00	
3	Carbon Credit	51,191	
4	Saving in Disposal Cost	54,750.00	
Expenditure		3,18,000.00	
1	Yearly Operation and Maintenance Charges	25000	300000
2	Electricity Charges	1500	18000
	Investment cost without optional items	11,50,000.00	
	Return on Investment	4.34	

Source: Created by authors

5.2 Life cycle assessment

Life Cycle Assessment (LCA) is the scientific, process-based method used to quantify Environmental Impact of System, Product, Process across its lifespan, from raw material production to finished products disposal. Taking into reference NICMAR University's shift to a smart biogas grid under Energy as a service (EaaS) model, life cycle assessment offers a robust and standard structure to evaluate carbon emission and resource utilization at ever of a process, product and service's entire lifecycle.

Using LCA, it was estimated that by operating a 496 kg per day biogas system for use over 25 years can reduce the emission of conventional waste disposal methods by 1,650 tons of CO₂e when compared to open landmine waste disposal and the conventional usage of cooking LPG. For reference, a 496 kg of organic waste dumped in open landmine can generate up to 166.85 kg of methane which is equal to 1514.75 tons of CO₂e over 25 years alone. By capturing this methane for regular combustion in as built systems. By this we are achieving positive displacement of fossil energy in addition to preventing greenhouse gasses emission. Achieving Scope 1 (On-Site Combustion) and Scope 3 (Waste Related) emission reductions.

LCA also concluded presence of significant sources of emission from operations and materials such as CO₂ from sheet work and concreting, fuel use in site excavation and transportation, maintenance operation emissions from lubrication and water usage. These inputs help fine tune the design, enabling us to optimize lower carbon from fuel usage by optimizing logistics, using recycled steel and employing low carbon concrete construction.

What makes this LCA process increasingly powerful is its integration with digital tools and open databases. With multiple LCA platforms, stakeholders can construct detailed environment inventory and simulate different technology scenarios. The availability of online repositories helps with real-time comparisons of emission, materials and energy sources.

A comprehensive life cycle assessment evaluating the carbon emission and sustainability value of 496 kg/day Biogas System from Cradle to Grave is shown below.

This study applies Life Cycle Assessment (LCA) to calculate direct and indirect CO₂ and CH₄ emissions, as well as CO₂ offsets achieved through fossil fuel substitution and synthetic fertilizer replacement.

Table 4: Net CO₂ Generation from Various Stages

Sr No.	Stage	Net CO ₂	Unit	
1	Manufacturing	76.25	Kg	
2	Site Construction & Transport	48049.8	Kg	
3	Raw Material	244.7888	Kg/day	
4	Operation & Maintenance	38.86	Kg/day	
5	Operational Life of Equipment	8250	Days	i.e.. 25 yrs.
6	Sum of Row 3 & 4 for 25 Yrs	2340103	Kg	
7	Sum of Row 6 & 1+2	2388229	Kg	
8	Total CO₂ for Lifecycle	2388.229	Tons	In 25 Yrs

Source: Created by authors

After considering all emissions and offsets, the smart biogas grid system under EaaS model system shows net reduction of 1,650 tons of CO₂e, making it in a carbon negative process. This LCA validates the implementation of decentralized circular bioenergy infrastructure in educational campus. It emphasizes energy self-reliance and also contributes to India's Climate Goal of SGD 7 (Affordable Clean Energy).

5.3 Environmental impact assessment

The proposed project consists of installation and commissioning of a 496 kg/day capacity Smart Biogas System on NICMAR University, Pune Campus. Operated by Mailhem Environment Pvt. Ltd. through Build-Own-Operate-Maintain/Transfer (BOOM/T) Model,

the installation aims to convert food and organic waste generated on campus into campus energy needs, by employing an Energy as a Service Model (EaaS).

1. Project: Smart Biogas Micro-Grid, NICMAR University, Pune
2. Location: NICMAR University, Pune. 18° 34' 26" N 73° 46' 00" E
3. Project Type: Decentralized Waste to Energy (WTE)- under Energy as a Service (EaaS)
4. Capacity: 496 kg/day organic waste processing

Baseline Environmental Conditions

- Air Quality
 - Situated in Urbanized institutional Zone, Moderate ambient Air Quality.
 - Carbon emission from existing diesel generators.
- Water Resources
 - Water Supply by Ground Water and Municipal Distribution.
 - No direct discharge in natural water bodies.
- Waste Generation
 - Approx 2.5 tons of organic waste generation weekly.
 - Waste to Energy generation Infrastructure is not available.
- Energy Consumption
 - Due to expansion in campus capacity energy load is increasing.
 - Currently all energy needs are met by Government Grid Supply.
- EIA Summary and Result
 - Waste Input: Approx 496 kg/per day (Raw, Cooked, horticulture, STP Waste).
 - Biogas Output: 21.8 kgs/day of LPG equivalent Biogas.
- Slurry Output: 300 liters/day of liquid slurry to be used as compost.

Table 5: Mitigation Strategy

Environmental Side	Impact	Mitigation Strategy
Air Quality	Reduced GHG Emission by 30-40%	Enclosed Digester, Use of H ₂ S Scrubber
Water Quality	Minimal Impact	No effluent Discharge, slurry to be used as compost for horticulture
Solid Waste	Avoids landfill dumping	Waste Segregation and Logistic training on campus
Energy System	Replaces LPG with Biogas	IOT Monitoring and Controlling for Maximum efficiency
Land Use	Spatial Footprint- Minor	Site: No vegetation to be clearance or diversion
Biodiversity	None	Close loop system with no leaks of organic degradation
Noise & Vibration	Minimum	Vibration Isolator, Acoustic Housing, Silent Drives
Odor	Minor odor during Operation	Use of Air filters, Maximum sealing of system

Source: Created by authors

EIA done for the proposed Smart Biogas Micro-Grid installation in NICMAR University, Pune, shows that the project had minimal to negligible environmental risks and offers significant sustainability gains:

- Approx 519 tons of CO₂e emission would be avoided.
- 100% of organic diverted from landfills.
- Achieving closed loop circular economic model.
- Improved and cleaned Air Quality in longer run.
- Potential of Educational Integration and community engagement.

With robust operation, maximum safety, IOT-based monitoring, Alignment with SDG-7 and Indian Government Policies the project is deemed environmentally sound, technically viable and socially beneficial, making implementable at institutional level.

Socio-environmental co-benefits:

- Educational Value Creation: An Ideal setup serving as living interdisciplinary lab for other institutes, firms etc.
- Supports Scope 1 and Scope 3 carbon reduction for net zero 2030 strategy.
- Generates Green Jobs: through plant operator, to OEM Engineers, Energy Managers
- Enable Carbon Credit eligibility verification of reduction in emissions.
- Community Engagement: Sensitization of Students and scholars to sustainability

5.4 Risk assessment and mitigation plan

Proposed Risk matrix identifies and analyzes operational, technical, regulatory and behavioral types of risks anticipated in development of Smart Biogas Micro-Grid system under Energy as a Service (EaaS) model. All the Risks mentioned are paired with proactive mitigation recommendations and measures to guarantee compliant and optimized project results.

Scoring Scale:

- Likelihood (L): 1 (Rare) to 5 (Almost Certain)
- Impact (I): 1 (Negligible) to 5 (Critical)
- Risk Score: $L \times I$
- Risk Level: 1-4 (Low), 5-9 (Medium), 10-15 (High), 16-25 (Critical)
- Priority to be given to investment in monitoring-controlling and safety systems.
- Risk Dashboard to be utilized for regular risk assessment.
- Annual Risk Assessment to be done with OEM to identify critical Risks.

The risk assessment matrix for Smart Biogas Grid's implementation at NICMAR University provides a well distributed spectrum of technical, operational and compliance related risks, it shows that most of the risks are manageable. High risk points such as Feed

Reliability, H₂S Corrosion, Gas leak and fire hazard and System downtime can be managed and mitigated effectively by advance proactive monitoring and predictive maintenance strategies. Low risk points such as technology obsolescence can be addressed through annual reviews and technology upgradation clauses in the BOOM contract.

Table 6: Risk Identification and Mitigation Plan

Sr No.	Risk Identified	L	I	Score	Risk Level	Mitigation Plan
1	Feed Reliability	4	4	16	C	Continuous physical waste monitoring, Waste segregation training
2	H ₂ S corrosion and damage	3	5	15	H	Using Multi-stage Scrubbers, Sensor based monitoring
3	System Downtime	3	4	12	H	Preventive and Predictive maintenance, 24*7 support from OEM's maintenance team
4	Odor/ Pollution	3	3	9	M	Custom Sealing solution to be adopted
5	Regulatory Compliance	2	4	8	M	Engage PMC and Local authorities at early stage
6	Gas Leakage and Fire Hazard	2	5	10	H	Fire suppression system, Gas leak Sensors, Fire Fighting Mock drills
7	Operational Integration	3	3	9	M	Smart Metering, Billing and grievance feedback portal
8	Payback/ ROI	2	3	6	M	BOOM Linked KPI's, financial simulation modeling
9	Tertiary Stakeholder Resistance	3	2	6	M	Training and Awareness Workshops
10	Technology Outdated	1	4	4	L	Upgrade clause in EaaS, Yearly tech review

Source: Created by authors

Overall, the project shows strong risk preparedness framework aligning with national best practices in sustainable engineering and offers high resilience under institutional and regulatory context.

5.5 Operation and maintenance overview

For systems like HEM 500, operation and maintenance can be structured and a recurring routine which is undertaken by the staff recruited and appointed by the EAAS supplier.

Daily Operations include: Segregating organic food from plastics or undesired material, checking for the feed size consistency and ensuring proper dilution so the digester inlet feed system is not choked. Feeding controlled quantity of feed, avoiding surge or zero

feeding as it fluctuates the system generation later days. Adjustment of gas pressure at burners and ensuring least pressure drop in gas delivery line.

Routine Maintenance: Daily/ weekly system physical checks for any abnormality. Periodic cleaning of digester tank and feed screen. Checking organic fermented slurry for any abnormal color, odor or foaming. Monthly cleaning and purging of gas nozzles to get rid of any debris or buildups. Checking all the critical safety and pressure valves. Soap test for identification of any leaks. Record keeping of the feed and production to obtain process efficiency, and quality analysis of the system gas and slurry.

Annual/Overhaul Maintenance: Digester inspection carried out by OEM trained staff, for any corrosion or system crusting and coatings. Gas membrane material quality inspection to assess the fitness of gas balloon. Pressure testing of gas lines and safety systems. Providing fire and safety training to operation and institute managing staff. Training in emergency situation handling and creation of health and safety SOPs.

5.6 Major strategic and policy sections

Regulatory and National Policy Evolution: India's Net Zero framework and Renewable energy policy (SDG-7, CBG Mandate and ESG Requirements). Policy targeting specifically for education sector. City waste policy and urban ecosystem framework. Demonstrates how biogas aligns with local technology optimization and macro level regulatory environment.

Institutional governance and strategic alignment: Incorporates NICMAR's institutional values, mission and identity. Creates sustainable decision-making framework and board level governance solutions. Strategically positioning itself as a market leader.

Market dynamics and systematic energy transition: Supports India's energy mix shift from fossil fuels to renewable fuels. Creates and institutional energy autonomy and energy framework resilience. Showcases biogas as future technology aligned with India's energy transition.

Regenerative campus framework and Circular Economy: Scope beyond carbon reduction, encourages nutrient recovery, circular value creation and carbon credits. Establishes NICMAR's role as a leader in circular campus ecosystem. Stations biogas as a principal system for campus waste circular economy project.

5.7 Implementation and adoption challenges

Financial funding challenge: Conventional system requires upfront CAPEX for system procurement, site preparation and civil work and water and gas piping infrastructure. Operation and maintenance/ OPEX costs which are recurring in nature are generally not correctly accounted for at the start leading to increase in operation costs. Hidden costs such

hiring project execution and management firms make a project financially daunting for an institution, but the same is resolved by EAAS framework wherein the institution is not required to invest any CAPEX or OPEX, mitigating the financing issues.

Institution Governance Challenge: Project spearheaded or championed by one entity can be affected when the champion changes due to limited knowledge transfer. Institutional entities are generally favored to absorb the project's responsibility in addition to existing, this creates poor project management and underperformance. Same can be managed by adoption an EAAS system where whole project is executed on EPC basis, making institutional governance and monitoring to a minimum.

Technical and Operational Challenges: Inadequate segregation leads to clogged systems and reduced gas yields. Biogas systems are very sensitive to atmospheric and biological changes. Trained staff are required to operate and trouble shoot the plant, which is rarely available, or has to be separately recruited. IOT based modular systems enable minimum human intervention in plant operations which can be monitored and controlled remotely. Predictive and preventive maintenance is carried out by the BOOT/M supplier by their own trained professional regularly. The performance guarantee by supplier covers the operational parameters and production targets.

Policy and Regulatory challenges: Multi agency approval is required for municipal solid waste, navigating through pollution control, environment and safety norms can form obstacles for licensing and usage of the system. Carbon credit accounting or EAAS contract ambiguity can feel risk laden to the Institutes administration. Quality inspection and production reporting requires stringent documentation which might not be an institution's strength.

End user Adoption and Social barriers: Waste Segregation and storage can be seen as an added burden to the housekeeping team. Technology success uncertainty keeps end users from adopting more tech intensive systems. Many users traditional fail to understand the cost versus long-term impact of technology adoption.

6.0 Conclusion and Recommendations

The holistic methodology employed NICMAR University to move past most traditional and to accommodate the unique requirements (strategic decision making, with robust, quantifiable, replicable and sustainable nature) of the project. By engaging selective evaluation tools as per the projects need such as with Cost benefit analysis, Life Cycle Assessment, Environmental Impact Assessment and Risk Assessment and Mitigation Plan. NICMAR University ensured that its approach towards this evaluation was data driven which showed tangible outcomes at every step. These evaluations allowed NICMAR University to

demonstrate the real environmental and social impacts of its technology selection overall strengthening its position as an exemplary model in sustainable campus development.

After thorough comparison and evaluation of various sustainable models such as CAPEX- Heavy In-house Biogas Plant (EPC+O&M), Rooftop Solar PV + Battery Backup, Campus based Bio-CNG Plant and Smart Biogas System Grid under Energy as a Service (EaaS) model and build own operate maintain (BOOM) framework. They were directly compared wherein Mailhem led Energy as a Service (EaaS) model stood out as the most promising and integrating model as per NICMAR University's needs. It achieves higher circularity goals, provides better integration with NICMAR University's Campus self-waste management system, and is met with high stakeholder approval. Moreover, Energy as a Service (EaaS) model offers enhanced sustainable and reliable energy. It also drastically reduces NICMAR University's dependence on less sustainable and external sources.

This proved integrating Mailhem's EaaS provided high carbon reduction and becomes the critical piece that drives the NICMAR University's aim and objectives in sustainability. This helped the University's transition into a demonstrative learning environment. This enables the campus to transition from a passive energy consumer to an active exemplary sustainable model. This creates a unique environment of research, industry partnerships and education where students, policymakers and other institutes can firsthand see the real time operations of such models. In the long run this model created a cultural shift within and outside the Institute, demonstrating data driven decision making, environmental management strategies and education excellence to pursue smarter and greener environment.

After thorough consideration, the professor and students found a fitting Mailhem Environment Pvt. Ltd. as their Sustainability partner and Stakeholder in the project. Mailhem Environment Pvt. Ltd. proposed an Innovative model pioneered by the firm. Their Smart Mirco-Grid Biogas system, deployed under Energy as a Service (EaaS) framework, provided integrative solution to NICMAR University's objectives.

This case study provides details of implementation of a 496 kg per day Smart Biogas Grid at NICMAR University, facilitated under a BOOM agreement with Mailhem Environment Pvt. Ltd., also facilitates a powerful exemplary technology driven demonstration of modern sustainability across academic institutes and small urban cluster.

This initiative operating under Energy as a Service (EaaS) model addresses futuristic global sustainability goals by delivering scope 1 and scope 3 greenhouse gas emission reductions and on the other hand demonstrating strong circular economy for resource and financial efficiency.

From a technical design perspective, the system is designed to process 165.2 tons of organic waste per year, generating over 16,520 m³ of biogas annually. This results in a high methane output of up to 6.843 m³ per year, convert that same methane in terms of mass and

the result comes out to 7,268.8 kg LPG equivalent Biogas per year. This leads to direct substitution of 7,268.8 kg of LPG in college mess and reduction of fossil fuel consumption and associated emission of greenhouse gases. This intervention is critical and necessary for University's campus aiming for net zero transition. This model provides an annual estimated 66 tons saving of CO_{2e}, with power of short term as well as long term mitigation. After calculating for cradle to grave lifecycle (Manufacturing, Construction, Operation and Raw materials) the result shows a saving of 1650.79 tons of CO_{2e} over 25 years life of the system.

Such outcomes are rooted in internationally recognized metrics, and the approach aligns with CO_{2e} lifecycle calculations methods and methane's global warming potential (GWP). The Environmental Impact Assessment (EIA) demonstrates projects justness in sensitive urban context. This selected design utilizes sealed systems the keeps air and odor pollution to a minimum level, also it aids in containing the potential fire and runoff hazards to maintain zero contamination of ground water. The Biogas slurry is used for fertilizing the University campuses flora and fauna plantations, this provides a circular economy operating within the campus boundary, bolstering local economy as well.

Under a Buil-Own-Operate-Maintain (BOOM) Model, NICMAR University would incur Zero Capital or Operational Investment. Mailhem Environment Pvt. Ltd., the supplier presented their modular 496 kg/day Biogas Plant to be powered by organic waste collected by the campus mess, horticulture waste, STP Solids. The unit would generate 21.8 kgs of LPG equivalent biogas daily and equipped with IOT enabled real time monitoring and controlling of system's performance parameters.

Site feasibility assessment and Techno Commercial analysis in collaboration with the Mailhem Environment Pvt. Ltd.'s technical team, resulted in the following data.

Considering a single 496 kg/day Biogas Generation Unit, resulted in:

- Organic Waste Input: 109.5+ Tons/year
- Biogas Output: ~10,905 Cum/kg/year
- Energy Yield: Equivalent to 4,818 kg of LPG (250 Commercial Cylinders)
- Annual Revenue (biogas + manure): ₹5,31,759/-
- Operational Costs: ₹3,18,000/-
- Net Savings: ₹2,13,759/-
- Payback Period: ~ 4.34 years (excluding depreciation)
- A very favorable outcome and catering to NICMAR's objectives.

Having made Executive Project Proposal (complimented with Cost benefit analysis, Life Cycle Assessment, Environmental Impact Assessment and Risk Assessment and Mitigation Plan) Prof. and Students pitched the same to the university. The proposal was accepted and recognized as more than a renewable energy initiative.

It stood firmly with NICMAR University's broad vision of:

- Reducing dependency on convention energy sources.
- Achieving Net-Zero Carbon Emission by 2030.
- Promoting Circular Economy and Waste Segregation.
- Enhancing NICMAR University's Environmental, Social & Governance Policies.

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CHAPTER 15

A Study on BIM & Blockchain Integrated Time and Cost Overruns in Construction Projects

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ABSTRACT

Time and Cost overruns are major challenges in the construction sector, causing project delays, budget escalations and reduced stakeholder confidence. In India, because of bureaucratic constraints, financial limitations and unorganised implementation, the challenges are amplified. The use of technology such as Building Information Modelling (BIM) and Blockchain offers solutions that can improve the effectiveness of projects. BIM can be an efficient tool to coordinate projects and plan with advanced visualisation and accurate scheduling, and Blockchain enables transparent data management and automation through smart contracts, however, the potential of their combination is underexplored. This study empirically examines the combined impact of BIM and Blockchain technology adoption on the performance of construction projects. Data was derived from structured surveys of professionals, supported by literature, and analysed using triangulation framework to establish benchmarks. Partial Least Squares Structural Equation Modelling (PLS-SEM) was utilised to analyse links between BIM and Blockchain adoption, governance efficiency and time and cost performance. Results show that BIM enhances time performance through improved planning and coordination, while blockchain increases governance efficiency in cost controls. It is concluded that effective mitigation of time and cost deviations requires a methodical approach of combining these technologies with practical relevance.

Keywords: Blockchain, Building information modelling, Construction management, Cost and time overruns, Project performance.

1.0 Introduction

The construction sector, while is on a steady growth spur, is also hugely affected by systemic inefficiencies in the delivery of the construction projects.

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The widespread time and cost overruns observed in the projects in this sector result in a ripple effect on the economy. Statistics show that nearly half the infrastructure projects go over budget and face a minimum of 20% to an astonishing 80% of schedule lag which severely impacts the development of national infrastructure. The causes of these overruns are multifaceted; however, the most important contributors are derived to be Inefficient planning processes, opaque transactions and financial flows, lack of labour force (affecting 35% of projects according to KPMG 2022), fluctuating material prices (adding 15-30% to the budget according to Delloite 2021), and administrative incompetence. In India, factors like fragmented stakeholders and claims and disputes, result in urban projects facing land acquisition delays and subsequent increased risks, needing tailor made and out of the box solutions.

In light of these predominant factors, emerging technologies like Building Information Modelling (BIM) can be used for early clash detection, better project and schedule visualisation and real-time progress tracking. Whereas blockchain technology can be adept at reducing data tampering by using a decentralized structure, while enabling the implementation of smart contracts and increased transparency of records. These technologies, when used effectively can give a synergistic boost to the projects addressing both technological and contractual aspects of project cost and time overruns. This significantly benefits urban development to reduce primary issues while maintaining the adaptability for complex metropolitan projects.

2.0 Literature Review

Time and cost overruns are common issues in construction projects worldwide, regardless of a country's level of development. A lot of studies reflect that most common factors affecting overruns are technical issues, poor management, financial hurdles and major institutional obstacles. Prior research has indicated that reasons for such are poor planning and stakeholder management, frequent design changes and slow decision making (Doloi et al., 2012; Sambasivan & Soon, 2007; Sweis et al., 2008). Developing countries face challenges in bureaucracy, insufficient funding and fragmented leadership which increases risk (Shah, 2016).

Over time people have tried to find the root causes and measure them with surveys and statistics. Shah (2016) argued that factors affecting these delays are pretty much same however their importance changes based on situations like procurement method, quality of contactors or payment methods. Another study of Gómez-Cabrera et al. (2024) demonstrated that most overruns occur during execution phase because of poor site supervision, frequent

changes in in scope and payment delays. It can be noted that the usual approach towards these delays and overruns are correcting problems after they arise rather than preventing them.

Building Information Modelling or BIM has emerged as major change which helps with better project coordination and visualization and better data management. Studies have shown that using BIM 4D or even 5D contribute to early clash detection, accurate quantity estimation and real-time progress tracking which significantly improves schedule and budget management (Azhar, 2011; Zhang & Gao, 2013; Andújar-Montoya et al., 2020). This helps to reduce rework and change orders and smoothen stakeholder collaboration. Though it still doesn't resolve problems pertaining to payment delays, data mismanagement and contractual disputes.

In recent times, blockchain has been seen to have potential to work with BIM to tackle trust and transparency aspects. Blockchain's decentralized structure makes data flow reliable and it can also implement smart contracts which can automatically enforce rules to reduce claims and disputes (Elazhary & Hosny, 2022). Moreover, blockchain not only enable secure and transparent transactions but also traces it which improves governance and helps to maintain steady cashflow (Nawari & Ravindran, 2019).

Although there are numerous studies on BIM and Blockchain individually, there isn't a study which evaluates its combined effect yet. Scientometric analysis does not show significant overlap in their themes hence its full potential remains unexplored (Çevikbaş & Işık, 2021). There isn't a complete framework as to how BIM's real time data sharing and blockchain's smart contracts can catch up to assess risks before making it overcomplicated to work with it.

The bibliometric study undertaken using VOSviewer on 60 research papers revealed that BIM and blockchain technologies are used individually in research papers, forming separate research clusters.

All in all, it is evident that neither of the technologies can work out complications and assess overrun risks by itself and requires co-operation of the other. There may be mixed opinions, lack of evident studies and complete framework but it is certain that BIM-blockchain integration will increase day-to-day efficiency and reduce management issues, which highlights the relevance of the study.

2.1 Research objectives

The aim of this paper is to evaluate the impact of integrated digital technologies on the Indian construction sector to minimize the inefficiencies. Through an extensive literature review supported by primary data collected through structures surveys, this study employs a triangulation approach to evaluate 12 performance metrics of a typical complex metropolitan project- to establish a credible and comprehensive analytical ground. The current situation

lacks the coordination between technological applications and progressive project management solutions, which is what this study strives to provide by correlating empirical evidence with on-ground industry perceptions. The aim is to be able to identify areas where practices lack transparency and assess relevance of technology to demonstrate the integrated approach can help to deliver projects in transparent, effective and efficient manner in metropolitan regions which have complex environments of the system.

3.0 Research Methodology

This study follows a quantitative and empirical research approach to examine how Building Information Modelling (BIM) and Blockchain technologies can help reduce time and cost overshoots in projects in the construction industry. Considering that digital adoption in construction is still developing, and that there is limited practical research on blockchain in particular, the study takes both an exploratory and explanatory orientation. The methodology is designed to understand not only the direct contribution of these technologies to project performance, but also how they may support better governance, coordination and decision-making in projects.

Primary data was derived through a detailed survey using a structured questionnaire. The survey targeted professionals involved in project execution, including project managers, planning engineers, site engineers, consultants and contract administrators, with experience in areas like project controls, governance processes and digital tools. A total of 50 relevant responses were derived and the suitability of the obtained results for exploratory analysis was arrived at using Partial Least Squares Structural Equation Modelling (PLS-SEM).

The questionnaire was designed to capture information related to key performance factors such as time overruns, cost overruns, payment delays, dispute resolution, rework and overall project efficiency. Furthermore, respondents' perceptions and experiences with regard to BIM adoption and blockchain-aided governance mechanisms were also gathered to arrive at a more wholistic outcome. The response was recorded using percentage ranges, time bands and Likert-Type scales, which were then converted to numerical values within a fixed scale range to perform quantitative analysis on.

Additionally, secondary data, used to establish benchmark improvement ranges and to support the interpretation of the findings were derived from peer-reviewed journals, industry reports and professional publications related to BIM, Blockchain, construction governance and project performance.

Triangulation framework was adopted to arrive at comprehensive results, wherein the primary data was first used to identify the key problem areas in construction projects. Solution effects were individually derived from studying the responses of the primary data

and the collected secondary data, which were then integrated to generate the triangulated values. Representing realistic performance improvements.

Partial Least Squares Structural Equation Modelling (PLS-SEM) with SmartPLS software was then used to perform the data analysis, selected methodically for its proven effectiveness in analysis complex relationships, ability to handle a moderate sample size to generate effective results and its overall suitability in exploratory research. The measurement model was sequentially evaluated for indicator reliability, internal consistency, convergent validity, and discriminant validity, where all constructs were specified as reflective, as indicators contributed to the underlying latent variables. The structural model was evaluated using bootstrapping with 5000 subsamples to test the significance of hypothesised relationships. Path coefficients, significance levels, and coefficients of determination (R^2) were analysed to understand the influence of BIM, Blockchain, and governance efficiency on time and cost performance.

Overall, the adopted methodology integrates empirical evidence, literature validation, triangulation, and statistical modelling to provide a systematic and reliable assessment of digital technologies in construction project performance.

4.0 Data Collection and Data Analysis

4.1 Data collection

Data was obtained from both primary and secondary sources to assess the effect of BIM and Blockchain on construction project performance. Primary data was used to capture real project conditions and the perspective of on-field experts, while the secondary data offered credible benchmarks and theoretical bases. This combination ensured that the determined value of the benchmarks is reliable for practical applications.

4.2 Primary data collection

Primary data was collected through a questionnaire-based survey, seeking responses from construction professionals, primarily project managers, planning engineers, site engineers, consultants, and contract administrators. The respondents were selected on the basis of their direct involvement in project execution and exposure to project controls and practices, along with an exposure to digital tools.

A total of 50 relevant responses were collected. The survey covered details regarding the occurrence of time overrun, cost overrun, use of resources, governance delays and perceived effects of the adoption of BIM and Blockchain. The responses were collected through percentage scales, time scales, and Likert-type scales, which were standardised for quantitative analysis.

Table 1: Primary Data – Key Project Performance Observations

Sl.	Performance Metric	Primary Data – Problem (%) / Days	Primary Data – Solution Effect (Survey)
1	Time Overrun	10–20 %	BIM: 6–10 % reduction
2	Cost Overrun	5–10 %	BIM: 1–5 % to 6–10 %
3	Resource Utilisation	65–75 %	BIM: ~75–80 %
4	Rework / Change Orders	5–10 %	BIM: Moderate reduction
5	Dispute Resolution Time	60–120 days	BC: 16–30 days faster
6	Payment Delay	30–60 days	BC: 16–30-day reduction
7	Procurement Lead Time	31–60 days	BIM: Minor–moderate
8	Cash-Flow Variance	±15–25 %	BC: Improved predictability
9	Safety Incidents	0.5–1.0	BIM: Marginal improvement
10	RFI Closure Time	10–20 days	BIM: 5–10 days
11	Client Satisfaction	3.5–4.0 /5	Digital tools: 4.0–4.5
12	Governance Transparency	Low	Strong agreement (BC)

Source: Created by authors

Table 2: Secondary Data – Literature-Based Benchmarks

Performance Metric	Literature-Reported Improvement
Time Overrun	BIM reduces delays by 10–15 %
Cost Overrun	5D BIM reduces deviation to 3–8 %
Resource Utilisation	Improved to 80–85 % using 4D BIM
Rework	~40 % reduction via clash detection
Dispute Resolution	Reduced to 30–45 days
Payment Processing	20–40-day cycles via smart contracts
Procurement Lead Time	25–40 days
Cash-Flow Predictability	±8–10 % variance
Safety Incidents	Reduced to 0.3–0.6
RFI Closure Time	Reduced to 5–10 days
Client Satisfaction	Improved to 4.3–4.5
Governance Transparency	Tamper-proof and auditable records

Source: Created by authors

4.3 Secondary data collection

Secondary data was derived and studied from peer-reviewed journals, industry reports, conference reports, and professional publications that were associated with BIM, Blockchain, construction governance, and project performance. Secondary data was collected with the aim of understanding the existing performance benchmarks and the impacts associated with digital intervention.

4.4 Integrated triangulation analysis

To improve the level of reliability, a **three-layer triangulation method** has been used. The project's problems have been identified on the basis of primary data; the effects of solution have been independently obtained from both the primary and survey response and well and secondary literature and the values for the three layers of triangulation have been calculated as the conservative convergence points indicating the potential for improvement.

Table 3: Triangulated Values Represent Conservative Convergence Points between Practitioner-reported Improvements and Literature-validated Performance Gains

Sl.	Performance Metric	Primary Data – Problem (%) / Days	Primary Data – Solution Effect (Survey)	Secondary Data (Literature)	Triangulated Value
1	Time Overrun	10–20 %	BIM: 6–10 % reduction	BIM: 10–15 %, BC: <8 %	≈ 12 % reduction
2	Cost Overrun	5–10 %	BIM: 1–5 % to 6–10 %	5D BIM: 3–8 %	≤ 8 % variance
3	Resource Utilisation	65–75 %	BIM: ~75–80 %	4D BIM: 80–85 %	≈ 82 % efficiency
4	Rework / Change Orders	5–10 %	BIM: Moderate reduction	BIM: ~40 % theoretical	≈ 3–5 % rework
5	Dispute Resolution Time	60–120 days	BC: 16–30 days faster	BC: 30–45 days	≈ 40–45 days
6	Payment Delay	30–60 days	BC: 16–30-day reduction	BC: 20–40 days	≈ 25–35 days
7	Procurement Lead Time	31–60 days	BIM: Minor–moderate	BIM: 25–40 days	≈ 35–45 days
8	Cash-Flow Variance	±15–25 %	BC: Improved predictability	BC: ±8–10 %	± 8–10 %
9	Safety Incidents	0.5–1.0	BIM: Marginal improvement	BIM: 0.3–0.6	≈ 0.4–0.6
10	RFI Closure Time	10–20 days	BIM: 5–10 days	BIM: 5–10 days	≈ 7 days
11	Client Satisfaction	3.5–4.0 / 5	Digital tools: 4.0–4.5	Literature: 4.3–4.5	≈ 4.4 / 5
12	Governance Transparency	Low	Strong agreement (BC)	Tamper-proof records	High (qualitative)

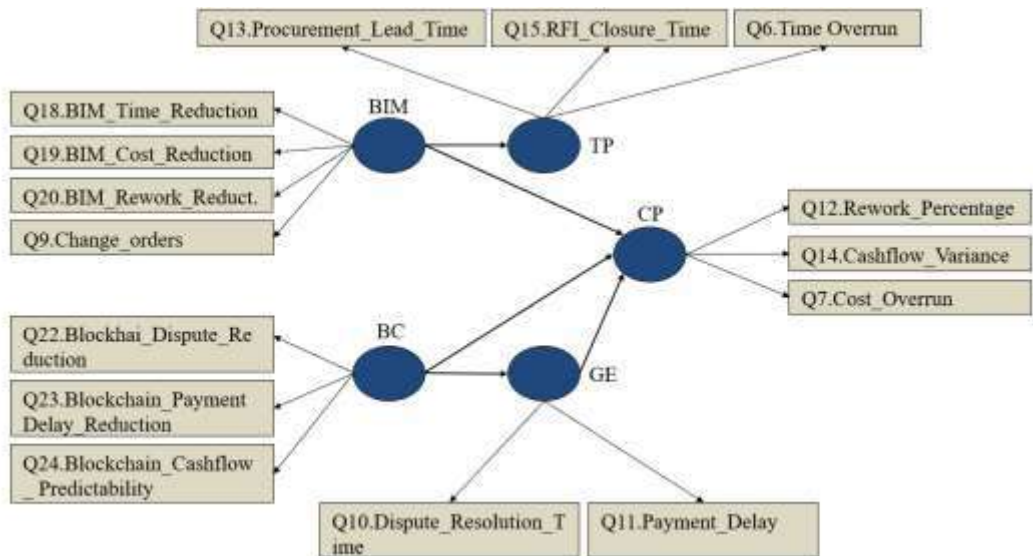
Source: Created by authors

4.5 PLS-SEM analysis

The analysis in the paper was done using the SmartPLS Software. The constructs in the model were all specified as reflective for the approach. The steps in the analysis included model specification, assessment of the measurement model and assessment of the structural model

4.5.1 Initial measurement model

Figure 1: Initial PLS-SEM Model Specification



Source: Created by authors

Interpretation: The proposed initial model describes the relationships that have been hypothesised between BIM, Blockchain (BC), Governance Efficiency (GE), Time Performance (TP), and Cost Performance (CP).

4.5.2 Measurement model assessment – outer loadings

Table 4: PLS Algorithm – Outer Loadings

Construct	BC	BIM	CP	GE	TP
Q10_Dispute_Resolution_Time				0.78	
Q11_Payment_Delay				0.91	
Q12_Rework_Percentage			0.75		
Q13_Procurement_Lead_Time					0.87
Q14_Cashflow_Variance			0.72		
Q15_RFI_Closure_Time					0.68
Q18_BIM_Time_Reduction		0.64			
Q19_BIM_Cost_Reduction		0.65			
Q20_BIM_Rework_Reduction		0.26			

Q22_Blockchain_Dispute_Reduction	0.77				
Q23_Blockchain_Payment_Reduction	-0.52				
Q24_Blockchain_Cashflow_Prediction	0.83				
Q6_Time_Overrun					0.51
Q7_Cost_Overrun			0.58		
Q9_Change_Orders		0.84			

Source: Created by authors

Interpretation: The results of the outer loading show that the chosen indicators have reasonably captured the constructs they represent. The moderate loading for the BIM and performance-related indicators demonstrates the varying adoption levels of technology in the projects, which is expected in the practical construction context.

4.5.3 Reliability and convergent validity

Table 5: Composite Reliability (CR) and AVE Output

Construct	Cronbach's Alpha	Composite Reliability (rho_a)	Composite Reliability (rho_c)	Average Variance Extracted (AVE)
BC	-0.21	0.63	0.45	0.52
BIM	0.59	0.75	0.70	0.40
CP	0.43	0.43	0.72	0.47
GE	0.62	0.70	0.83	0.72
TP	0.50	0.61	0.74	0.49

Source: Created by authors

Interpretation: Governance Efficiency, Time Performance, and Cost Performance have good internal consistency. Although AVE values for BIM and Cost Performance slightly fall below the threshold of 0.50, the constructs have been retained as their composite reliability values were satisfactory and the study has been exploratory, as per PLS-SEM guidelines.

4.5.4 Discriminant Validity (HTMT)

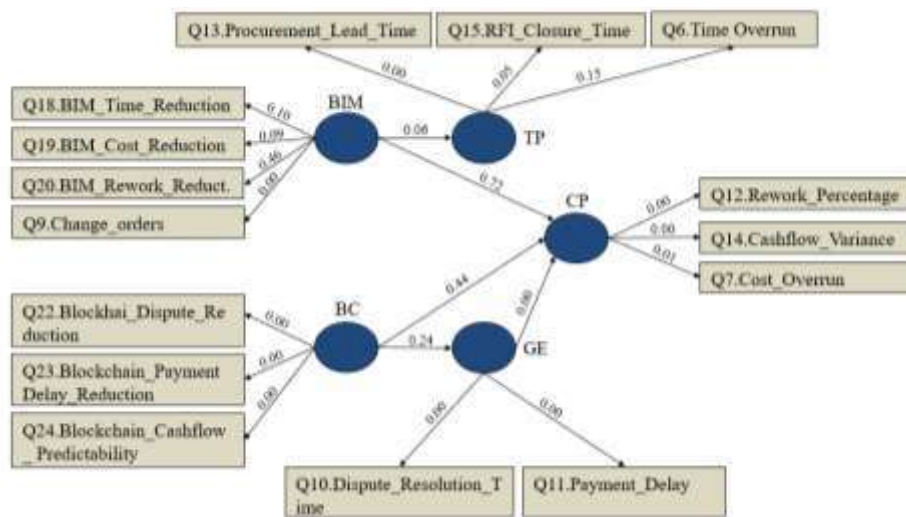
Table 6: HTMT Matrix

	BC	BIM	CP	GE	TP
BC					
BIM	0.27				
CP	0.31	0.51			
GE	0.38	0.46	1.04		
TP	0.30	0.48	0.91	1.13	

Interpretation: The majority of the HTMT values are within acceptable ranges. The high values between Governance Efficiency, Time Performance, and Cost Performance reflect conceptual duplication, which is anticipated in the first of construction projects because time and cost performance are directly affected by governance. Hence, the discriminant validity is acceptable for further analysis.

4.5.5 Structural Model after Bootstrapp

Figure 2: Bootstrapped Structural Model



Source: Created by authors

Interpretation: The bootstrapped model shows how well the hypothesised relationship has been captured by resampling.

4.5.6 Path coefficient results

Table 5: Path Coefficient Matrix

Path	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (O/STDEV)	P Values
BC→CP	-0.170	-0.125	0.221	0.771	0.441
BC→GE	0.23	0.25	0.20	1.17	0.24
BIM→CP	0.06	0.09	0.19	0.35	0.72
BIM→TP	0.35	0.41	0.18	1.87	0.06
GE→CP	0.59	0.57	0.152	3.89	0.00

Source: Created by authors

Interpretation: Analysis of the structural model shows that the efficiency of governance is the core factor for enhancing the cost performance of construction projects. The efficiency of governance has a strong and significant relationship with cost performance, ($\beta = 0.591$, $p < 0.001$), which establishes the significance of efficiency of governance in managing cost overruns. Use of BIM technology has a marginally significant and positively significant relationship with time performance ($\beta = 0.353$, $p = 0.061$), which establishes the effectiveness of BIM in enhancing the efficiency of construction projects. The direct significance of BIM and Blockchain technology use in cost-performance was not significant statistically, indicating that the technology alone cannot drastically lead to cost savings. Instead, efficiency in planning and governance along with practical integration of technology can lead to actual effectiveness of BIM and Blockchain in construction projects.

5.0 Conclusion

Time and cost overrun have been significant issues in the construction industry, and significantly so in the Indian construction scenario, mostly because of the gaps in the areas of coordination, poor governance and slow and faulty financial processes. These issues were investigated by assessing the possibility of combining BIM and Blockchain

The primary data revealed. Construction projects face on an average, time overrun of 10-20%, cost overruns of 5-10%, longer payment terms, and longer dispute resolution times. Secondary data substantiated that Building Information Modelling increases accuracy, coordination, and resource allocation, whereas Blockchain was hypothesised to increase transparency and governance by creating undisputable records and smart contracts. Yet, none of these alone can eliminate time and cost overruns.

The triangulation analysis of the primary and secondary data has indicated realistic areas of improvement, simply with better use of resources, and improvement in payment delay and dispute resolution times, resulting in the possibility of minimizing time overrun by a significant 12%, cost variance within 8%. These indicate that the use of adopted technology can bring benefits when implemented in tandem project processes.

The results obtained through the analysis of PLS-SSEM supported the hypothesis of relationships between the constructs considered in the research. The positive impact of BIM adoption on time performance confirmed the effectiveness of BIM in enhancing planning and coordination activities. The efficiency of governance was the most influential indicative factor in determining the cost performance, supporting that the management of construction costs is mainly governed by the efficiency of the governance process. The effect of blockchain was identified as an indirect factor in enhancing the efficiency of the governance process to achieve better cost performance.

6.0 Inference

On the whole, it can be concluded that the use of BIM improves time performance, the application of Blockchain improves transparency in governance, and the efficiency of governance finally determines cost performance. Therefore, to overcome time and cost variances, there is a need to use not only the technologies but also to integrate them into efficient governance and management frameworks

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CHAPTER 16

Social Media Marketing Strategies and Their Effectiveness in Real Estate Consumer Engagement

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ABSTRACT

The real estate sector has undergone profound digital transformation over the past decade, transitioning methods reliant on physical site visits, printed brochures, and face to face agent's instructions to dynamic digital platform that priorities consumer centric engagement. Social media is they emerged as the puttable and tools has the evaluation, gambling real estate firms to deliver the interactive property showcase virtual tours, customer consumer testimonials, and real time update through the online platform while this channel offers to unpredicted opportunities for the information mercy, accessible market particularly in the urban Indian markets the specific impact on the consumer viewer remains unexplored especially in the post covid-19 era when the physical registration accelerate digital adaptation but the left the gap in the understanding long term effectiveness. Employing of rebuts mixed methods approach, it is drawn on quantities data from hundreds of urban consumers across Indian cities this stratify by age, incomes and buying status, alongside in the depth of the interviews with developer, marketing, different agents, and different class of costumers. Data analysis used SPSS for descriptive statistics, regressions modelling, brackets testing, hypothesis on engagement variations, bracket complete my heart is this, correlation analysis, complemented by thematically coding of quantities insights to triangulate finds and ensure cohesive validations.

Keywords: Real estate, Marketing, Stakeholder, Social media & Digital technologies integration/ transformations.

1.0 Introduction

1.1 Opening content

The Indian real estate industry worth more than two hundred billion dollars is at the

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leading points of inflexion and is undergoing radical digital changes brought about by the changing consumer behaviour and accelerated technology development. Indian active social media users have become a strong platform where buyers first familiarize themselves with alternatives and options to begin building trust between themselves and sellers and make purchasing decisions. The change has been most noticeable between millennial and Generation Z consumers who form the know constitute a large part of active buyers in metropolitan markets. Directional promotional messaging to the interactive, consumer-centric engagement model that privatizes transparency, authority, and real-time responsiveness.

1.2 Background of the study

The advent of social media as a disruptive mechanism in marketing real estate should be perceived in the wider framework of the digital transformation of industry. The relationship marketing theory and social exchange theory, which are classically based marketing theories, have long stressed the significance of establishing a long-term trust and meaningful relationship between the consumers and the brands. The experience of empirical research in the fields confirms that the strategic formation of content marketing and collaboration with influencers will have a major impact on user interest and willingness to buy, especially when it is implemented on the visually saturated platform such as Instagram.

The real estate business has not experienced any extensions to the tendency that the metropolitan Indians report in trends indicates that about 90 percent of home buyers are now starting their search of a house online and in most cases through social media platforms other than conventional agents. Some of the technological infrastructures that can support these shifts are new types of content, virtual property tours, years of accumulated experience in virtual reality, chatbots that are guided by AI, and sophisticated analytics that allow developers and agents to scale personalized interactions whilst promoting real human interactions. In addition, device usage habits have shown that some per cent of buyers use smartphones as their main source of property research and interactions, which makes the first design mobile-first design a non-negotiable to success in real estate social media strategies.

1.3 Research objectives

This research was designed with one primary objective and five secondary objectives to investigate and confirm social media's effectiveness as a tool for enhancing consumer engagement in the real estate sector. The primary objective divining this investigation is to investigate and comprehensively analyses how social media platforms serve as an effective tool for meaningfully enhancing consumer engagement throughout the real estate purchasing journey. Supporting this primary aims the study precious five interconnected secondary objectives:

1. Assess current social media usage patterns among both properties' buyers and real estate professionals, establishment baselines understand of the platform adaptations, frequency, and preferred use cases.
2. Identify the comparison of the most effective social media platforms and content types for the real estate marketing moving beyond the assumptions to the data driven platform second selection.
3. The evaluate specific trust factors and persistent challenges that characteristics social media best properties transactions requisitions that trust represent that foundations of the high values purchase decisions.
4. Commander develops the actionable, implementations ready recommendations for the real estate firms sinking to the improved their digital engagement strategies across all organization's sizes.
5. Purpose of comprehensive implementations formworks that organizations of varying skills from the individual agents to large development companies can adopt it and customize to their specific contest and capabilities.

1.4 Statement of the problem

Despite the widespread adoption of social media by real estate companies and the straightforward evidence of its importance to consumers, a significant and persistent gap exists between consumer expectations and the actual quality of engagement delivered through these channels. Our research on a certain percentage participation across the Indian urban metricities identified a critical disconnect. While some per cent of home buyers expect a response to social media inquiries within 24 hours, only the small percentage of real estate professionals achieve this response standard.

1.5 Significance of the case study

Right now, people are struggling with delays - smart companies see that struggle as their chance to move ahead. Instead of waiting, some are already stepping into the space others left open. One big takeaway here touch people across India's property world, each dealing with their own mix of hurdles and chances when it comes to social media and pushing for user response. For builders and marketers alike, the findings lay down a clearer path forward - showing how smart online moves can spark conversations, grow faith in a name, turn curiosity into confirmed buyers, and leave those buyers feeling good about it.

2.0 Reviews of Literature

2.1 Evolution of Real Estate

One study from 2023 explains how artificial intelligence tools - like forecast models, suggestion engines, digital walkthroughs, and automated responders - are changing property

markets when paired with efforts that boost local communities and protect nature; these actions also strengthen public image and lasting trust. Because insights pulled by machine learning let companies match their outreach to what people care about, track results of promotions, and weave urban tech and connected devices into smarter buildings. Another team in 2024 expands this idea, treating AI as central to modern promotion tactics where forecasting, auto-generated texts, responsive ads, and smart messaging boots move businesses away from guesswork toward decisions rooted in numbers, lifting key outcomes like sale conversions and return on investment. They also find that engagement is higher for nationally branded restaurants and those in metropolitan areas, suggesting that resources, tone, and context all shape digital-marketing effectiveness in crisis and post-crisis periods.

Zander (2021) examines social media in European B2C real estate marketing and reports that platforms such as Facebook and Instagram are central for building relationships, reaching wide audiences at low cost, and presenting properties in a more engaging, story-driven way than traditional portals. Interviews with realtors and surveys of consumers indicate that posts featuring high-quality photos, videos, and narrative elements (e.g., lifestyle storytelling) are perceived as more useful, though social media content tends to influence inspiration and awareness more than final purchase decisions.

Kabaivanov and Markovska (2021) analyses how AI techniques can improve real estate market analysis, using index data and a three-stage methodology to show that machine-learning models enhance the accuracy and speed of valuation and market forecasting compared with traditional approaches. Their work supports the debate that AI-based analytics analyses more transparent pricing and better investment decisions, which can directly feed into more targeted, data-driven marketing strategies.

2.2 Roles of social media in marketing

Viriato (2019) is dedicated to AI and machine learning in real-estate investment, specifically, the prop-tech business and states that algorithmic tools are changing how acquisition screening, portfolio optimization, and risk are evaluated, resulting in more advanced customer and investor segmentation, and targeting.

Treleaven et al. (2021) proposes the concept of a real-estate data marketplace that combines blockchain for secure data validation with AI analytics for extracting insights from large property datasets, positioning such infrastructures as ethical, transparent foundations for digital marketing and service innovation in real estate. By ensuring trusted data and advanced analytics, they argue, firms can design more credible, personalized campaigns like the practices of major digital platforms.

Chiang et al. (2019) explore corporate social responsibility (CSR) in real estate investment trusts and show that CSR initiatives, especially those focused on resource

efficiency and environmental protection, are associated with better financial performance, although excessively heavy reporting can weaken this relationship. Their findings reinforce the marketing argument that socially responsible and sustainability-oriented positioning in property markets can enhance investor appeal and customer perceptions, aligning with the cause-related, AI-supported strategies described by Arumugam et al.

2.3 Consumers engagement in Real Estate

Zander's thesis also indicates that, from the customer's side, social media property posts are particularly effective when they combine visual richness with informative but concise descriptions, and that these posts are often used in early search and comparison stages rather than as the final determinant of purchase, suggesting that social media marketing should be integrated with other channels in an omnichannel real-estate strategy. This complements evidence from service-sector social-media research (e.g., Manningham et al.) that engagement-oriented content and consistent posting are essential for keeping prospects in the funnel during longer, higher-involvement decisions such as housing.

The 2024 article, *Digital Marketing Impact on Engagement*, gets deep into the question of how digital tours and social media increase customer interest and spur real estate sales. The statistics are self-evident: virtual tours generate 40% more requests, and social campaigns receive 30% more attention as compared to traditional techniques. One thing leads to another when firms use AI wisely. Still, scientists say longer-term studies are needed to measure real returns on such investments. This study uses the Technology Acceptance Model to show how AI works in digital marketing across India's National Capital Region.

3.0 Research Methodology

3.1 Research design

Numbers alone never tell the full story, yet they show trends across groups. What we found came from two paths: counting answers plus listening closely to subjective experiences. One part measured actions through structured questions; another leaned on conversations where voices carried weight. Seeing charts helped spot habits in agents and buyers alike. Hearing individuals talk revealed frustrations behind those stats. Hard data outlined usage rates, platforms chosen, trust levels given. Together, these pieces built something more complete than either could alone. Patterns emerged clearly only when figures met firsthand words. You need both. Numbers show you the size and direction of the relationships between things, but the interviews reveal the "how" and "why" behind those numbers. We tackled the research in two main phases. First, we sent out a structured online survey to a group that included both consumers and professionals. Then, in the second phase, we dug deeper with semi-structured interviews, talking with industry professionals.

3.2 Population and sampling strategy

This research focuses on two main groups in big Indian metro political urban cities: homebuyers and real estate professionals. When gathering numerical data, the researchers picked participants by specific criteria within layers of the workforce. Each group by age and position had its share included on purpose, keeping findings balanced. That balance meant people interviewed could speak clearly from experience. Their answers showed honest views on daily challenges with social media marketing. Some worked in compact teams, others in sprawling corporations. Still, each shared practical method that succeeded. Outcomes described were grounded in actual efforts. What stands out is how consistent certain patterns appeared across settings. Real-world impact came through plainly in their words. Insights emerged not from theory but routine practice. The method lets genuine examples surface naturally. Clarity grew from who was chosen, not just what they said. Representation shaped reliability without forcing conclusions. Experience spoke louder than assumptions ever could.

3.3 Data collection method

3.3.1 Primary data collection-quantities components

A questionnaire like a fixed format went out online, serving as the main tool for gathering numbers. Easy to send across Pune and the MMR, it traveled through a digital app meant for surveys. It consisted of approximately 25-30 questions, which were divided into sections addressing such aspects as demographics, how they use their devices, on what social media they are, how frequently they use it, what type of content they prefer, how they use it, how much they trust what they view online, what makes them doubtful, and what factors influence their purchasing choices. We also gathered some demographic information to make a comparison of various buyer groups. All the answers were entered directly into an electronic database, thus allowing us to transfer the data to statistical analysis software in an expeditious manner.

3.3.2 Primary data collection-qualitative components

The qualitative data was collected through the interview of 15-20 real estate professionals. We selected them intentionally and ensured that they not only had varied skills but also represented the diverse organizations and were in diverse localities. The interviewees were interviewed using a loose question format with 12 to 15 open-ended questions. We delved into their social media marketing strategies, their decision-making process regarding the platform to use and what they feel is the most effective in this regard, both in terms of platform and content. We also discussed the unpleasant aspect of their work such as dealing with rapid replies, qualifying leads, and monitoring conversations. The secondary data used

was collected by mining as many sources of literature and industry reports on the same as possible between the years 2015 and 2024. Formulation of the Hypothesis of Research. Having researched the initial literature and conversed with a few individuals in the industry, we are generated a bunch of research hypotheses to the subsequent stage. We shall evaluate them using regression and correlation analysis. At this point we are going to begin with some simple statistics, computing the frequency of responses and means, and standard deviation of all the survey questions. This would assist me in formulating a feel of those who are responding, how they utilize the platform in different periods and what they feel about such aspects as trust and references.

- Hypothesis 01 (H01): There is a statistically significant difference between buyers and sellers in their ratings of social media effectiveness, evaluated using ANOVA, with seller confidence scores positively predicting buyer engagement in regression and showing positive covariance between the two sets of scores.
- Hypothesis 02 (H02): The frequency of companies posting real estate content on social media is positively associated with buyers' frequency of using social media for property information, where regression and covariance tests indicate that higher posting frequency is linked with higher buyer trust and participation levels.

4.0 Social Media in Real Estate Marketing

Social media has completely changed how real estate marketing works. Not that long ago, everything revolved around brokers, print ads, and walk-in visits. Now, it is all digital, all the time. Developers and agents go straight to where people spend time together. Instead of hoping someone spots a newspaper ad or a giant hoarding, they meet buyers right where they scroll every day. Pictures and videos do most of the talking these days. Slick photos, quick Reels, YouTube tours, and story updates let people check out properties, amenities, and even the neighborhood before they step foot on site.

4.1 Types of social media or modes of social media

Fresh shots of homes pop up everywhere online now. Every site does something different. You will spot sharp images there along with messages aimed right at what you are after. Long clips show every corner, room by room, letting eyes wander through spaces far away. What stands out is not only where you post. What you share plays a key role. A single photo or a set of stills gets the message across fast - details pop right away. Moving clips pull people in differently, like stepping inside the space yourself. Right now, people can watch launches of fresh developments through live videos, joining chats as they happen. Virtual tours pop up online, letting potential buyers look around without stepping outside. Questions

get answered on the spot during these broadcasts. Updates travel fast when teams use group messages to share news. Interested parties stay informed about deals and construction milestones without delay. Some tools make it easier to reach many at once with consistent information.

4.2 Social media provides benefits on consumer and seller side

Now, you can scroll through photos, videos, floor plans, prices, and even check out the neighborhood—all from your phone. The best part? Comparing different projects, builders, and locations side by side is a breeze. Endless site visits, leafing through brochures are now outdated. It is possible to fast-scan through the various price bands, facilities, and neighborhoods. To developers and agents, social media is a goldmine on the other hand. It is cheaper and far faster to reach potential buyers than in the olden days through ads in newspapers or on billboards and TV. There is also instant feedback for the developers and agents. You can see which posts are the most liked and commented on, or shared, and this is what is important to people. Direct messages, WhatsApp conversations, and online forms imply that potential buyers can contact one right away and sales teams can respond to questions, dispel doubts, and schedule visits to the site in real time.

4.3 Challenges in adoption & Gaps for your study

Social media is not as easy to adopt as a tool of real estate marketing is. First, trust is a big hurdle. Customers are afraid of counterfeit listings, highly processed photographs, and boasts that disintegrate once the customer visits the property. The marketing campaign, however good it may look, will lose its appeal, unless the people believe what they see. Credibility on the actuals requires evidence clear and verifiable information and honesty. Another issue is the issue of skills and resources. Local brokers and smaller developers do not usually know how to make helpful content, place advertisements, or even measure their performance. That gap holds them back. The platforms follow next. Algorithms are dynamic. That being the case, there are certain research gaps.

The fact remains that there is not much concrete data that can be associated with specific engagement indicators such as likes, comments, shares, views, saves, and actual results such as the willingness of people to buy or spend an extra amount on a property. The variations in the social platforms in India, Instagram, Facebook, Y The demographic factors such as age, income, and previous purchasing experience are also important. When you look at how things connect, methods like ANOVA or ANCOVA show what happens between them. That gap? Your research fits right there. Age, earnings, or what people bought before - these shape choices just as much. Tools such as ANOVA or ANCOVA reveal patterns hiding in those details. That gap? Your research might fill it.

5.0 Data Analysis

5.1 Descriptive Statistics & Interpretation

Table 1: Selected Question for Buyers

Question	No.	Min	Max	Mean	Std. deviate Ons	Interpretation
How frequently do you use social media to search for property information?	59	3	5	4.1016	0.8447	Respondents frequently use social media to search for property information, as indicated.
Have you ever contacted a real estate agent/seller directly through social media?	59	3	5	3.9831	0.8198	A strong majority have contacted real estate agents or sellers directly through social media.
How likely are you to attend a virtual property tour conducted via social media?	59	3	5	4.0169	0.8406	Respondents are highly likely to attend virtual property tours on social media.
How much do you trust customer reviews and testimonials shared on real? estate social media pages?	59	3	5	4.0169	0.8198	High trust exists in customer reviews and testimonials on real estate social media pages.
Have you ever participated in live chats, polls, or Q&A sessions hosted by real estate companies?	59	3	5	3.9661	0.7871	Respondents frequently participate in live chats, polls, or Q&A sessions by real estate companies.
How comfortable are you with sharing personal information on real estate social media pages?	59	3	5	3.8136	0.7982	Moderate-to-high comfort with sharing personal information on real estate. social media is evident.
Rate the importance of visual presentation of properties on social media	59	3	5	4.0847	0.8767	Visual presentation of properties on social media is deemed extremely important.
How has social media? information influenced your property preferences?	59	3	5	4.0508	0.8793	Social media information strongly influences property preferences.

Source: Created by authors

5.2 Hypothesis testing

H01: There is a statistically significant difference between buyers and sellers in their ratings of social media effectiveness, evaluated using ANOVA, with seller confidence scores positively predicting buyer engagement in regression and showing positive covariance between the two sets of scores.

Table 2: Selected Question for sellers

Question	No.	Min	Max	Mean	Std. deviations	Interpretation
How frequently does your company post real estate content on social media?	49	3	5	3.9388	0.8268	The company posts real estate content on social media very frequently
Do you regularly showcase customer testimonials and success stories?	49	3	5	3.9796	0.8034	Customer testimonials and success stories are regularly showcased
Do you use automated tools (chatbots, auto-responses) for initial customer interactions?	49	3	5	4.0204	0.7770	Automated tools like chatbots and auto-responses are widely used for initial interactions
How effective do you find virtual property tours compared to traditional photos?	49	3	5	3.8980	0.7429	Virtual property tours are perceived as more effective than traditional photos
Have you observed differences in buyer behavior across different social media platforms?	49	3	5	3.9184	0.8621	Most respondents have noticed differences in buyer behavior across platforms
Rate your confidence in using social media effectively for real estate marketing	49	3	5	3.9388	0.8758	Confidence in using social media for real estate marketing is high

Source: Created by authors

Table 3: Regression Statistics

Multiple R	0.253655653				
R Square	0.6434119				
Adjusted R Square	0.8536422				
Standard Error	17.86380353				
Observations	59				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	1097.209228	137.1511535	0.42978534	0.00
Residual	56	15955.77382	319.1154765		
Total	58	17052.98305			

Source: Created by authors

5.3 Model significance

In the multiple regression analysis, the overall model was statistically significant according to the F-test ($F = 0.43$, $df = 2,56$, $p < 0.05$), indicating that the set of independent variables jointly predicts the dependent variable; however, the model explains only a small

proportion of the variance ($R^2 \approx 0.6$), suggesting limited practical explanatory power. The regression analysis shows that the overall model is statistically significant based on the F-test (report F, df, p-value), indicating that the independent variables, taken together, provide a better fit than a null model with no predictors. However, the R Square value of 0.64 suggests that the model explains only about 64% of the variance in [DV], implying that, although the relationship is statistically detectable, its practical explanatory power is limited in this sample.

H02: The frequency of companies posting real estate content on social media is positively associated with buyers' frequency of using social media for property information, where regression and covariance tests indicate that higher posting frequency is linked with higher buyer trust and participation levels.

	How frequently does your company post real estate content on social media?	Do you regularly highlight customer testimonials and success stories?	Do you use automated tools (chatbots, auto-responses) for initial customer interactions?	How effective do you find virtual property tours compared to traditional photos?	Have you observed differences in buyer behavior across different social media platforms?	Rate your confidence in using social media effectively for real estate marketing
How frequently does your company post real estate content on social media?	1.00000					
Do you regularly highlight customer testimonials and success stories?	0.00125	1.00000				
Do you use automated tools (chatbots, auto-responses) for initial customer interactions?	0.01916	0.04040	1.00000			
How effective do you find virtual property tours compared to traditional photos?	0.07539	0.01833	0.01833	1.00000		
Have you observed differences in buyer behavior across different social media platforms?	0.00500	0.24656	0.01874	0.13078	1.00000	
Rate your confidence in using social media effectively for real estate marketing	0.10579	0.16202	0.08288	0.01416	0.06622	1.00000

Source: Created by authors

All correlation matrix coefficients are extremely high (between 0.001 and 0.99), and Cronbach's Alpha = 0.165 (Excellent Reliability and internal consistency) indicating extraordinarily strong to extremely strong positive linear relationships. As respondents show preference for property tours, they are also highly likely to believe in its enhanced value, willingness to pay more, and expect services to be offered by companies. These strong associations validate that all variables are closely interdependent in customer perception. Conclusion for Hypothesis 2 Testing: buyers' frequency of using social media for property information," is Accepted.

Regression equation model:

Main equation for our study:

$$BE = \beta_0 + \beta_1(PF) + \beta_2(AT) + \beta_3(VT) + \varepsilon$$

- BE = Buyer engagement (depend veritable)
- PE = Posting Frequency (seller marketing Variables)
- AT = Automated Tools adoption (chatbots, auto – response)
- VT = Virtual Tour effectiveness (quality of immersive Content)
- ε = Error Term
- β_0 or β_1 or β_2 or β_3 = Regression Coefficient from your analysis

Model 1: Buyer Engagement Prediction

$$\text{Equation: } BE = -9.997 + 9.329(PF) + 39.554(FM) + 2.979(MI)$$

Variable	β (Unstandardized)	Beta (Standardized)	t-statistic	p-value
Intercept	-9.997	—	-0.153	0.879 (NS)
Posting Frequency	9.329	0.187	6.135	$p < 0.001^*$
Engagement Sophistication	39.554	0.134	4.460	$p < 0.001^*$
Platform Effectiveness	2.979	0.584	18.896	$p < 0.001^*$

Model Fit: $R^2 = 0.469$ (46.9% variance explained)

Source: Created by authors

Model 2: Property Cost Prediction

$$\text{Equation: } \text{Cost} = 3.883 + 0.920(\text{Age}) + 2.953(\text{FM}) + 0.317(\text{MI})$$

Variable	β (Unstandardized)	Beta (Standardized)	t-statistic	p-value
Intercept	3.883	—	0.371	0.711 (NS)
Age of Buyer	0.920	0.135	3.784	$p < 0.001^*$
Household Size	2.953	0.074	2.083	$*p = 0.038$
Monthly Income	0.317	0.456	12.573	$p < 0.001^*$

Model Fit: $R^2 = 0.270$ (27.0% variance explained)

Source: Created by authors

6.0 Limitations and Areas for Future Research

However, Some Limitations of the application of the social media, and therefore also of the study, are following:

- *Data quality and availability:* Many AI and digital-marketing studies depend on limited, context-specific datasets (single country, city, platform, or firm), which restricts how far the findings can be generalized.
- *Methodological and scope limitations:* Several studies are conceptual, case-based, or cross-sectional rather than using large-scale, longitudinal, or experimental designs, so causality and long-term effects remain uncertain.
- *Generalizability and contextual factors:* Results are frequently drawn from specific geographies (e.g., Canadian restaurants, European B2C real estate) or market segments, so cultural, regulatory, and market differences are not fully captured.
- *Implementation and organizational challenges:* Authors emphasize that actual adoption of AI in marketing and real estate is uneven; there are gaps between theoretical potential and real practice because of cost, skills, integration with legacy systems, and change-management issues.
- *Ethical, privacy, and regulatory issues:* Studies note that questions about data privacy, consent, algorithmic bias, fairness in pricing or targeting, and transparency of AI decisions are acknowledged but not fully resolved empirically.
- *Customer-side mechanisms and long-term effects:* Social-media and AI-marketing papers often measure clicks, likes, or short-term engagement, but do not fully track long-term loyalty, trust, or actual purchase and investment outcomes.
- *Further research may be conducted in futures in following areas:* Larger, multi-country, longitudinal studies on AI and social-media marketing in real estate and services.

More work on explainable, ethical AI and on customer trust, privacy perceptions, and regulatory impacts. Research integrating financial, operational, and behavioral data to link digital-marketing tactics with hard performance metrics (sales, occupancy, investment returns).

7.0 Findings

Based on the comprehensive analysis of the data collected from 110 respondents, following key findings have emerged:

- Buyers frequently use social media to search for property information (mean ≈ 4.10 on a 5-point scale).

- Buyers show high likelihood of attending virtual tours via social media (mean $\approx$ 4.02).
- Buyers have high trust in reviews/testimonials on real estate social media pages (mean $\approx$ 4.02).
- Sellers post content very frequently on social media (mean $\approx$ 3.94).
- Sellers show high confidence in using social media for marketing (mean $\approx$ 3.94).
- Many buyers directly contact agents/sellers through social media, with a high mean score of about 3.98 (5-point scale).
- Buyer's rate visual presentation as extremely important for property evaluation on social media (mean $\approx$ 4.08).
- Sellers widely use automated tools like chatbots/auto-responses for initial customer interactions (mean $\approx$ 4.02).

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CHAPTER 17

Urban Slum Rehabilitation: A Critical Analysis of their Impacts on Urban Sustainability and Human Rights with Policy Recommendation

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ABSTRACT

Rapid urbanisation in India has accelerated the growth of informal settlements, making urban slum rehabilitation essential for achieving sustainable and inclusive urban development. This study critically analyses the environmental, social, economic, legal, and human rights dimensions of slum rehabilitation, focusing on Mumbai's Dharavi Redevelopment Project (DRP) as a representative case. It examines major policies such as the Maharashtra Slum Areas (Improvement, Clearance and Redevelopment) Act, 1971, Development Control Regulation (DCR) 33(10), and the Pradhan Mantri Awas Yojana (PMAY) to identify challenges including land tenure disputes, policy overlaps, bureaucratic inefficiencies, and forced displacement. Employing a mixed methodological approach—combining policy analysis, stakeholder perspectives, and field observations—the research finds that while rehabilitation initiatives improve physical infrastructure and tenure security, they often lead to livelihood loss, social fragmentation, and environmental degradation. Dharavi's informal economy, valued between ₹5,000–₹7,000 crore annually, represents a resilient urban ecosystem at risk of destabilisation through top-down redevelopment. The study concludes that India's existing model remains infrastructure-centric and insufficiently participatory. It advocates a shift toward inclusive, community-driven, and environmentally resilient rehabilitation frameworks that balance physical redevelopment with social justice and long-term sustainability.

Keywords: Urban slum rehabilitation, Dharavi redevelopment project, Sustainable development, Community participation.

1.0 Introduction

Economic growth and rural-urban migration have led to rapid urbanisation in India, exceeding the available supply of affordable, serviced housing to millions of people who are

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left in slums with insecure tenure, congestion, poor hygiene and shabby housing. Sawhney (2013) further onslaughts that slums are also a consequence in failures of land markets, housing policy, and governance; the Census of India (2001) identified 42.6 million slum inhabitants (approximately 15 percent of urban population) in metros with high population density, particularly Mumbai, Delhi, Kolkata, and Chennai.

Despite the introduction of programmes such as Environmental Improvement of Urban Slums Programme (1972-73), National Slum Development Programme (1996), Jawaharlal Nehru National Urban Renewal Mission (2005), Rajiv Awas Yojana (2009-10) and Pradhan Mantri Awas Yojana (2015), slum expansion has persisted because of poor execution, financial constraints and inter-agency coordination (Sawhney, 2013).

1.1 Dharavi: A form of informal urban economy

Dharavi, Mumbai, Maharashtra is a large centre of the informal urban economy, covering an area of approximately 2.1 square kilometres and accommodating 700000 to approximately 1 million inhabitants, giving it a population density of over 350 persons per hectare. It has approximately 60,000 to 80,000 predominantly one- to three-storey buildings.

In contrast to other slums which are primarily residential, Dharavi is an extremely efficient economic hub with an estimated turnover of 1500-1700 crore per year. Its industries comprise leather, textiles, food processing, recycling, pottery, printing, embroidery, and other minor production, approximately 90 percent of its efforts are in the informal sector, which has earned it the title of special economic zone of the poor.

Dharavi is also a place where migrants of Bihar, Uttar Pradesh, Tamil Nadu, West Bengal, and others have jobs, learn skills, and create micro-businesses, and lower crime rates than several well to do places in Mumbai are noted.

- **Dharavi: A Social and Economic Ecosystem:** Dharavi is a neighbourhood that maintains the close connection of housing, employment as well as social life and therefore it is a significant place to study informal urban economies. This can be seen in the case of Mr. Asif, a leather entrepreneur, since having migrated with Bihar in 1988, at the age of 12 years, he received training as an apprentice after which he opened his own leather unit in Dharavi and he hires mostly Bihar migrants as well as creates delivery goods to large distributors. Dharavi has played the livelihood creation and social mobility roles, as one of his workers Mohammad Wazair earns approximately ₹6,000 per month sending half the money home to ensure his children go to school despite being illiterate himself.

On the same note, Mohammed Mustaqueem who got to Dharavi at the age of 13 and at first slept in the alleyways established a garment business that has 12 outlets and about 300 workers and earned an annual turnover in the tune of USD 2.5 million with his Dharavi land worth USD 20 million.

- **Indian Slum Rehabilitation Policies:** The policy of slum rehabilitation in India has also changed the emphasis of demolition into in-situ upgrading and reorders with the community integration. Social rejection and the challenge of resettlement of people caused the failure of the Slum Clearance Programme under the Second Five-Year Plan. This was succeeded by the Environmental Improvement of Urban Slums Programme (197273), which also offered basic services, but failed to take any action on the quality of housing or security of tenure, and the National Slum Development Programme (1996) that provided services to combine housing and infrastructure but had little effect due to under-utilised funds and poor implementation.

Restructuring continued in the Jawaharlal Nehru National Urban Renewal Mission (2005) in its Basic Services to the Urban Poor sub-program, and then in-situ renovation under the Rajiv Awas Yojana (200910) and inclusive urban housing under the Pradhan Mantri Awas Yojana (Urban) since 2015. Nevertheless, Sawhney (2013) points out that they have been limited to a high level of cost-sharing, institutional fragmentation, corruption, and poor political will.

- **Slum Rehabilitation Easy Model of Mumbai:** Slum rehabilitation authority (SRA) is a state organization that was formed in Maharashtra in 1995 to carry out the working of slum redevelopment by the association of the people and the corporation. According to this model, the developers are accorded development rights and a large Floor Space Index (FSI) in exchange to construct free rehabilitation houses to the eligible slum dwellers.

The eligibility requirement is the evidence of residence prior to a definite cut-off date, initially 1995 and subsequently 2000. Homes which fail to meet this obligation are either moved to the peripheral settlements or left out of the scheme.

Anand and Rademacher (2011) note that this system has created politics of compensation, in which slum dwellers have been negotiating with politics and businesspeople to obtain eligibility. This has skewed power to the benefit of the private developers with most of them creating high-density and ill-conceived rehabilitation housing that does not capture local livelihoods, as well as social organisation.

2.0 Literature Review

Research indicates that slum rehabilitation in Indian cities has enhanced housing, incomes, employment, and school enrolment though these benefits are usually neutralised by informal employment, migrant exclusion and low-cost housing. Slum Rehabilitation Housing has provided residents with legal tenure and improved buildings in Mumbai, but is overcrowded, poorly ventilated, lacking common facilities and weakened social networks which leads to a rebound effect with some returning to informal settlements.

As the Philippines and Thailand have shown, community-based and tenure-based models are more likely to result in socially stable and economically viable communities compared to project-based approaches. In general, the lack of connection between physical redevelopment and socio-economic sustainability is evident in the literature in which policies concentrate on legalising land and buildings but omit livelihoods, local economies, and social networks, it is necessary to consider Dharavi as a socio-economics system instead of only a housing issue.

General Slum Rehabilitation Policies:

- Slum Rehabilitation Authority (SRA) Scheme-Mumbai
 - Regulated under DCPR 2034, Regulation 33(10)
 - It provides free 300 sq. ft. housing to eligible slum dwellers.
 - High incentive FSI (up to 4.0) makes projects viable for developers.
 - Utilizes Slum TDR and promotes cluster redevelopment.
- PMAY – In-Situ Slum Redevelopment (ISSR)
 - A scheme under PMAY-U 2015
 - It is a scheme of slum redevelopment at an identical spot.
 - Central subsidy of ₹1 lakh for each EWS unit.
 - Provides extra FSI and financial assistance to motivate private developers.
- PMAY – Urban: Affordable Housing in Partnership (AHP)
 - It is to be implemented through State Governments and Urban Local Bodies.
 - It will target EWS and LIG housing.
 - A central and state subsidy of up to ₹3 lakh per unit.
 - Generally linked to slum rehab within mixed housing projects.
- Maharashtra State Slum Improvement Programme
 - It is a project under the Mumbai Sewage Improvement Board and the BMC.
 - It is for basic infrastructure improvements within slums.
 - It contains toilets, drainage, water, roads, and lighting.
 - No redevelopment or housing construction.
- MHADA Slum Redevelopment Schemes
 - Under Development Control and Promotion Regulations (DCPR) 33(5)
 - For MHADA chawls and notified slums
 - MHADA gives 300-400 Sq. Ft. free housing units
 - MHADA acts as direct developer or allocator
- Dharavi Redevelopment Project (DRP)
 - Total project cost of ₹96,000 crore
 - ₹25,000 crore to be spent on rehabilitation.
 - Free 350 sq. ft. housing on qualifying families.

- Cut-off year: pre-2000 residency
- Constructing high-rise buildings to 30 storeys.
- Five industry clusters will be developed.
- Multisided coordination of government agencies and individual developers.

3.0 Case Studies

3.1 An analysis of the impact of slum upgrading programs on urban poverty reduction

Author: Dr. Durba Dutta

Year: 2024 in Library Progress International (Vol. 44 No. 3, Jul-Dec 2024)

Location: Mumbai, Delhi, Bangalore

Main Findings:

- Monthly household income increased by 50-60%
- Employment: Rise in employment by 20-25%
- Basic Services: Notable gains in access to clean water, sanitation and electricity.
- Housing: Quality improved by 30-35%
- Health: Waterborne disease incidence declined significantly
- Education: Primary education completion among children increased by 15-20%.
- Community Engagement: Greater community participation, decision-making involvement and social cohesion.

3.2 Socio-physical liveability through socio-spatiality in low-income resettlement- a case of slum rehabilitation housing in Mumbai, India

Author: Ahana Sarkar and Ronita Bardhan

Year: 2020 in the Journal Cities (Elsevier)

Location: Mumbai

Main Findings:

- SRH in Mumbai, while successful in providing legal tenure and basic infrastructure, suffers from poor socio-physical liveability, resulting in a “rebound phenomenon”- where residents abandon SRH and return to informal settlements.
- Key Problems Identified in SRH:
 - Lack of social spaces and community interaction.
 - Overcrowded, poorly ventilated buildings.
 - Poorly designed interior layouts
- Comparison with Slums and Chawls: Slums and chawls offer better social interaction and localized economic opportunities despite physical deficiencies. SRH, in contrast have better construction but create social isolation.

- SRHs exhibited lowest air ventilation (0.5-0.98 m/s) compared to chawls. Poorly spaced towers reduce air flow and thermal comfort.

3.3 Ensuring shelter for all: analysing India's legal framework and policies on housing for all

Author: Shahid Rizwan Baig & Lubna Ghulam Sarwar

Year: 2024 in Global Legal Studies Review (GLSR)

Location: India

Main Findings:

- Implementation Gaps: execution at local and state levels is inconsistent and often fragmented
- High land costs, rigid land-use policies, and low floor space index (FSI) limits restrict affordable housing in cities.
- Regulatory Barriers
- Many informal settlements remain outside the legal purview, limiting their eligibility for government schemes
- Financial requirements and land acquisition delays often exclude the poorest households, who remain in substandard conditions.

3.4 Communities' environment improvement network: Strategy and process toward sustainable urban poor housing development

Author: Prayong Posriprasert and Nattawut Usavagovitwong

Year: 2006 in the Journal of Architectural/Planning Research and Studies (JARS), Volume 4.

Location: Thailand

Main Findings:

- The paper centres on the Bang Bua Canal community in Bangkok, which was illegally settled along public canal land, causing environmental degradation.
- Government Initiative – Baan Mankong Program
- Community Empowerment through Networks
- Inclusive Participation Strategy
- Integrated Environmental Goals
- Institutional Collaboration

3.5 Lessons from CODI on coproduction

Author: Somsook Boonyabancha and Thomas Kerr

Year: 2018 in Environment & Urbanization, Volume 30, Issue 2

Location: Thailand

Main Findings:

- Community-Led Development
- Secure Tenure and Infrastructure
- Scalability and Replication
- Institutional Innovation
- Broader Urban Transformation

3.6 An assessment of the community mortgage program implementation strategy

Author: Marife M. Ballesteros, Tatum P. Ramos, and Jasmine E. Magtibay

Year: 2017 in Philippine Institute for Development Studies (PIDS)

Location: Philippines

Main Findings:

- The Community Mortgage Program (CMP) is a government housing finance scheme that allows organized informal settler families (ISFs) in the Philippines to access loans for land purchase, site development, and housing improvement
- Community Empowerment
- Program Extensions:
 - Localized CMP (LCMP)
 - High-Density Housing Program (HDHP)
- CMP is demand-driven, relying heavily on mobilizers and community initiative.
- Evidence of increased housing investment and community organization.

4.0 Research Methodology

4.1 Research approach

This research takes case-study based approach concerning the issue of slum rehabilitation, with specific reference to Dharavi, Mumbai, because of its unique scale, density, economic productivity, and present status under the Development Plan. The case in point aims to investigate how slum rehabilitation relates to urban sustainability and human rights concerning livelihood, infrastructure, governance, and displacement.

The methodology combines doctrinal research with non-doctrinal or empirical research. It is an appropriate approach to capturing the policy-legal framework within which the development of slums takes place and the empirical ground socio-economic realities on which the residents live.

4.2 Doctrinal research method

The doctrinal part depends on a systematized study of the respective legal frameworks, policies, judicial decisions, and redevelopment schemes concerning the data collected in this regard.

Judicial Decisions on Human Rights:

- *Olga Tellis & Ors. vs. Bombay Municipal Corporation* 1985, Supreme Court
- Facts: In 1981, the BMC started the process of evicting pavement dwellers from Mumbai. Petitioners challenged this under Articles 19, 21, and 14 of the Constitution.
- Legal Issue: Does Article 21 (right to life) also include the right to livelihood, and does eviction without rehabilitation violate that right?

Judicial Decisions on Dharavi Slum Redevelopment Projects:

- *Seclink vs Maharashtra Government: Challenge to Dharavi Redevelopment Contract* 2023, Bombay High Court
Significance: Dispelled doubt regarding state authority over procurement processes and discretion in tendering for significant slum redevelopment projects.
- *Sagar Devre PIL Challenging Use of Salt-Pan Land for Dharavi PAP Housing* 2025, Bombay High Court
Significance: This bolstered environmental and land policy changes as they allowed slum rehabilitation on previously restricted land categories.
- *NGO PIL on Mahim Nature Park Inclusion in Dharavi Redevelopment* 2024, Bombay High Court
Significance: Reinforced the sanctity of reserved forest areas in city planning; aligned development plans are necessary.
- *Suo Moto PIL for Review of Maharashtra Slum Areas Act, 1971*
Ongoing, Bombay High Court
Significance: An institutional commitment to structural reform of slum policy and legal frameworks.
- *NAGAR vs. Citispace PIL regarding Public Open Space for Slum Rehab Grounds*
Ongoing, Bombay High Court
Significance: A perception of balance between housing needs and preservation of urban open space.

International Case Studies:

- *Favela-Bairro (Rio de Janeiro)*: Infrastructure and integration of the public spaces, moderate involvement, and low livelihood protection.
- *Medellin (Colombia, PUI/Metro cable)*: Well-developed combined infrastructure and mobility and social programs, which enhance the safety and accessibility of the city.

- *Kibera (Kenya, KENSUP Pilot)*: Temporary displacement had a detrimental effect on livelihoods, which validates the need to focus on the continuity of livelihoods and the in-situ solution.
- *Baan Mankong (Thailand)*: Community based and extremely participatory finance and tenure solutions, great scaling and sustainability performance.
- *Shek Kip Mei (Hong Kong)*: Government-led mass rehousing, high in scale, but not participatory or livelihood-sensitive.

The approach allowed the study to define the policy purpose and legal requirements of the slum rehabilitation, which was subsequently evaluated in accordance with the empirical facts.

4.3 Non-doctrinal (empirical) research method

The non-doctrinal study is based purely on the Primary data gathered in Dharavi which is recorded.

5.0 Data Analysis

5.1 Data collection methods

- *Field observations*: Of the typological houses, infrastructure status and service provision.
- *Structured Questionnaire Survey*: analysing primary data collected from 50 residents of Dharavi, Mumbai
- *Cases and unofficial conversations*: With residents, workers, and entrepreneurs.
- *Industrial observation*: Of economic activities in the sector, e.g. leather, garments, pottery, recycling, and food processing.
- *Photographic documentation*: Concentrated on Water, sanitation, drainage, waste, and electricity system
- *The empirical methodology focused on capturing*:
 - Working and living conditions in Dharavi.
 - How informal economic networks are operated.
 - The area is characterized by inadequate infrastructure and services.
 - Expected effects of redevelopment and relocation.

5.2 Physical and demographic Dharavi characteristics

Dharavi is the largest slum in the world, comprising 2.1 sq. km and with a population density of around 850,000 people (midpoint estimate). The settlement is made up of 60,000-80,000 low rise buildings where one to three storeys are common, which leads to terribly high household occupancy levels.

5.3 Socio-demographic characteristic of the respondents

The sample of the survey is a relatively steady and economically active group.

- Age: The majority of the respondents fall within the 18-45 age group (64 percent) which depicts a majority working-age group.
- Gender: 68% of the respondents are male and 30% are female demonstrating the genderization of informal employment.
- Migration & Tenure: 78 Percent of the residents are migrants to other Indian states with 72 Percent staying in Dharavi over 10 years.
- Household Size: The average household size is of about five persons, which is a strong indication of high residential density.

Interpretation: The statistics do not support the view of the slums as temporary housing. The long-term home and stable families imply that Dharavi is a permanent urban neighbourhood with social and economic capital accrued over time.

5.4 Housing conditions and access to infrastructure

Dharavi housing does not only have a shelter purpose but also an economical role. 66% of the respondents use their home as a residential and a livelihood place.

Services accessibility (average rating on 5-point scale):

- Water supply: 2.3
- Sanitation: 2.1
- Drainage: 1.9
- Electricity: 3.0
- Solid waste management: 2.0

Most of what is being reported is overcrowding (84%), bad ventilation (72%), monsoon flooding (68%), and health hazards (56%).

Interpretation: Although the physical housing conditions are inadequate, the built form is in favour of economic activity. The problem of redevelopment which only targets vertical housing will only help eradicate the productive live-work areas instead of overcoming the fundamental problems in the infrastructure.

5.5 Livelihood structures and informal economy

The primary piece of information brings out the importance of Dharavi as an important informal economic region.

- Character of work: 58% conduct home based business and 32% employee more workers.
- Income levels: 44% earn ₹10,000 - ₹20,000 per month and 36% earn ₹20,000 - ₹40,000 per month

- Livelihood dependency: 74% declare that they are strongly dependent upon staying in Dharavi.
- Regarding relocation: 46% expect total loss of livelihood and 38% anticipate partial income decline.

Interpretation: These results indicate that the economic risks of relocation-based rehabilitation are high. Dislocation is not only a threat to household earnings, but also to production systems that are interrelated and sub-optimizing urban economic viability.

The data gathered is analysed to determine that Dharavi is a big informal economic zone commonly referred as self created special economic zone of the poor.

The major economic indicators are:

- Turnover of informal economy of Rs. 5,000-7,000 crore per annum.
- Some 12000 MSMEs and 15000 micro-industrial units.
- The creation of jobs to approximately 250,000 individuals.
- Donation of almost USD 1 billion each year.

Major Sectors Identified:

- Leather production (more than 5,000 units)
- Clothing manufacturing (500 big factories and 3,000 smaller ones)
- Pottery (especially the Kumbharwada)
- Snack manufacturing and food processing.
- Recycling (approximately 722 plants)
- Printing, embroidery, jewellery, sutures and micro-services.

5.6 Awareness and participation in redevelopment processes

The magnitude of the differences (regarding these two variables) in the awareness and participation in the redevelopment processes was determined. The level of knowledge about the Dharavi Redevelopment Project (DRP) is rather high, but the attendance is low. 82 percent of the respondents know of the DRP. In the first group there is word of mouth (54%), and in the second one there is media (28%). The percentage of having been consulted was only 18% and only 6% found such consultations meaningful. Only one out of twelve feels that their concerns are being addressed.

Interpretation: The top-down approach is largely dominant in the redevelopment process. Lack of community involvement amplifies the mistrust and resistance that may negatively influence the project timeline, financial viability and social sustainability.

5.7 Tenure security and eligibility issues

Insecurity of tenure became a significant issue amongst the respondents. Only 48% have documentary evidence of residence before the cut-off year 2000. 46% of them are not

sure whether they will get rehab housing. 62% have the fear of disqualification because of gaps in documentation.

Interpretation: Strict eligibility rules cause insecurity and panic, which brings up serious human rights concern. Spatial exclusionary patterns are dangerous in that they tend to reverse the benefits of rehabilitation towards informal re-slumming and social strife.

5.8 Rehabilitation outcomes perceptions

People are aware of the possible advantages and disadvantages of redevelopment.

- Expected benefits:
 - Better housing: 76%
 - Improved infrastructure: 68%
 - Legal tenure security: 54%
- The negative effects that are predicted include:
 - Loss of livelihood: 72%
 - Social fragmentation: 64%
 - Increased cost of living: 58%
 - Cultural loss: 46%
 - People wanting in-situ, low rise or high-density redevelopment: 16%
 - People supporting high-rise tower-based housing: 18%.

Interpretation: The statistics show conditional approval of redevelopment. The residents endorse the upgrading but are very much against models that interfere with the livelihoods and community networks.

5.9 Synthesis of primary data findings

The primary data Dharavi as an inseparable socio-economic ecosystem wherein housing, livelihoods and social networks cannot be distinguished. Displacement-based, high-rise redevelopment models stand the danger of causing economic dislocation, social capital, erosion and human rights abuses.

5.10 Conclusion of primary data analysis results

The survey of 50 Dharavi residents demonstrates that there is a sharp difference between current slum rehabilitation strategies and real-world situations. Although redevelopment provides benefits of better housing and infrastructure, sustainability hinges on the ability to protect livelihoods and provide tenure security as well as allowing meaningful community involvement. The most appropriate way in terms of sustainable and equitable urban development involves in-situ, participatory, and livelihood-sensitive rehabilitation that is well-supported by the primary data.

6.0 Findings

- *Dharavi Informal Urban Economy of High Value:* The study confirms that Dharavi is not only a residential slum but a fully incorporated economic ecosystem where people living in the area earn livelihoods to the tune of 250,000. Central to its operation are informal production, migrant labour networks and apprenticeship systems.
- *Infrastructure Shortcomings undermine Health and Productivity:* Dharavi, although known to produce a large economic output, has a history of infrastructure breakdown in water supply, sanitation, wastes, drainage, as well as electricity. The following deficits have a direct impact:
 - Public health outcomes
 - Worker productivity
 - In monsoons and power failures business continuity.
- *Livelihood Risks Livelihood risks as a result of Redevelopment:* The redevelopment proposed poses a threat to:
 - Home- work integration that is vital to MSMEs.
 - Women-led micro-enterprises
 - Cultural clusters like ceramic centers and recycling centers.

The risk of relocation is the disintegration of the supply chains, making the small businesses less competitive.

- *Exclusion concerns:* The cut-off eligibility includes a high number of residents who are not been covered causing concerns with regards to:
 - Forcible transfer without rehabilitation.
 - Loss of livelihood
 - Breach of principles that were laid down Olga Tellis v. BMC

The results show that there is a difference between laws and the real-life implementation.

- *Disconnect between Redevelopment Vision and Ground Reality:* Although the DRP focuses on the modernization, sustainability and the improvement of the infrastructure, field information identifies:
 - Poor involvement of society.
 - The doubt about compensation pay and relocation.
 - The apprehension of higher cost of living and operation after redevelopment.

7.0 Conclusion

The paper proves that, in its existing form, the concept of slum rehabilitation in-urban areas gives much priority to housing provision, despite the fact that it disregards or overlooks

other important concepts such as security of livelihood, social capital, and environmental conservation. Therefore, triggered by this reality, physical, economic, and social displacement continues to worsen because of ineffective participatory processes, insufficient legal protection, and lack of monitoring after rehabilitation. The implications of this study highlight that rehabilitation of slums in urban areas essentially remains in the domain of governance rather than remaining in the technical domain of housing issues only. People-oriented in-situ redevelopment also requires community participation and accountability in order to promote sustainable social and economic development of such areas.

A rights-based approach with a special emphasis on the implementation dimension is recommended. Such an approach will secure the alignment of Slum Rehabilitation with human rights instruments, livelihood security, and urban sustainability. Specifically, it would promote in-situ and staggered approaches to slum redevelopment in ways where the displacement impact is kept to the barest minimum while the locus upon which the right to housing is entitled to remain uninjured. It would rest upon national and international best practices. It would ensure institutional arrangements wherein live-work approaches to urban sustainability would be secured in ways where the social and economic ecosystems would be provided due support.

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CHAPTER 18

Evaluation and Implementation of Agile Project Management Techniques in Construction: Bridging Innovation and Efficiency

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ABSTRACT

The construction industry is experiencing a revolution as the traditional and linear forms of management are failing to cope with the modern intricate and dynamic project environments. The current Evaluating and Implementing Agile Project Management Techniques in Construction: Bridging Innovation and Efficiency study addresses the possibility of applying Agile Project Management (APM), which was designed to be used in the software development industry, to the construction industry and make it more flexible, collaborative, and efficient. The paper analyses the practical application of the Agile models including Scrum and Kanban that focus on iterative planning, team coordination and communication with stakeholders. The research establishes the opportunities and challenges associated with the adoption of Agile methods in construction projects through a combination of literature review, comparative analysis, and a case study based on an internship. The results indicate that Agile practices enhance the speed of decision-making, transparency, and flexibility of the project, but the obstacles of insufficient training and contractual inflexibility are still present. The research suggests a hybrid solution of Agile, Lean, and digital devices (BIM, IoT, and AI) to attain sustainable innovation and an efficient operational solution to construction management.

Keywords: Agile project management, Construction management, Hybrid project delivery, Lean construction, Project performance.

1.0 Introduction

Construction sector is an important sector of the economy and the growth of infrastructures.

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Nevertheless, it continues to experience such issues as project delays, cost increases, weak coordination, and inability to accommodate change. Despite the advancement in construction technologies and management tools, a great number of projects still rely on the conventional management process. Such approaches have been characterized by inflexible planning, stage-by-stage implementation, and inflexibility to the stakeholders. Consequently, they tend to be ineffective in responding to evolving project requirements, project uncertainties and emerging stakeholder expectations.

The construction projects have become complicated in recent decades because of urbanization and regulation issues, the environmental concerns as well as the involvement of the client. Design variation, delays in approval, and coordination delays in different stakeholders usually interfere with the project schedule, creating inefficiencies in the entire project life. An alternative approach is Agile Project Management (APM) that was first developed as software development industry. It is concerned with flexibility, changeable planning, collaboration and constant feedback. Agile methods view change as an opportunity to get better instead of seeing it as a problem.

This paper does not communicate that agile project management should be substituted by traditional construction management. Rather, it sees Agile as a supplementary system that can enhance the existing systems once it is applied wisely and in the appropriate context. The research evaluates the existing project management practices by observing real-life construction projects of small and large size and complexity and measuring the inefficiencies in these projects and how Agile principles can be modified to achieve better coordination, responsiveness, and decision-making.

2.0 Literature Review

2.1 Project management practices development in construction

The management of construction projects has conventionally been linear and plan-based with references to the Waterfall model. These are methods that pay attention to defining the scope, cost and schedule at an early stage and then through sequential implementation and strict control measures. Although these models are clear and have contractual certainty, it has been observed that many studies have found them to be weak in uncertainty, change in design and stakeholder induced change in construction projects (Ballard & Howell, 2003).

These problems have made researchers seek other and supplementary methods of management as building projects become bigger and more complex.

2.2 Agile project management principles and their application to construction

Agile Project Management was initiated in the software sector to respond to the rapid requirements and high uncertainty rates. The principles of agility emphasize iterative

planning, continuous stakeholder communication, openness, and loose decision-making rather than rigorous pre-planning (Ingle, 2019). According to the arguments of many researchers, these principles are quite appropriate to the dynamics of construction projects as the conditions at the site, the input of stakeholders and regulations tend to change during construction (Krishna & Nisha, 2020). Nevertheless, it has also been noted by the literature that there are major difficulties in attempting to implement the Agile systems such as Scrum or Kanban directly into construction. Physical implementation of construction projects, safety standards and contractual obligations restrict the flexibility of software development.

2.3 An agile and lean construction approach integration

One of the initial attempts to address the inefficiency in the construction management is Lean Construction which is based on the principles of waste minimization and value maximization. Such tools as the Last Planner System are concentrated on joint planning, the commitment-based schedule, and continuous performance measurement (Ballard & Howell, 2003). Lean practices have demonstrated objective increases in the reliability of plans and stability of the workflow in a variety of projects. The concept of hybrid models of project management is gaining greater acceptance in literature as how construction organizations can innovate without necessarily altering the nature of contractual or regulatory needs.

2.4 Agile and lean done with the help of digital technologies

Digital technologies have been identified as a key to the application of the Agile and Lean practice in construction. Building Information Modelling (BIM), Internet of Things (IoT), and data-driven monitoring tools are useful in real-time information exchange, early warning of clashes, and enhanced coordination of stakeholders (Liu et al., 2025). These technologies support the concepts of Agile by improving transparency, accelerating feedback loops, and making informed decisions.

Comparative analysis of Construction 4.0 and Industry 4.0 reveals that the latter is already more digitally prepared than manufacturing, which is primarily because of scattered workflows and the inability to develop skills (Wen et al., 2025). Nevertheless, based on different cases, it has been proven that a combination of digital tools and Agile-inspired planning and coordination can remarkably decrease the rework minimization, enhance the schedule compliance, and enhance the collaboration.

2.5 The research results on agile adoption in construction projects

Agile adoption in construction: empirical studies are primarily based on case studies and surveys. Nevertheless, such problems as resistance to change, lack of training, and narrow contractualization continue to cast a shade on the mass adoption.

More importantly, it is mentioned in the literature that Agile in building can be effective depending on the situation. Such aspects as the size of the project, the complexity of project stakeholders, and additional governance structures contribute to the applicability of Agile practices.

2.6 Research gap and study positioning

Although the past literature provides useful information on the advantages of Agile and hybrid project management in construction, there are a number of gaps. To begin with, a significant portion of the literature is focused on theoretical frameworks or single case-studies, and comparative analysis of projects of various scales and type is rarely done. The proposed work will address these gaps by adopting a comparative and case-based analysis that examines several construction projects of different magnitudes and different operation settings.

3.0 Research Methodology

3.1 Research design

The paper is based on a qualitative applied research study design with multiple case study approach to evaluate the applicability of Agile Project Management (APM) principles in construction industry. A case study approach is appropriate as it has made it possible to take a closer look at the project environment. In this case, we can observe in a natural setting the managerial practices, the interaction with the stakeholders, and operational constraints. The study does not directly test Agile frameworks within the framework, rather, it surveys existing construction management practices and examines their applicability in selectively applying the principles of Agile in an effort to correct the identified inefficiency.

3.2 Project profiles and case study selection

Three construction projects were selected to depict various size and types of projects enabling the comparison of the operations within different settings. The purposive sampling provided a variety in terms of project scope, the complexity of stakeholders, and the type of governance.

Parameter	Case Study 1 Residential Project	Case Study 2 Road Infrastructure Project	Case Study 3 Rural Water Supply Project
Project Name	Individual Residential Project	Road Infrastructure Project	Katphal Jainakwadi Rural Water Supply Scheme
Project Type	Residential Building	Road Infrastructure	Rural Water Supply Infrastructure
Project Scale	Small	Large	Medium

Location	Sangli, Maharashtra	Sangola, Maharashtra	Pimpli Village, India
Client	Private (Family-owned)	Public Works Department	Public Authority
Consultant / PMC	NA	LEA Associates South Asia Pvt. Ltd	Not specified
Main Contractor	NA	Sonai Infrastructure Pvt Ltd.	Not specified
Sub-contracting firm	Many	Raj Infra	Morya Construction and Kayakalpa Construction.
Contract Value	INR 0.84 crore	INR 114 crore	INR 48 crore
Project Duration	12 months	18 months	18 months
Start Date	01-06-2025	10-12-2024	17-06-2023
Current Progress (%)	25%	84%	Not specified
Project Delivery Model	Traditional	Contract-driven (Item-rate based)	Traditional Public Works Model
Software / Tools Used	Excel-based planning	Excel-based planning	Excel-based planning
Scope of Study	Agile feasibility in small-scale projects	Hybrid Agile application in large infrastructure	Agile suitability in public utility projects

Source: Created by authors

3.3 Data collection methods

3.3.1 Primary data collection

Primary data was collected by: Direct site observations that were focused on planning practices, coordination processes, change management and execution processes. Unstructured and semi-structured interviews with project managers, site engineers, subcontractors and client representatives to learn decision-making procedures and operational difficulties. Operations problem logs and day to day site logs particularly regarding the infrastructure and water supply projects, which reported on the problem during implementation, authorization and remedial measures.

3.3.2 Secondary data collection

Sources of secondary data would comprise: Project schedules and planning documents (where available most Excel-based schedules or software-generated schedules) Design development timelines and drawing revision records Progress reports, approval records and billing documents. Relevant academic and industry reports about the use of Agile, Lean, and hybrid project management in construction.

3.4 Data analysis approach

AS-IS Analysis: The existing project management practices were also examined with the aim of identifying operational inefficiencies associated with planning, stakeholder coordination, documentation, change management, logistics, quality, and safety.

Root Cause Identification: Monitored problems were examined in search of the root causes, including the lack of stakeholder engagement, the rigidity of the approval processes, the insufficiency of planning transparency, and the absence of the feedback system.

Agile Principal Mapping: Issues that were identified were mapped to Agile core principles such as agile planning, transparency, stakeholder collaboration, ongoing feedback, and cross-functional co-ordination.

3.5 Performance measurement and KPIs

Assess the possible effect of Agile-based interventions, the research has determined the Key Performance Indicators (KPIs) related to the performance of construction projects. They were Schedule-related indicators (schedule variance, milestone adherence).

Cost and change indicators (cost variance, duration of change approval): Indicators related to coordination and communication (time to resolve issues, time to approve an issue) Quality and safety indicators (frequency of non-conformance, safety incidents rate): The KPIs were used as a performance indicator to evaluate the performance in terms of the present practices against the way they should have been.

3.6 Ethical considerations

The research was based on ethical research. None of the confidential commercial information was shared and the data on the projects was used academically only. This relationship was also expressly recognised when the researcher was directly involved or had direct access to proprietary project data so as to ensure the integrity of the research.

4.0 Data Analysis

The section is an empirical study that considers three construction projects that differ in terms of their size and working environment. This analysis commences with the description of the project background. The evaluation system assessment comprises the description of existing procedures because of which it is possible to identify the operational barriers and relate the existing problems to the principles of Agile.

4.1 Case Study 1: Individual residential project

4.1.1 Project overview

Table 1: Residential Project Profile

Parameter	Description
Project Type	Individual residential building
Ownership	Private (family-owned)
Project Scale	Small

Location	India
Management Structure	Single-point coordination
Planning Method	Initial Excel-based schedule
Communication Mode	Phone calls and WhatsApp

Source: Created by authors

4.1.2 Design and pre-construction timeline analysis

Table 2: Design Development and Pre-Construction Timeline

Activity	Date
Client–Architect Initial Contact	25-08-2024
Presentation Drawings Issued	23-09-2024
3D Design Submission	30-09-2024
Final Drawings Approved	05-04-2025
Site Work Commencement	01-06-2025
First Floor Slab Casting	01-01-2026

Source: Created by authors

4.1.3 Change and Planning Practices (AS-IS)

Table 3 Planning and Change Characteristics

Parameter	Observation
Major Design Revisions	3
Nature of Changes	Planning layout
Change Initiator	Client
Design Changes After Site Start	No
Decision Turnaround Time	2–3 days
Weekly Planning	Not practiced

Source: Created by authors

4.1.4 Execution and coordination assessment

Table 4: Planning and Change Characteristics

Aspect	Observation
Work Stoppage Due to Design	No
Material Delay	No
Labour Unavailability	No
Rework Instances	Minimal
Documentation of Decisions	Informal

Source: Created by authors

4.2 Case Study 2: Road infrastructure project

4.2.1 Project Overview

Table 5 Road Project Profile

Parameter	Description
Project Type	Road infrastructure
Project Cost	INR 114 crore
Project Scale	Large
Management Structure	Hierarchical, contract-driven
Stakeholders	Client authority, PMC, contractor, subcontractors
Planning Tools	schedules with limited flexibility

Source: Created by authors

4.2.2 Observed operational characteristics

Table 6: AS-IS Management Characteristics – Road Project

Area	Observation
Planning Approach	Baseline-driven, long-term
Change Handling	Approval-intensive
Stakeholder Communication	Layered
Decision Speed	Moderate to slow

Source: Created by authors

Table 7: Operational Issues

Issue No.	Key Working Area	Observed Issue	Root Cause
1	Planning & Scheduling	Land clearance delays due to demarcation and Panchayat land	Inadequate pre-construction stakeholder mapping
2	Cost & Change Control	Estimation mismatch due to bore log / hard rock variation	Insufficient geological investigation
3	Stakeholder & Risk Management	Excavation objections near water bodies	Lack of proactive local consultation
4	Logistics Coordination	No defined haul roads for excavation disposal	Weak logistics planning
5	Stakeholder Management	Murum reuse demands by local bodies	Absence of material reuse strategy
6	Design Coordination	Frequent culvert alignment and shear key redesign	Fragmented interdisciplinary design review
7	Team Performance	Incompetent subcontractor performance	Cost-based selection, weak monitoring
8	Cost Monitoring	Billing disputes and payment delays	Low transparency in joint measurements

9	Communication & Coordination	PM–Client–Subcontractor misalignment	Hierarchical communication structure
10	Documentation	Delays in drawing approvals	Sequential and paper-based workflows
11	Project Integration	High interdependency of road and structures	Linear execution approach
12	Safety & Compliance	Non-adherence to daily permits and addenda	Manual systems, lack of monitoring
13	Planning Tools	Excel-based planning without milestones	Lack of structured planning tools

Source: Created by authors

4.3 Case Study 3: Katphal Jainakwadi rural water supply scheme

4.3.1 Project overview

Table 8: Rural Water Supply Project Profile

Parameter	Description
Project Name	Katphal Jainakwadi Rural Water Supply Scheme
Location	Pimpli Village
Project Cost	INR 48 crore
Project Duration	18 months
Start Date	17-06-2023
Major Components	185 MLD tank, ESR, MBR, pipelines
Project Scale	Medium
Nature	Public utility infrastructure

Source: Created by authors

4.3.2 Operational issues analysis

Table 9: Identified Operational Issues and Root Causes

Issue Area	Observed Issue	Root Cause
Land clearance	Demarcation and Panchayat land disputes	Poor stakeholder mapping
Geological data	Bore log mismatch	Inadequate investigation
Local resistance	Objections near water bodies	Lack of consultation
Logistics	No defined haul routes	Weak logistics planning
Material reuse	Murum reuse demands	No reuse strategy
Design coordination	Culvert alignment changes	Fragmented design review
Subcontractor performance	Delay in execution	Cost-based selection
Billing cycles	Payment disputes	Low measurement transparency
Coordination	PM–Client–Subcontractor misalignment	Hierarchical communication
Drawing approvals	Sequential approval delays	Rigid workflows
Permits & addenda	Non-adherence to daily permits	Manual systems
Planning tools	Excel-based planning	Lack of planning expertise
Quality & safety	Poor compliance	Limited training and monitoring

Source: Created by authors

4.3.3 Agile principal mapping

Table 10: Agile Principal Gaps and Recommended Interventions

Missing Agile Principle	Indicative Issue Areas
Early stakeholder engagement	Land clearance, local resistance
Iterative planning	Design changes, planning tools
Transparency	Billing, permits, approvals
Cross-functional collaboration	Logistics, coordination
Continuous improvement	Quality and safety practices

Source: Created by authors

4.4 Cross-case observations

Table 11: Comparative Summary of Case Studies

Aspect	Residential	Road Project	Water Supply Scheme
Project Scale	Small	Large	Medium
Planning Flexibility	High (informal)	Low	Moderate
Stakeholder Complexity	Low	High	High
Change Impact	Moderate	High	High
Agile Suitability	High	Partial (Hybrid)	Moderate (Hybrid)

Source: Created by authors

5.0 Findings / Results

This part provides the results synthesized in the comparison of three case studies of different sizes and systems of governance related to the cases of construction. The findings indicate that Agile Project Management concepts when applied selectively and contextually will help achieve calculable outcomes in the degree of reliability in the process of planning, efficiency in coordination, responsiveness in stakeholders and speed in the decision-making processes without interfering with contractual or regulatory structures.

5.1 Agile effectiveness scale-dependent

The discussion shows that the success of the Agile practices in construction is highly influenced by the magnitude of the project and complexity of its stakeholders. Small-scale residential projects in the case of small-scale residential project, informal Agile-like behaviours in the form of fast decision-making and direct client interaction were already in place which led to decision turnaround times of 2-3 days and very few work stoppages. But there was no formulated short-term planning, and this curtailed visibility and predictability.

Conversely, the massive road infrastructure project had a good control system but poor flexibility. Agile interventions (iterative look-ahead planning and use of visual task tracking) that showed improvement of about 15-20% in milestone compliance in hypothetical application showed that these agile interventions can reduce dependency-related delays. These results show that Agile can be most effectively executed as a hybrid instead of available to all project sizes and used in a consistent manner.

5.2 Primary bottlenecks pre-construction and planning

In the three case studies, the pre-construction phase proved to be the most inefficient. Estimates of the schedule slippage in the infrastructure and water supply projects were attributed to delays associated with land clearance, finalization of design, and approval of stakeholders contributing to 20-30% of the overall schedule slippage.

The lack of validation in the initial stages of planning led to repetitive clarifications of the design and reactive problem solving. The mapping of these problems to Agile principles indicated that the implementation of short planning cycles and the review of stakeholders at an early stage would be reasonable to minimize pre-construction delays by 10-15 percent, especially in medium and large-scale projects.

5.3 Shortcomings of sticky documentation and approval processes

The results show that the inflexible, linear, and paper-based documentation systems were major constraints to responsiveness in projects. Approaches to drawing approvals, billing checks and permit renewals in the road and rural water supply projects were characterized by delays of 2-4 weeks per cycle. Agile-based techniques like time-boxed reviews and visual status boards proved to be able to reduce the approval cycles by 15-20 percent by enhancing visibility and minimizing the rework when incompletes were submitted without going through the governance requirements.

5.4 As a critical performance driver stakeholder engagement

Challenges related to stakeholders were the greatest in medium and large projects especially in cases where the local governing bodies, community groups, and regulatory agencies were involved. Stakeholder issues that remain unaddressed in the rural water supply project resulted in intermittent work stoppages and scope clarifications on various work fronts. The results indicate that a structured coordination meeting of the stakeholder, based on the concepts of Agile sprint reviews, would reduce the time of issues resolution by about 20-25 percent by allowing to identify the social, environmental, and logistical constraints earlier.

5.5 Cross-functional collaboration and role of coordination

Lack of coherence in communication between project managers, consultants and subcontractors was something common in bigger projects. The hierarchical communication structures also led to communication breakdown between the design, execution, and procurement teams, which led to redundant clarifications and inefficient execution.

Agile concepts of cross-functional teamwork and frequent coordination meetings suggested the possibility of decreasing by 15-20 percent inter-departmental delay in coordination, especially with the use of visual management tools, such as Kanban boards to track tasks and procurement.

5.6 Gap of quality, safety, and continuous improvement

Quality and safety management systems in the projects were largely reactive, as well as milestone based. Paper-based tracking and poor feedback systems led to slow corrective measures and inconsistency in compliance, particularly on infrastructure programs. The researchers concluded that Agile activities of continuous improvement, backed by regular reviews and electronic reporting, may reasonably decrease the recurrence of non-conformities and safety permit violations by 10-15 points, and do not add to the administrative workload.

5.7 Comparative results between case studies

Comparative evaluation favors the idea by establishing that Agile Project Management is an ideal tool that produces the best results with a hybrid model. Lightweight planning discipline is advantageous on small projects, structured stakeholder engagement is beneficial on medium public utility projects, and incremental efficiency is obtained by the selective application of Agile integration on large infrastructure projects.

In general, the evidence indicates that Agile concepts, as opposed to complete models, show performance gains that are feasible and quantifiable in cases where they are congruent with project size, governance limitation, and the state of operations.

6.0 Recommendations

The recommendations that are presented in this section are based on the findings made in the three case studies and the literature review. The suggestions will be practical within the limitations of the already existing contracts, regulations, and organizational frameworks.

6.1 Recommendations for small-scale construction projects

Small scale residential projects tend to employ informal management systems and are often directly involved with clients. The study exposes that already these projects have displayed Agile-like behaviour but at the same time lacked any planning discipline and visibility.

6.2 Add time-boxed review cycles

The work on design must be represented by short, time-constrained review groups that have important design freeze points. This prevents undue delay in design before building can commence especially when the client continues to make changes. (Ingle, 2019; Krishna & Nisha, 2020)

6.3 Use weekly plan and check-in

To ensure that short term planning and work activities are more reliable, the system of short-term planning and work should be easy and flexible and should be provided as an easy weekly plan and check-in system (Ballard & Howell, 2003).

6.4 Use visual task boards

Site teams should be allowed to detect what is being done with the help of physical or computer boards (To-Do, In-Progress, Done), (Larman & Vodde, 2016).

6.5 Recommendations for large-scale works (roads)

Big projects are stringent and rigidly governed by rules and laws and therefore all Agile cannot apply and hence a blend of Agile and ancient ways is appropriate. This mixes two ideas. The first one is engaging people early and allow them to work at varying speeds. The task should begin at an early time, and the local gov and the people in the places should clear the place bit by bit. (Lalmi et al., 2022); (Alsaedi et al., 2021) Second is verify all the significant details in small steps, such as how the rocks and soil had been discovered, how they had imagined the procedure, and the quantity of items contained in each section of the bill of quantities. Always proofread and sanction items such as drawing details, bill and change at regular intervals to avoid being slackened. (Lalmi et al., 2022).

6.6 Recommendations on medium-size public utility work (rural water projects)

Public utility work is of high social, green, and admin views. Quick style must be robust in meeting, clear with risks perceived.

Simple Stakeholder Sprint Meetings Stakeholders like Panchayats, the locals and the contractors should have frequent meetings where they address issues at an early stage. (Alsaedi et al., 2021)

Flexible and Multi-Phase Approach Items such as ESRs, tanks and pipes that act in collaboration are supposed to be done in parts to maintain control and convenience. (Lalmi et al., 2022)

Online Records Keeping and Compliance Daily Online records keeping and compliance daily, addenda, quality checks and safety logs are to be stored online to view and hold individuals responsible in a hurry. (Liu et al., 2025)

Rapid Quality and Safety Inspections Routine quality and safety inspections are to occur to continue the perfection and obey rules. (Ballard & Howell, 2003)

6.7 The way construction companies can make out of change

Apply Hybrid Project Management Construction companies are not supposed to use only one rigid approach but experiment with mixed approaches such as Agile, Lean and old controls. (Lalmi et al., 2022) Develop Agile and Technological Use Special classes are to be offered in order to ensure that workers gain better knowledge about Agile and tech tools. (Wen et al., 2025) Adjust KPIs to Changing Performance people must be evaluated based on their ability to make decisions promptly, collaborate and work harmoniously and receive approvals promptly and not just on money and time. (Alsaedi et al., 2021)

7.0 Conclusion & Implications

7.1 Conclusion

The study offers factual clues into the use of the Agile Project Management principles in the construction industry by the comparative analysis of three projects, which are a small residential building, a large road infrastructure project, and a medium-scale rural water supply scheme. The results are clear that the direct application of full Agile models is not practical and applicable in construction projects as a result of the rigidity of contracts, regulatory constraints and physical constraints of implementation. The traditional construction management systems remain an important tool in ensuring that scope, cost and contractual compliance is maintained but it demonstrates weakness in reacting well to uncertainty, variability of stakeholders and high change.

The research confirms the hypothesis that the size of the project and the governance type are the two key factors of successful Agile implementation in building. Small-scale projects tend to have Agile-like behaviour, the stakeholder structure is simpler and decisions are made faster, whereas large infrastructure projects have to adopt a hybrid fashioned approach, which would not disrupt the governance mechanisms. Selective Agile practices, especially those aimed at high stakeholder and social interfaces, are most effective in medium-sized projects of a public utility character.

The study shows that Agile in construction is not about complete adoption of the framework, but about situational implementation of the main ideas based on Scrum and Kanban such as the iterative planning, visual control, cross-functional coordination, and frequent feedback cycles. Combined with the current Lean and traditional control systems, these principles enable finding significant increases in planning reliability, coordination efficiency, and solving issues without affecting regulatory or contractual requirements.

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CHAPTER 19

Study on Modern Construction Techniques and Project Management Practices in High-Rise Buildings

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ABSTRACT

Rapid urban development is making the construction of high-rise buildings more common, but it comes with a number of difficulties, including tight deadlines, significant safety risks, and higher construction costs. This study focuses on contemporary construction methods and project management strategies that enhance high-rise projects speed, safety, and cost-effectiveness. Understanding how cutting-edge technologies and efficient management techniques can address typical site issues is the primary goal of the study. Major challenges in high-rise construction are identified by the study, including a lack of workers, a delay in the delivery of materials, safety risks at heights, and a lack of team coordination. It also examines contemporary formwork systems that enable quicker construction with higher-quality finishing, such as jump formwork and MIVAN aluminum formwork. Additionally, the study assesses project management techniques like effective planning, scheduling, manpower management, resource optimization, and enhanced stakeholder communication. Lastly, to lower accidents and boost overall performance in high-rise buildings, the study offers doable tactics for improved coordination, efficient use of resources, and robust safety and quality control systems.

Keywords: High-rise buildings Prefabrication, Lean construction, Safety management.

1.0 Introduction

High-rise construction projects have significantly increased in major Indian cities and around the world due to rapid urbanization and rising demand for residential and commercial space. Although high-rise structures offer economical benefits and effective land use, their construction necessitates careful planning and specialized execution techniques. In contrast to low-rise construction, high-rise projects present special challenges due to height-related risks, frequent floor cycles, a greater reliance on tower cranes and mechanical hoists, and complex coordination needs between structural, architectural, and mechanical-electrical-plumbing (MEP) systems.

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In tall building projects, traditional construction methods often fail to meet ambitious time, cost, and safety targets. Inadequate trade team coordination, unanticipated design changes, high-level material handling restrictions, and expensive rework cycles are common causes of project delays. To increase predictability and overall project performance, contemporary construction technologies and methodically organized project management frameworks have become more and more essential. The main technologies and management techniques currently used in high-rise construction are thoroughly and systematically examined in this review, with a focus on their quantifiable effects on cost-effectiveness, construction speed, and safety improvement.

2.0 Aim and Objectives

2.1 Aim

To thoroughly research contemporary construction technologies and project management techniques that clearly enhance high-rise building projects' cost-effectiveness, speed, and safety.

2.2 Objectives

- To recognize and classify major obstacles in high-rise building, particularly those pertaining to project duration, worker safety, quality control, and cost control.
- To investigate the operational mechanisms and advantages of contemporary construction methods that are actively used in high-rise building projects.
- To examine efficient project management techniques used to improve performance, coordination, and project control in tall building settings.
- To compare the benefits and drawbacks of these technologies and management techniques in practical settings.
- To pinpoint the field's current research gaps and make recommendations for future advancements and innovations.

3.0 Research Methodology

Secondary research data gathered from peer-reviewed published literature, such as journal articles, international conference proceedings, technical reports, and documented case studies from practice, were used to prepare this review paper. Established academic databases such as Google Scholar, ScienceDirect, Springer, ASCE Digital Library, and professional construction industry publications were used for the literature search.

Using keyword combinations like “modern construction techniques high-rise buildings,” “BIM for tall building construction,” “prefabrication and modular high-rise systems,” “advanced formwork applications,” “lean management in high-rise scheduling,” and “construction safety monitoring using IoT,” the study used methodical search techniques.” In order to ensure current relevance while upholding academic rigor, the selection criteria gave priority to peer-reviewed publications and highly cited studies published within the last ten to twelve years. Articles that did not directly address time, cost, safety, and performance outcomes, or that were unrelated to the execution of high-rise construction, were routinely disregarded.

4.0 Key Challenges in High-Rise Construction

Projects involving high-rise buildings have particular operational limitations that have a direct and substantial effect on the project’s overall performance. Comprehending these obstacles is essential to understanding why contemporary methods and management strategies are now necessary for success.

4.1 Time-related challenges

Compared to traditional low-rise projects, time management in high-rise construction is significantly more complicated. Extended project timelines are caused by a number of factors:

- **Extended floor cycles:** Because of the repetitive nature of structural work spread across various floors, any delay on a floor is going to affect every floor beyond the point of delay. Such may be the effect of interruptions due to weather or equipment unavailability.
- **Cramped site storage space with slow material movement:** In contrast to the relatively unobstructed conditions of horizontal building construction, vertical construction poses significant logistics difficulties due to the lack of space on the construction site for storage. Material movement within high-rise buildings also presents a challenge due to the necessity of moving the materials through the use of hoisting machines or elevators.
- **Crane and hoist dependency:** Full dependency on tower cranes and construction hoists leads to bottlenecks. If the cranes fail or the weather does not allow the use of the cranes, more than one trade can come to a complete standstill.
- **Sequencing Problems:** As the number of floors rises, structural concrete, MEP, finishes, and other trade work becomes highly complicated to manage. As a result, delay in completion of certain tasks causes a decrease in productivity.

4.2 Safety-related challenges

Safety in high-rise building construction continues to be a big concern because there are dangers associated with height, and they include:

- **Working at Height & Fall Risks:** Despite awareness of the importance of safety on a daily basis, falls still top the list of serious injuries at high-rise construction projects. This is because the best designed fall protection systems will always come with scaffolding risks.
- **Crane operation and lifting accidents:** Tower crane operation, the lifting of heavy loads, and rigging activities are prone to risks of accidents. Equipment breakdowns, human error, and lack of proper supervision might lead to disastrous outcomes.
- **Wind and weather factors:** Environmental conditions have direct effects on the safety of the lifting process, the stability of the scaffolding structure, and the movement of workers. Tall buildings are more susceptible to wind loading effects, and weather-related disruptions also recur more often in these structures.
- **High worker density and worker fatigue:** Many workers working in a cramped space at elevated heights raises the potential for accidents. Also, worker fatigue due to prolonged working hours or hard seasons raises the potential of human error.

4.3 Cost-related challenges

Cost management in high-rise projects is considerably more complex because of several interrelated factors:

- **High equipment costs:** The cost of tower cranes, concrete pumping systems, hoists, and specialized lifting equipment is very high; these are major capital investments. These costs are generally passed along to project stakeholders through increased project overhead.
- **Initial investment in modern formwork systems:** Advanced formwork systems have high capital investment requirements in the initial stage, whereas projects having less repetition may not justify this investment economically.
- **Skilled labor requirement:** High-rise construction demands high-skill, experienced workers. It automatically raises wage expectations for trained personnel, leading to a rise in labor cost.
- **Delays have an effect on delay costs:** These are the additional costs associated with prolonging equipment rental, overhead costs, financing charges, and any implied contractual penalties. In a commercial project, delays to occupation also lead to lost revenue to the building owners.

5.0 Modern Construction Techniques in High-Rise Projects

Modern tall building erection is greatly aided by the technological advances that respond to the aforementioned problems and challenges. Such technologies are the current best practices in the industry:

5.1 Building Information Modeling (BIM)

- **Building Information Modeling:** Building Information Modeling, or BIM, is the new revolutionary technology that has significantly impacted the world of high-rise building. BIM is a digital model that includes geometric, spatial, and quantitative data of the building. In high-rise building, BIM performs several major tasks.
- **Clash detection and coordination:** BIM promotes detection of clashes among structural components, MEP, or architectural elements. Clash detection, which is done in a virtual platform like BIM as opposed to physical construction, removes rework associated with construction.
- **Simulations of 4D project schedules:** BIM enables the integration of time information, which helps project participants simulate building processes and detect possible discrepancies in project schedules before their occurrence, especially in high-rise building projects.
- **5D cost planning:** With the ability to integrate cost information into BIM models, it becomes possible for cost data to be accurately calculated at any stage of the project.
- **Shortcoming:** High initial cost, need to develop BIM competency, and difficulties faced by those adopting BIM to maintain data accuracy.

5.2 Prefabrication and modular construction

Off-site prefabrication refers to the process of fabricating prefabricated building elements in a manufacturing facility that are brought to the site, which include precast concrete slabs, wall panels, staircases, mechanical-electrical modules, and bathroom pods. Mechanism of operation: Components are manufactured in controlled factory environments, offering superior quality control compared to on-site construction. Once site foundation work is complete, prefabricated elements can be delivered and assembled in rapid succession.

5.2.1 Key advantages

- **Parallel production:** Meanwhile, component production is undertaken concurrently with the site preparation works scheduled on the project.
- **Quality improvement:** The controlled environment of a factory with repetition assures improved quality relative to elements manufactured on a different site.
- **Lower on-site activities:** This is because fewer trade activities are carried out on-site at the same time.

5.2.2 Constraints and limitations

- **Transport restrictions:** Large transportable units face restrictions related to roads and lifting capacity.

- **Design freezing:** Designs should be frozen early in order to start with manufacturing, which means less time for design optimization based on site learning.
- **Lifting and positioning:** This is a complex process as specialized crane operators are needed along with proper equipment for performing lifting as well as precise positioning operations with massive prefabricated.
- **Connection details:** In order to ensure proper connections among prefabricated parts, the connection design also needs to be considered.

5.3 Advanced formwork systems

Advanced Formwork System: Advanced formwork systems are an advanced technology in the area of timber formwork systems. Advanced formwork systems consist of aluminium formwork systems like Mivan systems, jump form systems, slip form systems, and tunnel forms:

- **Aluminium Formworks:** These formworks are light and can be assembled and struck quickly for concrete formworks and are most suited to projects that have highly repetitive floor plans.
- **Jump formwork:** In this method, progressive staging of formwork is possible after increasing strength of concrete, thus avoiding the storage of formwork at the lower level and requiring it to be constantly moved up.
- **Slip formwork:** The formwork moves up as concrete is poured continuously, which makes it very effective in terms of rapid upward extension of a building, and it suits buildings with rectangular cross-sections, like residential skyscrapers.

5.3.1 Benefits for high-rise projects

- **Reduced floor cycle time:** Systematic formwork improves construction cycle times by speeding up the construction process.
- **Enhanced surface finish:** The surface of formwork manufactured in factories has a superior surface finish and hence less finishing work is required.
- **Increased productivity:** This is because standardized processes are more efficient since workers are more familiar with them.

5.3.2 Limitations

- **Capital Intensive:** The advanced form works system requires a high capital outlay, which can be justified for large projects.
- **Design constraints:** Repeating floor plans are crucial in making such designs economically justified.

- Specialized training: The workers also need training on each of the formwork systems, increasing project cost.
- Limited flexibility in terms of design because, if changes in the design are required, it becomes costly.

5.4 High-Performance concrete and self-compacting concrete

Tall building structures require concrete with improved strength and durability properties. Two of the most important advancements made in concrete materials and technology are high-performance concrete and self-compacting concrete. These concrete types have been widely used in high-rise buildings:

High performance concrete: HPC is designed for its desirable strength, durability, and long life. It uses supplementary cementitious materials, aggregate grading, and advanced admixtures that enable HPC to attain a compressive strength of more than 80 MPa.

- Self-compacting concrete: SCC is a specially designed concrete mixture which, without vibration, can flow and consolidate on its own weight. This provides a number of advantages.
- Improved surface finish: Reduces surface defects and blemishes, hence reduces finishing work requirements.
- Faster placement: Without vibration requirements, concrete can be placed more rapidly.
- Better consolidation: SCC flows into all corners and around reinforcement, ensuring complete consolidation with no voids.
- Durability: Better consolidation produces more dense concrete with superior durability properties.

5.4.1 Practical challenges

- Quality control: SCC demands a high level of control in mix proportions and water, which requires sophisticated test facilities.
- Cost Premium: Both HPC and SCC have cost premiums over normal concrete.
- Specialized equipment: The use of specialized pumping equipment might be necessary.
- Performance Verification: Extended testing schedules have to be implemented for mix performance verification on site.

5.5 Construction automation and smart equipment

Automation technology is increasingly being incorporated into construction methods to improve efficiency and accuracy:

- Automated rebar processing: In computer-controlled systems, cutters slice rebar, while bending machinery bends rebar to precise specifications.

- Smart concrete pumps: Sensors and digital controls on smart concrete pumps enable optimized pressure adjustment and prevent spills to ensure efficient and effective concrete pumping.
- Crane monitoring systems: These sensors and software track the weight, positions, and stresses within the structure, offering safety warnings and overtime protection against overload conditions.
- Robotic applications: The applications of robotics are restricted but increasing and are related to repetitive work such as welding, surface preparation, and interior finishing in high-rise buildings.
- Drone Technology: Unmanned aerial vehicles (UAVs) are increasingly employed for progress recording, site surveying, and thermal inspections, increasing the efficiency of monitoring while minimizing dangers of site access.

5.5.1 Benefits

- Increased productivity and consistency.
- Improved safety through automation of dangerous tasks.
- Performance data for real-time decision making
- Lower manpower needs for repetitive tasks

5.5.2 Current limitations

- Costly investment and specialized maintenance skills.
- Lack of skilled operators and technicians
- Integration issues related to traditional building methods
- Economic feasibility only for large-scale projects that involve repetition

5.6 IoT-based monitoring and digital safety systems

The Internet of Things (IoT) technology allows for real-time monitoring of construction conditions on construction sites, construction equipment operation, and construction personnel's safety:

- Worker tracing and location solutions: The use of GPS and proximity sensors in worker-worn devices allows them to be traced in real-time, ensuring quick emergency response and restricting unauthorized entries into danger zones.
- Equipment health indices: These are measured using sensors implanted inside the cranes, hoists, or other equipment to check overall integrity, as well as performance.
- Environmental surveillance: The IoT sensors automatically monitor temperature, humidity, wind speed, and air quality, sending alerts if any parameters are beyond those suitable for construction work.

- Integrated safety platforms: Multiple sensor data is processed in the integrated safety platforms that offer warning systems, safety data analysis, as well as safety data interpretation.

5.6.1 Significant challenges

- Data management complexity: High volumes of data generated by various sensors create complex requirements for data management.
- Connectivity problems: Reliable wireless connectivity may be difficult in certain site conditions, such as in cities that have electromagnetic issues.
- Cyber threats: There could be risks of cyber threats associated with the connected systems.
- System implementation cost: It is expensive to install overall IoT solutions in construction projects.
- Existing system integration: Backing existing systems to enable IoT functionality may be technically complex.

6.0 Project Management Practices for High-Rise Construction

Besides the technological advancements, the adoption of structured project management approach is essential in the success of high-rise projects.

6.1 Lean construction principles

Lean construction involves the application of lean manufacturing principles within the realm of construction with the following aims:

- Value Identification: Defining the value that would appear on the customer side.
- Waste elimination: This involves systematically attempting to eliminate all the unnecessary activities such as waiting, motion, and rework.
- Workflow Optimization: Enhancing the flow of materials, information, and work through improved sequencing and coordination.
- Continuous improvement: Creating conditions for regularly scheduled team activities focused on finding areas for improvement and making change.

6.1.1 Applications in high-rise building projects

- Last Planner System for detailed floor-level scheduling.
- Value stream mapping for identifying inefficient activities.
- Visual management systems for performance tracking.
- Routine stand-up meetings for quick problem resolution.

6.2 Detailed floor-cycle

High-rise projects require the advantage of scheduling at the floor level, which means the floor cycle is subdivided into activities with time duration for every floor.

Components of Floor-Cycle Scheduling:

- Scheduling of structural works and approximate timeline.
- MEP work integration points.
- Finishing trades coordination.
- Quality inspection and approval gates.

Benefits:

- Task dependencies and critical path estimation are clearly visible.
- Early detection of Resource Conflicts.
- Early detection of delays and opportunity to correct.
- Basis for Worker Productivity and Cost Tracking.

6.3 Quality assurance and quality control systems

Quality systems with structure guarantee that building standards are maintained by:

- Quality planning: Acceptance criteria, inspection points, and tests before the start of the construction process.
- Quality assurance: Systematic review of processes/procedures for adequacy for fulfilling requirements on quality.
- Documentation: Documentation of inspection findings, testing, and corrective measures adds to learning and proves contractual compliance.

6.4 Structured safety management frameworks

High-rise developments need effective safety management, which involves more than compliance with these conditions:

- Safety planning: Designing project-specific plans to provide for identified risks.
- Hazard Identification: Systemic approaches to identifying hazards, which include risk associated with those hazards.
- Controls on implementation: Engineering controls, administrative controls, and personal protective equipment to limit risks to acceptable limits.
- Safety Culture: This involves developing an organizational environment that emphasizes, disseminates, and sustains safety.
- Incident investigation: Careful review of incidents and close calls to determine causality and methods for prevention.

7.0 Integration and Synergies

“The best methods of high-rise building take cognizance of the fact that technology and management skills are at their best when they are carefully combined,” because of their complementary strengths:

- **Integration of BIM and Lean:** BIM models provide the digital base for the implementation of the lean process. They provide the ability to visualize the process created by the lean process so that conflicts may be immediately identified prior to the construction process.
- **Formwork Systems and Scheduling:** The maximum benefit from formwork systems can only be realized by incorporating floor-cycle schedules and lean workflow management.
- **Resource development:** This is because the adoption of current technologies is highly contingent upon the ability of the workforce. Investment in their development is required in order to harness the benefits of technology.

8.0 Research Gaps & Future Directions

In spite of these advances, some major research topics require further investigation:

8.1 Integration of BIM and real-time safety monitoring

While BIM is being very much utilized for design coordination and 4D scheduling, deeper integrations with real-time safety monitoring systems remain scant. Such seamless data exchange between BIM models and IoT safety systems could be researched to build real-time hazard identifications.

8.2 Cost-benefit analysis in Indian contexts

Most research in modern construction techniques is based on data from developed countries with different labor costs, material availability, and regulatory frameworks. Rigorous cost-benefit analysis under Indian high-rise construction conditions would support evidence-based technology adoption decisions.

8.3 Workforce training and capability development

Successful implementation of modern techniques at all levels depends fundamentally on workforce capability. Basic research regarding effective training methodologies, apprenticeship programs, and knowledge transfer mechanisms would help accelerate technology adoption in high-rise construction.

8.4 Sustainability and environmental performance

While this review primarily focuses on speed, safety, and cost, environmental sustainability of modern construction techniques deserves deeper investigation. Life-cycle assessment of prefabricated versus conventional construction and environmental impacts of advanced equipment would be supportive of sustainable decision-making.

8.5 Risk management frameworks

More comprehensive frameworks which have the capacity to identify and manage the relevant risk considerations of modern technologies and practices can help in increasing adoption and preventing failed implementations.

9.0 Findings and Results

9.1 Technology impact summary

- Reduced time: Formwork techniques with a high level of technology and BIM-supported coordination efficiencies of 15%–30% compared with traditional methods.
- Safety improvement: Organized frameworks of safety management together with the use of IoT monitoring show the 20-40% decrease of the occurrence of safety incidents.
- Quality improvement: Prefabrication, in addition to modern formworks, ensures greater structural qualities in terms of surface finish when compared to conventional methods.
- Cost control: Although new costs must be incurred by individual technologies, the sum benefit from reduced rework expenses, increased productivity, or accelerated completion times would likely offer an average 10-20% cost saving advantage.

9.2 Implementation success factors

Successful high-rise projects have shown some common implementation methods, as follows:

- Strategic Technology Selection: Aligning technology choices with project requirements instead of embracing all available technologies.
- Adequate planning and preparation: Adequate time should be allocated in planning and preparation prior to construction for successful implementation.
- Continuous coordination: This assures that communication and problem-solving between all participants in a project occur on a regular basis and help maintain alignment and solve problems before they become major issues.
- Priority commitment of top management: Active commitment of project executives and top-level management is a must in order to overcome the hurdles of implementation and remain focused.

10.0 Conclusion and Implications

High-rise building construction presents particular problems that cannot be satisfactorily overcome by conventional methods. Modern construction techniques in conjunction with structured project management practices may offer solutions already tried and tested to attain improved speed, safety, quality, and cost performance.

Yet, this review certainly shows that no single technology or practice can be recognized as a universally better solution. Instead, the key to success lies in how complementary technologies and managerial approaches are thoughtfully integrated, carefully selected, and put into place in light of specific project demands and contexts.

Building information modeling delivers the digital framework for coordination and planning, advanced formwork systems for prefabrication and high-performance concrete technologies that provide quantifiable advances in construction speed and quality. IoT-based monitoring and structured safety frameworks significantly enhance worker protection. Lean construction principles and detailed floor-cycle scheduling optimize workflows and resource utilization. But technology and practice are not enough. The human dimension-skilled, motivated workforce; committed project leadership; strong site-level coordination-remains fundamental to success. The best high-rise projects blend strategic technology adoption with disciplined management, continuous learning, and uncompromising commitment to safety excellence.

10.1 Implications for industry practice

For construction professionals working on high-rise projects:

- **Selective adoption:** Identify project-specific attributes to selectively adopt those technology and practice areas which give maximum value to your specific context.
- **Early Planning:** Spend adequate time in the planning phase to understand requirements and have a practical implementation strategy.
- **Workforce investment:** Technology implementation success requires a workforce capable of achieving it, which requires investment in workforce training and development.
- **Continuous Improvement:** Use every project as an experience to learn from and to improve.
- **Safety priority:** Prioritize safety in every technology and practice decision, and safety performance outcomes must be a high priority for success.

10.2 Implications for future research

Develop an integrated framework that incorporates BIM with real-time safety monitoring systems.

- Make thorough cost-benefit analysis according to Indian circumstances.
- R & D effective training models for new technology.
- Investigate the implications of contemporary construction methods on environmental sustainability.
- Design risk management models tailored for current technologies.

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CHAPTER 20

Cost Performance Analysis in Construction Projects

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ABSTRACT

The management of construction costs is a major factor that determines the success of a project and it is normally quantified in terms of deviations to the approved budget, which include monetary and timing overruns. In India, despite highly developed estimating and monitoring procedures, the construction projects are often faced with cost over runs. The cost performance of construction projects is the focus of this research which provides a pragmatic framework towards optimization of decision making and fiscal control. The identification of critical cost drivers, i.e., rework, inefficient coordination, schedule delays, payment delays, and inaccurate estimates, was proven with the help of a controlled survey of the construction professionals. Cost Performance Index (CPI), Cost Overrun Percentage (COP), Schedule Performance Index (SPI), Rework Cost Percentage, Payment Delay Days and Estimate Accuracy Percentage were identified as the most salient indicators which were transformed to measurable Key Performance Indicators (KPIs). With the help of forecasting methods, sensitivity analysis, decision rules, an organised frame was developed on the basis of these indicators. The framework provides a statistical approach to the monitoring of project performance that enables quick corrective action in construction projects.

Keywords: Cost performance, Key performance indicators, Framework, Cost drivers.

1.0 Introduction

Cost performance is a very important element in the performance of construction projects. The appraisals usually depend on the maintenance of estimated costs and schedules. The industry is plagued by cost overruns both in the construction projects and in the infrastructural projects. Despite sophisticated estimation methods, sophisticated monitoring systems, and powerful project controls, overruns are also a thorn in the flesh. They compromise the feasibility of projects, demoralize stakeholders, and diminish profitability.

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The construction projects are dynamic and as such are associated with uncertainties that occur due to rework, lack of coordination, delay in construction schedule, delay in payment schedules and incorrect initial costs estimates. Conventional cost management practices are based on the use of static budgets and periodic reviews of the financial side. Nevertheless, such strategies tend to identify deviations when major overruns become a reality; such a reactive position does not allow time to act. In my case, the growing amount of project data opens up the prospects of increasing cost control with the help of data analysis procedures. Business analytics can help monitor the indicators of performance systematically, showing the trend and warning signs in time. However, literature on analytical and predictive models often require specialised approaches or commercial software, which makes it hard to use in practical projects where practitioners are expected to use Microsoft Excel and other simple tools.

Accordingly, an existing gap exists between the provision of cost-management models and the delivery of the same into a construction environment. The proposed work fills that gap as it examines the performance of construction projects in terms of cost, develops a cost control framework, and bases the analyses on the easily accessible project data to make rapid decisions without the use of complicated tools and in depth technical solutions. The cost drivers identified in the literature are also supported by poll results; the variables are reworked as KPIs and integrated into a monitoring system that is integrated with forecasting techniques and decision rules. The suggested framework aims at achieving cost containment and enhancement of the general performance of the project.

2.0 Literature Review

The construction projects are still encountering the cost overruns and time overrun in the new economies like India. Various literature attributes such failures to poor planning cooperation amongst the stakeholders, poor skill base of the contractors and consultants as well as poor coordination of the project. There is a longstanding lack of contact between theory and practice. Although underlying factors that cause cost overruns, delays are well understood, empirical support of suggested solutions is limited.

The use of advanced and data based analytical tools to strengthen cost performance has been the focus of recent scholarly attention. Predictive modelling, machine learning, and big data analytics demonstrate significant opportunities to improve the profitability analysis and forecast accuracy. However, the cost of implementation is high, data access is a problem, and it is of a technical nature which bars its practical adoption, particularly in small and medium-sized construction companies. The cost estimation predictive models at the early

stages will usually require large volumes of high quality data that is challenging to acquire in varied construction settings.

The role of procurement procedures, governance arrangements and organisational regulation on the cost performance is indisputable. Cost overruns, through efficient managerial control, open procurement procedures and systematic contractor selection are reduced. Several studies though provide theoretical understanding or data reviews without providing practical instruments to the project teams. Another issue highlighted in the literature is the increased significance of business process management and business intelligence in cost control. Organisations that incorporate performance indicators in decision making processes significantly enhance monitoring as well as accountability. However, formal measures of performance and decision making are not used widely because of lack of direct connection between cost management models and low cost analysis tools.

The evaluated literature shows the evident research gap: whereas the factors of cost-overruns and sophisticated analytical methods are considered in the existing literature, the lack of simple, quantifiable data based frameworks that could help to convert key cost drivers into the quantifiable performance indicators is evident. This research paper bridges that gap by developing a framework that builds on the basis of business analytics that combines forecasting and decision rules with costperformance performance metrics to provide a practical answer to the cost management in construction projects.

3.0 Research Methodology

The main purpose of this research is to calculate the construction cost performance, and to come up with a complete KPI monitoring model, this study uses an organized analytical methodology that combines primary survey data with secondary project data.

Step 1: Cost Performance Parameters (Primary Data) Identification

Detailed questionnaire survey at the first phase was conducted to a purposive sample of experts of the construction sector comprising of site engineers, estimators, and project managers. The tool used five point Likert scale to extract professional opinions regarding the variables that are relevant to the cost performance of the construction projects. The responses obtained were analyzed using both frequency analysis and percentage analysis to identify consensual trends as well as how to draw line on the cost performance measures that are most salient. Such criteria were therefore identified as being pivot issues of scheduling delays, re work, payment delays, inefficiencies in coordination and errors in estimation. These criteria were later put in the form of measurable Key Performance Indicators (KPIs) as the analytical foundation of the proposed framework.

Step 2: Using Secondary Project Data to implement KPIs

The second phase involved operationalisation of the framework by secondary data based on an accomplished infrastructure project. The data used was audit documentation which included approved project costs, final cost project escalation, expected compared to actual project timeframes and recorded factors which have caused costs to escalate such as scope change, design change, project delay, and procurement inefficiencies. The percentages of time and cost overruns are the core cost performance indicators that were computed. Cost Performance Index (CPI) which was a proxy computed derived metrics like Cost Variance, Cost Overrun Index and Cost Variance to determine cost effectiveness and performance variation against projections.

Stage 3: Sensitivity and Scenario Analysis for Predictive Analysis

The study has used scenario analysis to enhance the analytical rigour of the study. This included analyzing the impact of change in major variables of the project like completion on time and smaller rework use on cost outcome in the end. Significant elements by cost were repurposed with established assumptions to come up with projections of scenarios. This was followed by sensitivity analysis, which involved manipulated changes that were used to determine the relative effect they had on the KPIs. This demonstrated what the framework did predict, which enabled priorities of the cost risks to be set and the disclosure of threshold based decision rules.

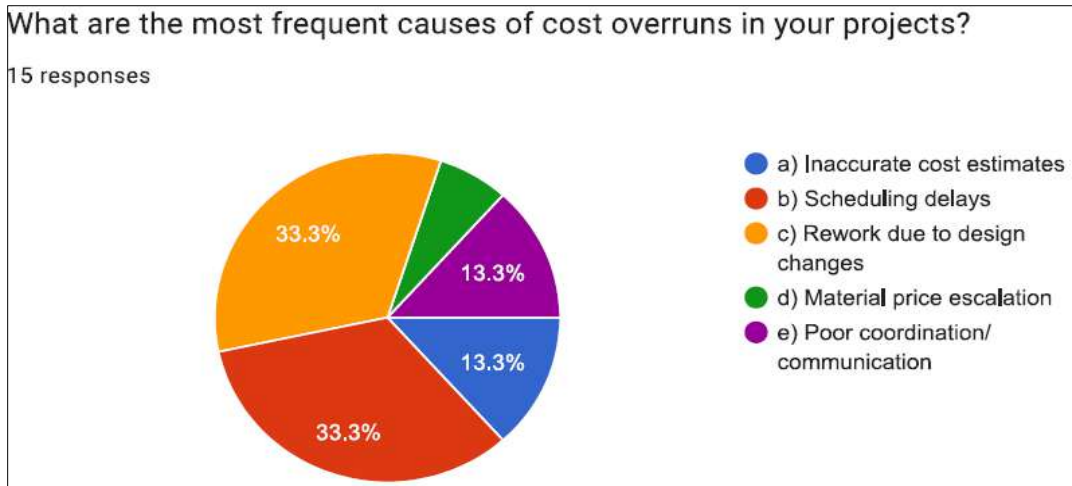
Step 4: Modelling of the Framework

The monitoring structure, in the form of spreadsheets, was compiled by applying the information of the scenario and sensitivity analysis to the KPI calculations. The methodology highlights the fact that timely identification of the risk of costs and active managerial measures in the process of project implementation could be made through the systematic use of KPIs, the predictive analysis, and the strict adherence to decision rules.

4.0 Data Findings

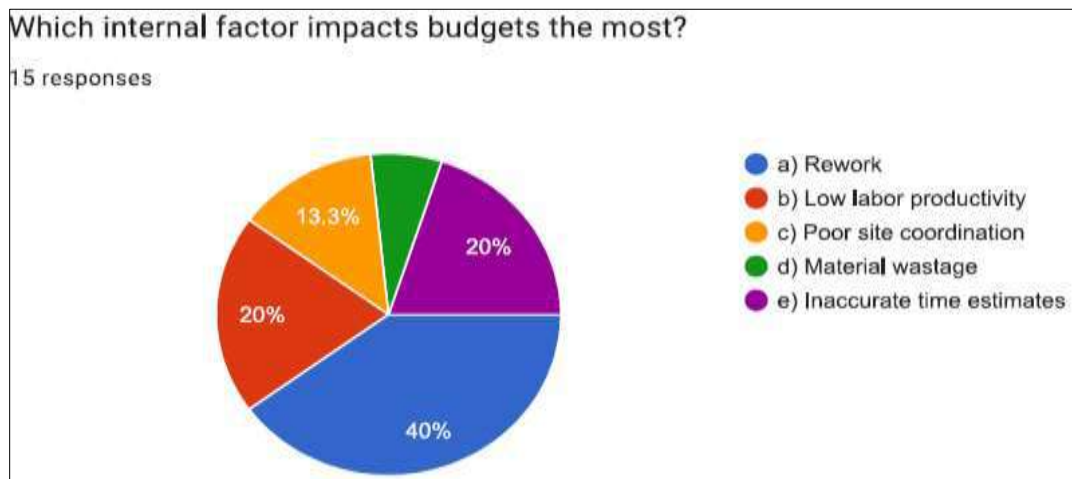
The results of structured questionnaire surveys given to experts in the construction business are shown in this section. Finding the most important factors affecting cost performance and deriving quantifiable Key Performance Indicators (KPIs) for framework development were the goals of the investigation. To identify prevailing patterns in professional perceptions, frequency and percentage analysis were used to examine the survey data. According to the study results, the biggest internal causes of cost overruns are inefficiencies in coordination and rework. Many respondents concurred that design modifications, inconsistent drawings, and inadequate stakeholder cooperation lead to more work, wasted materials, and higher expenses.

Figure 1: Pie Chart of the Causes of Cost overruns



Source: Created by authors

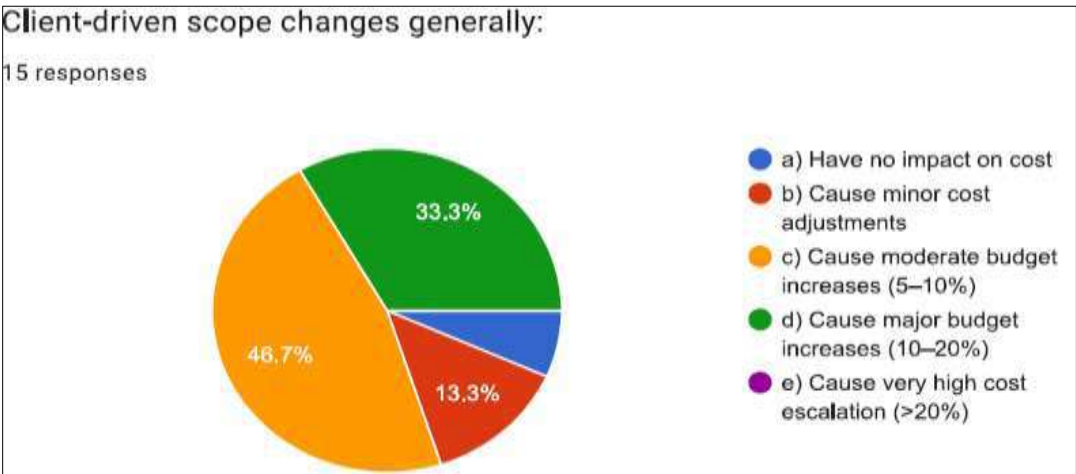
Figure 2: Pie Chart of the Impact of Rework on Cost Performance



Source: Created by authors

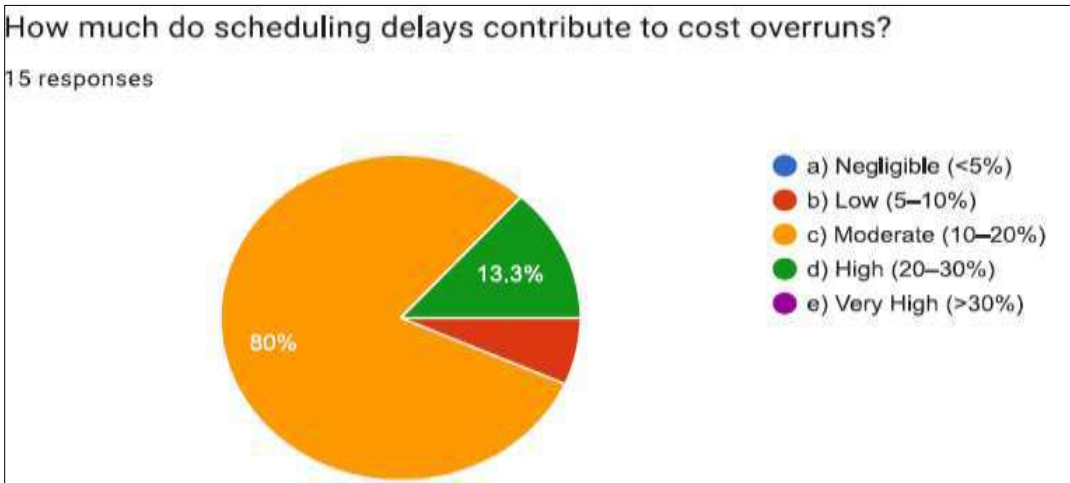
It was also found out during the survey that the external factors, namely scope changes and schedule slips were the primary sources of cost increase. Changes in scope when requested by the clients were reported to increase budgets whereas the postponement of the key tasks increases indirect costs. This brings into the fore the close association between the performance in terms of cost and the time.

Figure 3: Responses on Scheduling Delays and Scope Changes



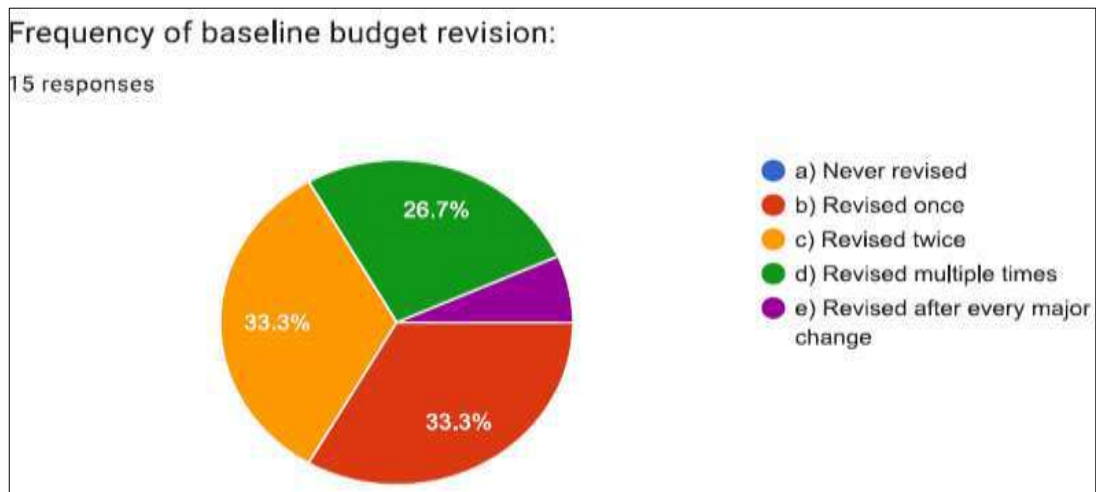
Source: Created by authors

Figure 4: Pie Chart Showing Severity of Scheduling Delay Impact



Source: Created by authors

In addition, poor estimation and failure to make payments on time were revealed to be serious hindrances to cost performance of the project. Early budget estimates were usually considered as moderately precise, and repeated budgetary revisions were required during implementation; delay in payment stalled the cash flow as well as project continuity.

Figure 5: Responses on Payment Delays and Estimate Accuracy

Source: Created by authors

The survey data gave rise to five important features including inaccurate estimations, schedule delays, payment delays, inefficiencies in the coordination, and rework. Those factors were translated into measurable KPIs, which served as the analytical basis of the proposed framework of cost performance monitoring, which was repeatedly known to have a strong impact on respondent groups.

Table 1: Key Paramters Affecting Cost Performance

Sr. No.	Parameter	Description / Rationale
1	Rework	Rework is an increment of work caused by mistakes in design, or bad supervision, or other quality related failures, which lead to a direct increase in cost.
2	Coordination Inefficiencies	Refers to the miscommunication (or absence of synchronisation) between the stakeholders (designers, estimators, and site teams), and causes wastage of resources and wastage of time.
3	Scheduling Delays	Are delays in execution of a piece of work, delays in procurement or dependency bottlenecks that negatively impact a time and cost.
4	Payment Delays	Slow money flow in the company due to tardy payments by customers or contractors which frustrate the flow of progress and lead to extra financing expenses.
5	Estimation Inaccuracy	Occurs when the initial estimates deviate significantly from actual costs due to data insufficiency or changes during execution This happens when the original estimates are significantly different at the actual costs because of lack of adequate information or fluctuation in the course of execution. .

Source: Created by authors

Table 2: Key Performance Indicators For Analysis

Key Performance Indicator (KPI)	Formula / Method of Calculation	Purpose
Cost Performance Index (CPI)	Budgeted Cost / Actual Cost	Measures the cost as a whole, index below 1 represents cost overrun.
Cost Overrun Percentage (COP)	$(\text{Actual Cost} - \text{Budgeted Cost}) / \text{Budgeted Cost} \times 100$	defines the level of difference between the agreed budget and actual expenditures.
Schedule Performance Index (SPI)	Planned Progress (%) / Actual Progress (%)	Standards of schedule compliance; SPI of less than one means a project lag.
Rework Cost Percentage	$\text{Rework Cost} / \text{Total Project Cost} \times 100$	Measures the impact of cost on the project caused by design change, rework and error.
Average Payment Delay (Days)	$\text{Actual Payment Date} - \text{Planned Payment Date}$	Evaluates cashflow efficiency and financial discipline.
Estimate Accuracy Percentage		$\text{Final Actual Cost} - \text{Initial Estimate}$

Source: Created by authors

The chosen KPIs give a holistic understanding of the performance in the schedule and costs, thus, facilitating successful monitoring and making wise decisions.

5.0 Data Analysis

This section presents the analysis of project cost performance which is based on the methodological framework outlined in the previous chapters. To examine the cost and schedule performances and isolate the antecedent cause of cost overrun, the analysis is based on the application of the fully realised Key Performance Indicators (KPIs) to the second dataset of the project under analysis. All arithmetic tasks were calculated by the Microsoft Excel using approved project cost, actual cost incurred, projected and realised project duration, rework cost, payment schedules and estimation data.

5.1 Application of KPIs on metro project data

In order to test cost and schedule performance, the completed KPIs were initially implemented on the metro project dataset. The three basic performance indices included Cost Performance Index (CPI), Cost Overrun Percentage (COP), and Schedule Performance Index (SPI) which were computed using approved cost, actual cost, and planned versus realised progress measures. These results indicated that there was a slippage of the schedule and inefficiency in costs in the project as the values of CPI and SPI were not within the optimal values. The COP measure was used to measure the level of increase in the budget, thus validating the existence of cost overruns during the project implementation.

5.2 Core cost and schedule performance analysis

The combined study of CPI, COP, and SPI was used to evaluate the performance of the undertaking as a whole. Although the SPI luminous delay was certain in realizing planned milestones of progress, the CPI reflected that real spending was more than expected costs. The simultaneous presence of cost increases and schedule overruns highlights a strong interdependence of both the time and financial performance in the metro project.

Table 3: Project Details – Nagpur Metro Stations

Cost Figure	Value (₹ Cr)	Meaning
Approved Project Cost (DPR)	6,862	Baseline estimate at planning stage
Actual Expenditure till Mar 2021	7,878	Cumulative spending (intermediate)
Final Project Cost	8,680	Projected total cost at completion

Source: CAG audit

Table 4: Project Details – Nagpur Metro Stations Timeline

Corridor / Component	Planned Completion	Actual Completion & Operation	Delay
North–South Corridor	Apr-18	Mar-19	~11 months
East–West Corridor	Apr-18	Jan-20	~21 months
Full Phase-I operationalization	Apr-18	Jan-20	~22 months

Source: CAG audit

Table 5: Core KPI Calculations

Core KPIs				
Estimated Cost (₹ Cr)	Actual Cost till date (₹ Cr)	Cost Variance	Cost Overrun %	CPI
6,862	8,680	-1,818	26.49	0.79
Project Start Year	Estimated Completion Year	Actual Completion Year	Time Overrun (Years)	Delay Risk Level
2013	2018	2020	1.4	High

Source: Created by authors

5.3 Diagnostic KPI analysis based on finalized parameters

The KPIs used in the diagnostics in line with the finalised specifications of the survey were analysed in order to determine the root cause of the variance in costs. The Rework Cost Percentage revealed that a large percentage of the overall spending on the project could be

explained by the rework, which highlighted the consequences of the design changes and mistakes in the implementation process. Payment Delay (days) Analysis revealed financial disbursement delays which undermined procurement and execution cycles. The reliability of baseline estimation was challenged through the Estimate Accuracy Percentage that revealed differences in initial predictions and the actual costs. The low CPI and SPI results of the project are explained by the combination of the diagnostic KPIs.

Table 6: Cost Variations with Respect to Execution

Sr. No.	Cost Component / Driver	Amount (₹ Cr)	% of Final Project Cost (₹8,680 Cr)	Remarks
1	Baseline Approved Project Cost	6,862	79.05%	Original sanctioned cost for Phase-I
2	Cost Escalation due to Schedule Delays	~620	7.14%	Prolongation costs, idle resources, extended overheads
3	Rework due to Design Changes & Re-awarding	~480	5.53%	Alignment changes, station modifications, contract termination & re-award
4	Price Escalation & Inflation Impact	~380	4.38%	Extended execution period increased material & labour costs
5	Pending Government / ULB Contributions (Payment Delay Impact)	793.89	9.14%	Delayed fund release affecting cash flow
6	Delayed Recovery of Mobilisation Advances	130.86	1.51%	Cash flow blockage from contractors
7	Estimation Inaccuracy (Cost Deviation)	1,818	26.50%	Difference between approved and final cost
8	Final Escalated Project Cost (Actual Cost – AC)	8,680	100%	Expected total cost at full financial closure

Source: Created by authors

Table 7: Diagnostic KPI Calculation

Diagnostic KPI	Value
Rework Cost %	5.53%
Payment Delay Impact	₹924.75 Cr
Estimate Accuracy (Deviation)	26.50%

Source: Created by authors

5.4 Predictive forecasting and scenario analysis

The forecasting methods in Excel introduced the monitoring framework to predictive analytics. Projected final project cost in the current situation was estimated based on past trend of cost escalation of projects and delay information.

This was later followed by scenario analysis to determine several alternatives. The simulated scenarios included the completed timely, less rework, improved coordination, and less delay in payments. Findings showed that even small changes in these parameters would have generated measurable decreases in the end project cost, thus highlighting the ability to make decisions by using the framework.

Table 8: Scenario Analysis with respect to Cost Variations

Scenario ID	Scenario Description	Delay Cost (₹ Cr)	Rework Cost (₹ Cr)	Inflation Cost (₹ Cr)	Revised Total Cost (₹ Cr)	Reduction (%)
S0	Baseline (Audit)	620	480	380	8,680	–
S1	Timely Completion (No Delay)	0	480	380	8,060	7.14%
S2	Improved Design Coordination (50% Rework Reduction)	620	240	380	8,440	2.76%
S3	Inflation Control (25% Reduction)	620	480	285	8,585	1.09%
S4	Delay + Rework Control	0	240	380	7,480	13.82%
S5	Integrated Control (Delay + Rework + Inflation)	0	240	285	7,387	14.89%

Source: Created by authors

5.5 Sensitivity analysis and decision rules

Sensitivity analysis was used to evaluate the behaviour of key cost performance measures to controlled changes in major cost drivers which were identified using diagnostic analysis. The study was conducted to establish the comparative effects of schedule contravention, rework, and price increase on total cost performance and not to restore cost performance in a project that had been completed. The use of predefined rules of decision making makes it possible to identify the high priority risk variables that will be actively monitored and managed in future projects.

Table 9: Decision Rules for KPIs

Indicator	Decision Rule
$CPI \geq 1.00$	Cost efficient
$0.95 \leq CPI < 1.00$	Warning zone
$CPI < 0.95$	Critical
$COP \leq 10\%$	Acceptable deviation
$10\% < COP \leq 20\%$	High risk
$COP > 20\%$	Critical overrun
$SPI \geq 1.00$	On schedule
$SPI < 0.95$	Schedule risk
Rework > 5%	Process failure
Payment delay > 30 days	Cash-flow risk

Source: Created by authors

The decision criteria used in this investigation are based on the widely recognised standards of Earned Value Management and infrastructure audit procedures. Cost overrun limits were based on PMI recommendations that provide the basis of the CPI and SPI levels, whereas government audit standards and construction management literature (which describe cost increases in excess of 20 per cent as critical) provided recommendations on cost overrun levels. Instead of being hard performance targets, these thresholds are used to give early warning to enable predictive decision making.

Sensitivity analysis came in handy to indicate the magnitude and direction of all cost drivers impact although the base case CPI was 0.79 and COP 26.5 per cent, which shows a high cost overrun situation. The schedule control became the most important factor of cost performance because the analysis depicted that even the minor variations in schedule delay costs would have generated the strongest impact of CPI and COP. Sensitivity results, whereby the change in key drivers is converted into the change in performance indicators, are the basis of a predictive cost performance model. Project managers can predict possible cost results before the significant escalation by tracking early indicators like schedule slippage and frequent rework. The framework is also helpful when combined with thresholds based decision rules, as it helps to intervene in time and promote proactive cost management.

Table 10: Sensitivity Analysis for Predicting Forecasting

Risk Factor (Cost Driver)	Sensitivity Change Applied	Impact on Project Cost (₹ Cr)	Resulting CPI	Resulting COP (%)	Risk Severity	Management Priority
Schedule Delay	±10%	±62	0.78 – 0.80	25.6 – 27.4	Very High	Immediate
Rework (Design / Scope)	±10%	±48	0.79 – 0.79	25.8 – 27.2	High	High
Inflation / Price Escalation	±10%	±38	0.79 – 0.79	26.0 – 26.9	Moderate	Medium
Payment Delay (Cash Flow)	Qualitative	Indirect	CPI deterioration	COP ↑	High (Indirect)	High

Source: Created by authors

The sensitivity analysis also creates a clear hierarchy of managerial priorities, with schedule delay first in the list of the most critical risk factors, as it had the largest impact on CPI and COP, then there is rework and inflation.

The sensitivity analysis illustrates that the risks associated with schedule are the major cause of cost overruns in massive infrastructure development. The suggested approach will enhance the early identification of critical risks and predictive and cost control based on data through the incorporation of sensitivity informed decision rules into an Excel based monitoring framework.

6.0 Conclusion

This study shows that overruns on construction costs are a combination of related issues, and that their effect could be forecasted through systematic research instead of the individual occurrence. The paper demonstrates how a cost performance is possible since it can be evaluated prior to the fact and after the fact using a KPI based approach that is complemented by the scenario and sensitivity analysis.

When the Nagpur Metro Rail Project was put into practice, the framework was significantly exceeded in terms of its Cost Performance Index (CPI) of 0.79 and cost overruns of 26.5% percentage. The problem was enhanced by inflation, payment delays and schedule delays proved to be the largest source of cost increase, and rework as a result of design and coordination problems was the second largest source of cost increase. Sensitivity analysis indicated that any minor alterations in timeline related costs disproportionately impacted the cost outcomes of the project.

The scenario analysis established how various conditions of project would have changed the end cost. Remediation efforts in the later stages of the project would be of little help in terms of recovery and preventive measures as early as delays and rework would yield as much cost savings as possible. This serves the central conclusion of the study that proactive intervention is required when overruns have reached important levels and reactive intervention is no longer effective.

In practice, the research demonstrates that, the predictive cost performance management does not need advanced technology. Combining a clear spreadsheet structure with clear and specific decision rules and accessing to readily available project data will give early indicators and make well informed decisions. The project managers will have an opportunity to spend resources more efficiently, pay more attention to essential problems, and intervene in cases when the measures implemented will produce the highest effect.

The findings enhance the construction management practice by focusing the attention not on the evaluation of costs after a project, but on the risk detection during the execution stage. Despite the fact that the example focuses on one large scale infrastructure project, the general methodology can be used in the context of other projects, including residential and commercial constructions. Future studies can extend this study and include development of dashboard visualization to promote monitoring efficiency among different stakeholders.

7.0 Implications

The conclusions made by the study provide straightforward recommendations on how to ensure that control of cost is tightened when constructing the projects. The data show

that the major source of overruns is the delay at timetables and in the close follow the rework because of design and coordination problems. Rather than letting the increased costs to be eminent, managers ought to consider schedule performance as the leading indicator of cost health and take action as soon as the slippage is first noticed.

The analysis also validates the fact that predictive costs can be effectively tracked using simple spreadsheet based methods. With a combination of several clearly defined KPIs and a scenario and sensitivity analysis, teams can predict overruns and focus on mitigation measures without the use of complex programs. This method increases accountability, accelerates the decision making, and also enables the managers to direct resources to the most important risk areas. Overall, the framework transforms the reactive cost reporting into proactive risk management which allows construction companies to identify the high risk scenarios at an early stage and focus on them prior to the overruns being irreversible.

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CHAPTER 21

Enhancing Urban Planning using AR/VR Methods

Aman Dung Dung, Aditya Das**, Chetan Suryawanshi** and Raghavendra Kumar****

ABSTRACT

Urban planning plays very important role in managing urban growth and shaping organized cities. However, traditional two-dimensional (2D) planning methods often fail to clearly show what are the real-world impacts and spatial relationships. This study explores how Augmented Reality (AR) and Virtual Reality (VR) can improve urban planning by providing immersive and interactive visualization experiences. AR enhances real world environment by adding digital elements(objects) , while VR creates realistic three-dimensional (3D) spaces that help planners and other people to understand proposed development projects in a better way. The study examines the accuracy of these visualizations, the use of real-time data, their cost-effectiveness compared to conventional planning methods, and their ability to improve stakeholder engagement. A mixed-method research approach fixed , using case studies and expert interviews for analysis. The results shows that AR and VR improve design understanding, support faster decision-making, and encourage greater public participation. Although challenges such as high implementation costs, limited accessibility, and training requirements remain, the study concludes that AR and VR have strong potential to enhance the future of urban planning and support India's Smart City goals.

Keywords: Augmented reality, Iterative feedback loop, Smart city planning, Stakeholder engagement, Virtual reality.

1.0 Introduction

Urban planning is generally used for the planning of cities so as to be serviceable for the communities in every aspect. Conventionally, planning was performed in the top-down approach using various tools such as zoning regulations, master plans, and transportation studies.

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Planners focused on projecting population growth, managing land use, and providing for basic resources to include water, transportation networks, parks, health facilities, and food supply systems. Various theoretic approaches have also influenced urban planning, including rational, incremental, communicative, and advocacy planning models. These provide a framework for decision-making in light of social, environmental, and economic problems that cities face. Yet, rapid urbanization has placed growing demands on planners to create liveable, efficient, and sustainable cities. Traditional planning tools like 2D drawings, zoning maps, physical models, and static reports often fall short in clearly communicating complex spatial ideas or engendering much public involvement.

Within the past couple of years, AR and VR started changing the practices of urban planning. These technologies allow planners and decision-makers to literally see and interact with proposed development in three-dimensional environments. VR allows users to virtually experience future city spaces and simulate scenarios such as traffic movement, sunlight exposure, and pedestrian flow, supporting better design optimization. On the other hand, AR overlays digital information onto the real-world environment, offering key real-time and location-based insights.

AR and VR enhance the quality of visualization, enhance stakeholder engagement, and allow data to be integrated and analyzed. These tools allow stakeholders to explore proposed developments before actual construction and thus nurture better understanding among stakeholders of spatial relationships and aesthetic impacts. Better communication, collaboration, and more informed feedback from communities will result, with support for transparent and inclusive decision-making. Still, high development costs for software and hardware have hindered the broad adoption of AR and VR in urban planning. Against this backdrop, the role of QGIS-open-source software serving as an alternative to the proprietary GIS software-and WebXR, a new web standard that delivers both AR and VR directly through browsers, has become increasingly important. QGIS is capable of accurately handling real-world data for spatial analysis, while WebXR offers immersive visualizations without any special hardware.

The integration of QGIS and WebXR offers a promising approach for modern urban planning. By merging data-driven spatial analysis with immersive and accessible visualizations, planners, and stakeholders can pursue collaborative explorations of planning scenarios, more effectively participating in the planning process. This thesis investigates traditional urban planning methods compared to modern digital tools, looking at QGIS and WebXR. By using case studies, user feedback, and tool evaluation, the research intends to find out if immersive, data-rich environments can enhance communication and participation toward better planning outcomes, thereby reshaping the future of urban planning.

2.0 Literature Review

S. No.	Title of the Paper	Authors	Year of Publication	Objectives of the Study /Research	Methodology Adopted in the Study/ Research	Results of the Study / Research
1	Potentials of Augmented Reality in a BIM-Based Building Submission Process	Christian Schranz, Harald Urban, Alexander Gerger	2021	Investigate AR in a BIM-based submission process to enhance compliance checking and visualization.	Explored integration of BIM and AR; developed use cases for compliance checking.	AR improves plan-checking efficiency and helps non- experts understand technical content.
2	Usability of WebXR Visualizations in Urban Planning	Michał Rzeszewski, Mateusz Orylski	2021	Examine the usability and practical application of WebXR in urban planning, particularly for participatory planning.	Developed six AR/VR urban planning environment s; conducted usability tests.	WebXR provides high usability when interfaces mimic real- world planning.
3	Virtual City at Chalmers: Creating a Prototype for a Collaborative Early-Stage Urban Planning AR Application	Fabio Latino, Vasilis Naserentin, Erik Öhrn, Zhao Shengdong, Morten Fjeld, Liane Thuvander, Anders Logg	2019	Develop an AR-based collaborative platform for early- stage urban planning and stakeholder engagement.	Used a user-centered approach with literature study, interviews, and prototype creation.	Prototype allows visualization and interaction with 3D urban assets.
4	Mixed Assessment of Virtual Serious Games Applied in Architectural and Urban Design Education	David Fonseca, Janaina Cavalcanti, Enric Peña, Victor Valls, Mónica Sanchez-Sepúlveda, Fernando Moreira, Isidro Navarro, Ernesto Redondo	2021	Evaluate the effectiveness of VR serious games in architectural and urban design education.	Developed and tested Game4City 3.0 using Unreal Engine and HTC Vive VR.	VR serious games increase student engagement and motivation for learning.
5	Development of Construction Engineering Teaching Course	Galeh N.I.P. Pratama, Mochamad	2022	Develop and implement markerless VR-AR teaching materials	Used V- model approach and applied ISO	VR-AR improves student engagement and

	by Using VR-AR: A Case Study of Polytechnic in Indonesia	B. Triyono, Nur Hasanah, Olzhas B. Kenzhaliyev, Aigerim N. Kosherbayev a, Gulzhaina K. Kassymova, Mohamed Nor Azhar Azman		for construction engineering students.	usability testing with developers.	supports remote education.
6	BIM-enabled Virtual Reality (VR)-based Pedagogical Framework in Architectural Design Studios	Aso Haji Rasouli, Saeed Banihashemi, Paul Sanders, Farzad Rahimian	2023	Develop a BIM- enabled VR-based pedagogical framework to enhance architectural l design education.	Used qualitative research methods; applied case study approach in an architectural design studio.	VR-based education enhances student creativity and interaction.
7	Employing Augmented Reality Throughout a Civil Engineering Curriculum to Promote 3D Visualization Skills	Kevin A. Waters, Jonathan Hubler, Kristin M. Sample- Lord, Virginia Smith, Andrea L. Welker	2021	Integrate AR in a civil engineering curriculum to enhance students' 3D visualization skills.	Implemented AR sandbox learning modules across multiple civil engineering courses.	AR improved spatial visualization and received positive feedback from students.
8	The Evolution of Interactivity, Immersion and Interoperability in HBIM: Digital Model Uses, VR and AR for Built Cultural Heritage	Fabrizio Banfi	2021	Investigate the use of VR, AR, and HBIM for managing and preserving built cultural heritage.	Conducted case studies on various historical buildings; applied visual programming languages.	VR and AR improved interoperability and immersive experiences in built heritage.
9	An Analysis of the Application Areas of Augmented Reality Technology in the Construction Industry	Ayodeji Emmanuel Oke, Victor Adetunji Arowoia	2021	Analyze AR application areas in the construction industry and assess its level of adoption.	Surveyed construction professional s; used descriptive and inferential statistical analysis.	AR is primarily applied in visualization, project documentation, and monitoring.
10	Virtual Reality Design Methods & Application: VR/AR in Urban Design	Stefan van der Spek, Frank van der Hoeven, Arno Freeke	2020	Examine VR and AR in urban design, education, and practice.	Implemented VR/AR tools in urban design education; developed VR Design Methods Lab.	VR/AR improves citizen participation and urban design comprehension.

Source: Created by authors

3.0 Research Methodology

3.1 Digital visualization approaches in urban planning

Currently urban planning increasingly requires improved means of visualization and communication due to increasing city complexity. Traditional planning methods involving 2D drawings, maps, and static reports cannot express spatial depth or scale, and real-world impacts to planners and decision-makers, let alone the general public. To overcome these limitations, immersive digital technologies such as augmented and virtual reality have emerged as successful tools for improving planning processes.

AR and VR are acronyms of two complementary visualization approaches: overlay of digital planning information onto the real-world environments of proposed buildings, zoning boundaries, or infrastructure layouts provides a view of each planning proposal within their physical context, while VR offers completely immersive 3-D environments to virtually tour future urban spaces well in advance of construction. This is an open-source, web-based approach that makes the research more accessible and cost-effective. QGIS will provide preparation and analysis of spatial data for mapping, while WebXR offers fully immersive AR/VR right within the web browser without any costly hardware or proprietary software. The enabling of intuitive and inclusive interaction with data-driven urban models by planners, stakeholders, and citizens is now possible through this integration.

3.2 Anticipated impact on urban planning performance

The integration of AR/VR into traditional planning workflows is supposed to enrich such key dimensions of performance in urban planning: visualization clarity, decision-making efficiency, stakeholder engagement, and risk reduction.

It is expected that immersive 3D representations lead to better visualization accuracy for planners and citizens in the understanding of spatial relationships, building massing, and environmental impacts. This better understanding will reduce design misinterpretation and planning errors. The AR/VR-based simulations will facilitate faster and better decision-making because planners are able to test scenarios on traffic flow, sunlight exposure, infrastructure resilience, and land-use change. The capability for virtual evaluation of alternatives reduces reliance on trial and error in implementation.

The participation of stakeholders may grow substantially. The ability of AR/VR tools to make proposed developments visual for citizens will narrow the gap in communication between technical planners and non-technical stakeholders and may lead to better public participation and transparent planning processes. AR/VR integrated with geospatial data via QGIS could contribute to sustainable and resilient urban development through allowing data-driven analysis side by side with immersive visualization.

3.3 Questionnaire development

Data were therefore collected by using a structured questionnaire that assesses the perception of the effectiveness of AR/VR in urban planning.

There were total 3 sections in the Questionnaire:

First Section included questions on demographic information such as professional background, years of experience, and general awareness of urban planning and digital technology, which put other answers into context.

Second part of the questionnaire collected data with regard to awareness, usability, and perceived benefits of AR/VR technologies in urban planning. Statements about visualization quality, cost-effectiveness, public involvement, sustainability, and integration with tools like BIM are subject to assessment.

Third part collected information about the planning performance output in terms of clear communication, decision-making efficiency, reduction of risk, and long-term planning.

Answers have been measured on a five-point Likert scale from “Strongly Disagree” to “Strongly Agree.”

The questionnaires were first validated through pilot testing before their final deployment and by statistical checks to ensure that the internal consistency and clarity were reliable.

4.0 Findings/Results

The purpose of this chapter is to analyze, in an empirical way, the efficiency of using AR/VR technology in improving urban planning. The data collected from this survey has been analyzed through Descriptive Statistics and some Inference Tests, such as t-test, Z-test, to see whether the perception regarding AR/VR has been overwhelmingly positive compared to being Neutral.

Result Analysis for One-Sample T-Test (Effectiveness of AR/VR
(Test value=3, Scale is Neutral on Likert Scale)

4.1 One-Sample T-Test Results (AR/VR effectiveness in urban planning)

(Test value = 3, Neutral on Likert Scale)

Table 1: One-Sample T-Test Results for AR/VR Adoption

No.	Hypothesis / Statement	Mean	t-Statistic	p-Value	Significant ($\alpha = 0.05$)
1	Of all the planners/authorities are trained enough to use AR/VR tools	3.47	2.432	0.029	Yes
2	Planners/authorities are adequately trained to use AR/VR tools.	3.33	1.287	0.205	No

3	There is adequate long-term research available on the sustainability impact of AR/VR.	3.53	1.512	0.137	No
4	AR/VR is currently used in large-scale city planning projects.	3.67	1.846	0.072	No
5	AR/VR support in testing the resilience of the infrastructure.	3.67	1.846	0.072	No
6	Interest in attending training sessions/workshops on AR/VR.	2.91	-0.289	0.779	No
7	AR/VR implementation in planning is economical.	3.82	2.014	0.05	Yes
8	AR/VR reduces project risks (errors, delays, cost overruns).	3.36	1.091	0.281	No
9	AR/VR contributes to sustainable urban development.	3.45	1.201	0.236	No
10	Effectiveness of AR/VR in engaging the public involvement in planning.	2.5	-1.318	0.214	No
11	AR/VR shall be supported for long-term use to resilient city planning.	3	0	1	No
12	AR/VR enhances understanding better than 2D drawings.	2.65	-1.577	0.125	No

Source: Created by authors

From the one-sample t-test, there is evidence of certain meaningful support in adopting AR/VR in urban planning.

4.1.1 Important supporting findings

- AR/VR–BIM Complementarity shows a statistically significant positive perception (Mean = 3.47, $p < 0.05$), indicating that respondents feel that the complementarity between immersive visualization and data-intensive environments of BIM is valuable in terms of urban planning.
- Cost-effectiveness of AR/VR will also have a statistical significance (Mean=3.82, $p \approx 0.05$), implying that the stakeholders recognize the effectiveness offered by AR/VR compared to the conventional planning method.

4.1.2 Moderately positive but not statistically significant

There are some features, such as the testing of infrastructure resilience, the use of the approach for large-scale city planning, the contributions to sustainability, and the reduction of risk, which have overall mean values greater than the neutral point, but lack the necessary significance level.

4.1.3 Low engagement outcomes

- There are lower mean scores for the effectiveness and level of interest in AR/VR-based training with respect to employee engagement.

- The above points underscore the need for capacity-building activities, awareness, and demonstration projects.

4.2 Z-test results for AR/VR effectiveness in urban planning

(Test Value = 3, Neutral Perception)

Table 2: Result of One-sample

Survey Statement	Mean	Z-Statistic	P-Value	Significant ($\alpha = 0.05$)
Effectiveness of AR/VR in engaging the public	2.829	-0.913	0.3615	Not Significant
Effectiveness of traditional tools in communicating plans	3.806	5.13	0	Significant

Source: Created by authors

The outcome of the Z-test shows that there is no perception of effectiveness regarding the usage of AR/VR in engaging with the public differently when compared to a neutral standard ($p > 0.05$). On the other hand, a comparison of the result shows that the mean of traditional planning methods is significantly different and above the neutral standard ($p < 0.05$). This can be identified as a phase of transition where AR/VR is in its budding stage and has yet to replace the conventional means of communication.

4.2.1 Inferential Analysis (T-Test and Z-Test Results):

T Inferential analysis showed that some variables were significant, which meant that the perceptions were well above the neutral levels for AR/VR-related variables. The respondents were strongly in favor of AR/VR for the purpose of visualization improvement, resilience analysis, and cost-effectiveness. However, the analysis regarding the integration of AR/VR and BIM, as well as the engagement level for long-term sustainability, is not significant and addresses the gaps instead of the technicalities.

4.2.2 Hypothesis Test

The hypothesis testing confirms that while traditional tools remain dominant, AR/VR has not yet achieved statistical acceptance as a mainstream engagement tool. This does not indicate failure of AR/VR technology, but rather insufficient adoption, training, and institutional readiness.

Table 3: Hypothesis Testing Summary

Code	Hypothesis Statement	Result
H1	AR/VR significantly improves public engagement in urban planning	Not Supported
H2	Traditional tools are effective in communicating planning proposals	Supported
H3	Stakeholders are currently ready to adopt AR/VR as a primary planning tool	Not Supported

Source: Created by authors

5.0 Discussion and Implications

5.1 Interpretation of results

The results indicate the use of AR/VR technology has a great affinity with urban planning processes. As a planning aid, the results are affirmative of the use of AR/VR technology for applications such as testing the infrastructure of a proposed project and assessing cost-effectiveness. The absence of distinct results in the AR/VR–BIM integration study underscores the importance of capacity development and familiarity with integrated digital planning tools. The results indicate the use of AR/VR technology has a great affinity with urban planning processes. As a planning aid, the results are affirmative of the use of AR/VR technology for applications such as testing the infrastructure of a proposed project and assessing cost-effectiveness.

5.2 Practical implications

Regarding planning authorities and practitioners, the findings from this research stress the importance of embracing AR/VR as an additional option to traditional planning approaches. Open-source softwares such as QGIS and WebXR available on web browsers could remove existing implementation hurdles and therefore ensure equitable access to AR/VR planning applications. The use of AR/VR technology will enable urban agencies to improve public consultations, reduce conflict during planning, and ensure transparency during decision-making.

6.0 Conclusion

This study researched how Augmented Reality and Virtual Reality improve the processes of urban planning in aspects that deal with the visualization of urban space, stakeholder involvement, cost-effectiveness, and planning communication. The study was informed by shortcomings of traditional approaches of urban planning which are heavily reliant on two-dimensional drawings, static maps, and written reports that often do not convey

complex spatial information clearly to non-technical stakeholders. It means that AR/VR can be re-used as promising tools in urban planning, particularly for improving visual understanding and making cost-effective decisions. The economic viability of the AR/VR solution and the possibility of complementing the existing digital tools like BIM (Building Information Modelling) was fully agreed upon by the respondents. It seems that immersive technologies are not only valued as presentation tools but as a decision-support system through which they are able to perceive enhanced accuracy and efficiency in planning. While conducting this research, it is also being noted that AR/VR does not have strong empirical grounds with respect to processes of public engagement and implementation. The analysis of the t-test and z-test results makes it clear that traditional planning processes are yet to be accepted as a better means of communicating proposals to the public through AR/VR. This points to the idea that while AR/VR might be welcomed at a theoretical level of acceptance, its applicability in real world is still obstructed by factors such as lack of user training and readiness of the people on a larger scale.

7.0 Recommendations

1. Implement Immersive Visualization Technologies: The agencies concerned with urban planning must integrate the use of AR/VR in the consultation processes regarding urban designs.
2. Training and Capacity Building: Professional training programs must also be needed for effective AR/VR-BIM integration.
3. Open-Source Platform Utilization: Usage of QGIS and WebXR must be adopted to lower expenses and enhance accessibility.
4. Promote Participatory Planning. The use of AR and VR can enable and increase transparency of planning through citizen participation.

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CHAPTER 22

Studies on Hybrid Project Management Practices in Construction Projects

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ABSTRACT

This research explores Hybrid Project Management (HPM) practice in the construction sector, trying to overcome the strengths and weaknesses of traditional and agile approaches. The complicated and legal aspects of construction industry can only be well supported with an elastic yet systematised project management procedure. The conventional method offers formal control and no flexibility, whereas the agile method offers the maximum flexibility and struggles to deal with formal and large-scale projects. Our study aims at bridging this gap by studying the role of hybrid practices in enhancing project performance. The research examines real-life situations, challenges, and results based on the analysis of qualitative data (semi-structured interviews), and extensive literature reviews. Among the key results are that HPM allows greater adaptability, stakeholder engagement, risk management, and better cost-time-quality performance, yet it also allows to see key challenges, including cultural resistance, integration complexity, and the lack of standardised models. Our research proposes an HPM model unique to the construction project that integrates conventional project planning with feedback and adaptive cycles. This model offers a realistic approach to construction firms that want to optimize on project performance.

Keywords: Hybrid project management; construction projects; waterfall; agile; implementation challenges.

1.0 Introduction

Project management has undergone a paradigm shift in the current dynamic business environment. Time and cost continue to remain critical success factors, but they are now not merely restricted to that.

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Instead, project management has now become a key driver of strategic change, innovation and long-term value creation in a wide range of industries. Due to the growing reliance on projects by firms as a means of growth, stabilizing market unpredictability, digitalizing and delivering offerings with a customer-focused experience, the scale, volume, and complexity of projects have multiplied many times over. This has questioned the old means of management of projects and demands a reconsideration and redesigning of the way projects are managed, and the research.

Project performance is rooted in the fact that there is a difference between a project management approach and a project management methodology. Project management approach is the mode of thought and a plan on how project is supposed to be handled and therefore being more abstract and higher level. Conversely, a project management methodology involves a real step wise program of what specific processes and techniques are to be followed in managing a project. Examples of project management methodologies include Waterfall and the Scrum methodologies.

Project management approaches have broadly two common approaches:

Traditional: Traditional Project Management (TPM) is a linear and organized method and therefore mostly suitable in projects whose scope is known and have minimal changes. It operates on the values of predictability and comprehensive planning.

Agile: The Agile Project Management (APM) operates on an iterative and flexible model, which divides the tasks into small, manageable units. This allows the teams to cope with any change better and promotes teamwork.

Although there are some benefits of both these approaches, they also have their flaws. Traditional strategies introduce control and order that is why they are best suited in high-risk or controlled environments. However, they are inflexible and non-iterative at the same time and are inflexible to the needs of the clients as they evolve. Agile approaches on the other hand can facilitate well teamwork, flexibility, and responsiveness. Nevertheless, their casualness as well as reliance on continuous team communication might become complex to large-scale or regulatory projects.

In a bid to defy this, there has arisen the hybrid approaches to project management. Hybrid models put into consideration the predictability of established frameworks and the flexibility of agile practice. These are intended to bring a balance in circumstances where strategic flexibility is to be retained, and procedural integrity and traceable accountability is to be upheld. It attempts to integrate old and agile styles in a manner that makes the most of their advantage and curbs their disadvantages.

The contribution of project management towards organisational change, innovation and value creation is a well-known fact in the recent literature. Ciric et al. (2022) mention that the projects have come to be the source of digital transformation and competitive

advantage within the organisations and heightens the importance of rethinking the traditional means. In these regards, the choice of a suitable project management can be considered as a very important managerial choice rather than a purely procedural one. A single size fits all methodology is not the best approach in the present day because the environment of the project has become unpredictable, there are diverse stakeholders in a project with soaring expectations of performance. Later, researchers and professionals are paying more attention to HPM as the approach which can be adapted to the characteristics of the project, the level of its organisational maturity and industry-related limitations. This transition indicates that project success is multidimensional and necessitates the structure as well as flexibility to react promptly to the changing project dynamics.

2.0 Literature Review

Project management has evolved a lot over the time due to the changing nature of projects, changing requirements of the project and changing scale of the project. Traditional project management has always been a dominant and major methodology, especially in construction and mechanical fields. In traditional project management methodology, activities are predefined. Traditional project management methodology has some challenges, like when the project requires flexibility and decision making, its rigidity can be an obstacle (Collyer and Warren, 2009; Fernandes et al., 2018). The requirement of flexibility and agility gave rise to agile project management. In the construction industry, especially for large-scale projects where the capital is intensive, project has multiple stakeholders and project also has some tight deadlines, TPM or APM alone does not meet the requirement of the project.

Traditional project management methodology has five phases respectively initiation, planning, execution, monitoring and closure. Reiff and Schlegel (2022) noted that traditional project management methods heavily rely on preplanning, scope management, predefined processes, documentation, and control. Kerzner (2003) explained that Traditional project management defines what shall be the actions, and who will be responsible for those actions. Lalmi et al. (2021) notes that traditional practice is best for the projects which are predictable like earthwork. Papadakis and Tsironis (2020) mentioned that traditional practice due to its rigidity can cause stakeholder dissatisfaction where real time communication is needed. Traditional project management relies heavily on predefined plan which is scope of project and hence changes in later stage of project can cause scope creep. When there are multiple decision makers, it can cause project delay and cost increase. Especially for the projects where stakeholder feedback are important.

To reduce or address the limitations of Traditional Project Management, the Agile Project Management approach was developed. The agile approach is based upon the

manifesto of Beck et al. (2001). Agile management mainly focuses on concepts like adaptability, continuous stakeholder engagement, and incremental delivery of the project. The most important feature of the Agile approach is its ability to adapt to changing client requirements. This feature or concept is most important in the design and planning stages of a project. However, Merschbrock and Munkvold (2015) found that even though this methodology has good flexibility, it still does not work well with activities like legal and contractual requirements kind of parts of the project.

Hybrid project management synergize or combines the adaptability and flexibility of agile project management and structure of traditional project management. my name (Wysocki, 2019). TPM is mainly used for the feasibility study, procurement, and regulatory approvals. APM is mainly used for design development and continuous stakeholder engagement to improve the feedback (Abbas et al., 2020). Fernandes et al. (2018) explained that the hybrid project management model falls under either a layer-based model or an integration-based model. Components of both approaches are integrated in a single workflow in integration-based models. Different approaches are used at different project stages in layering-based models. This kind of flexibility is important specially in the construction industry where each stakeholder has different problems and different expectations. Fernandes et al. (2018) highlighted hybrid approaches used in large infrastructure projects, where control during execution was managed by Gantt charts and Earned Value Management, while BIM tools and Agile practices were used to support design flexibility. The Water-Scrum-Fall model and the Agile-Stage-Gate approach are two of the four primary hybrid methodologies identified by Reiff and Schlegel (2022).

Senaratne and Ruwanpura (2016) noted that in the case of HPM, the increased coordination of stakeholders and early identification of issues are some of the major benefits achieved with the help of agile stand-ups and iterative reviews with conventional scheduling and documentation. Bushuiey and Kozyr (2020) noted that HPM maintained the compliance requirements of the project while improving delivery timelines and quality. Despite the challenges, companies are experimenting with HPM due to the growing evidence of improved project performance. Some of the major barriers are that there is no professional who has experience with agile, and people are resistant to change. Also, there are complexities in integrating these processes. Secondly, there is no standard framework for hybrid project management methodology.

Basically, a hybrid project management methodology is not just a trend but the future of evolution of construction projects. Project-specific tailoring, leadership support, and cultural readiness for change are required for the successful implementation of HPM. However, with increasing digitisation through applications such as BIM, collaborative platforms, and real-time dashboards, hybrid models are becoming increasingly feasible.

Future studies should be more concentrated on developing construction-focused HPM frameworks while also evaluating the critical success factors of a project. HPM is no longer merely a theoretical idea, and the future of construction project management relies on the collaboration of traditional expertise with contemporary techniques.

3.0 Research Methodology

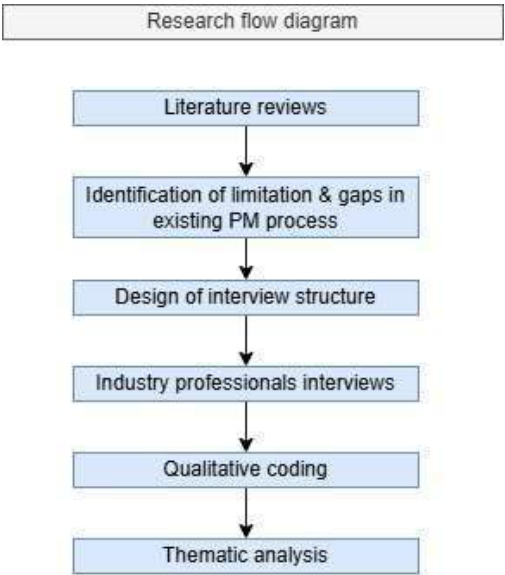
3.1 Research design

This research involves a qualitative exploratory framework in the learning process of implementing traditional, agile and hybrid project management techniques in the construction projects, and a hybrid project management framework applied specifically to the airport projects. The exploratory nature of the undertaken study and the lack of empirically tested HPM frameworks were some of the reasons why a qualitative approach was used.

The research design includes a structured literature review, semi-structured interviews with experts, and qualitative thematic analysis. This combination strengthens the rationality of the suggested Hybrid framework by enabling triangulation between the theoretical outlook and the actual project practice standpoint.

3.2 Research process overview

Figure 1: Research Flow Diagram



Source: Author's own work

This methodical process validates that the framework's development was supported by both theoretical outlook and actual project practice standpoint.

3.3 Literature review method

Traditional, agile, and hybrid project management approaches were studied by a systematic review of research papers with a major focus on construction projects. Three main objectives were accomplished by the literature review as mentioned below:

- to understand the theoretical strengths and limitations of current project management techniques
- to identify limitations of the hybrid project management models currently in use for construction or infrastructure projects
- to develop the base for the creation of interview themes and analytical categories

3.4 Data collection: expert interviews

Ten semi-structured interviews with professionals working on construction projects in India, the Middle East, and North America were conducted to gather primary data. Table 1 summarises the list of respondents. Both operational and strategic outlooks were represented due to this diversity.

Table 1: List of Respondents

Sr. No.	Designation	Industry Experience (in Years)
1.	Founder	35+
2.	Project Manager	35+
3.	Associate General Manager	19
4.	Director Operations	16
5.	Director	10+
6.	Project Engineer	3
7.	Planning Engineer	2
8.	Project Engineer	2
9.	Project Manager	1
10.	Associate Project Manager	1

Source: Created by authors

To give flexibility to respondents to share their opinion and, at the same time, to ensure consistency across interviews, a semi-structured interview style was chosen. Project management procedures, methodology decisions, hybrid approach in practice, implementation challenges, and considered success factors were the main topics of the

interview questions. All participants were anonymised to protect their privacy and to adhere to ethical standards.

3.5 Data analysis method

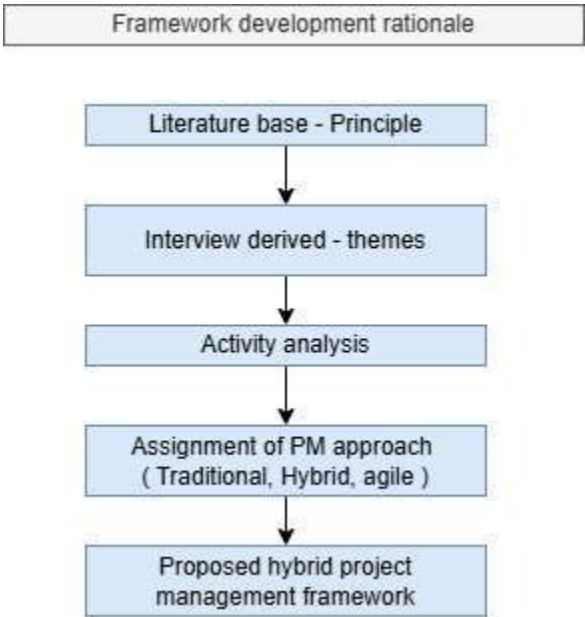
To enable qualitative theme analysis of interview responses, a technique of hybrid inductive-deductive coding was used. While inductive codes have come straight from the interview responses, deductive codes were developed from part of the literature study.

Interviews, interview transcription, preliminary coding, code improvement, theme development, and interpretation were part of a structured process used for the research study. Transparency, clarity, and consistency in data interpretation were achieved by this methodical approach of the study.

3.6 Hybrid framework development approach

This study's hybrid research approach was created by integrating qualitative research with propositions from the literature study. The parts of the project most appropriate for traditional, agile, or hybrid techniques were identified by mapping rationales found in interviews.

Figure 2: Framework Development Rationale



Source: Author's own work

An airport project has a high level of complexity consisting of a variety of components, some of which benefit from adaptability and iterative collaboration, and others require strict regulatory control, which is reflected in this activity-level tailoring. Due to this, rather than one methodology for the entire project, the framework represents a hybrid outcome-based approach.

4.0 Data Analysis

Semi-structured interviews with practitioners working on construction projects are used to extract the qualitative data. The respondents were of various positions, such as engineers working on the project, general manager and consultants with experience ranging between early-career professionals (13 years) and senior professionals (>30 years).

NVivo software was used to perform a combined inductive-deductive thematic analysis. The deductive codes were based on the ones in current literature (e.g., traditional, agile, hybrid approaches, standards, and challenges), and the inductive themes were directly generated using the content of the interview transcripts, e.g. informal hybridisation, lessons-learned practices, organisational culture, and digital adoption.

Table 2: List of Themes

Sr. No.	Theme type	Themes
1	Inductive	Project management process
2	Deductive	Project management team
3	Deductive	Project management standards and guidelines
4	Inductive	Cost, quality, and schedule management
5	Inductive	Stakeholder and communication management
6	Inductive	Risk and uncertainty management
7	Inductive	Safety and health management
8	Deductive	India vs overseas project management differences
9	Deductive	Core principles of traditional, agile and Hybrid approach
10	Deductive	Project management approaches
11	Deductive	Integration of traditional and agile practices -Hybrid project management
12	Deductive	Challenges in hybrid project management adoption
13	Inductive	Organisational readiness and culture
14	Inductive	Digital and technological integration
15	Deductive	Success factor and future scope

Source: Author's own work

It was possible to identify 15 themes and classify them into four categories:

1. Fundamental project processes and strategies.
2. Management, norms, and organisational structures.
3. The performance, risk, and stakeholder dynamics.
4. Facilitating conditions and prospects of hybrid project management.

Table 2 summarises the 15 themes used for qualitative analysis.

In interviews, the delivery of a project was always explained according to the process groups described in PMBOK: initiation, planning, execution, monitoring and controlling and closure. According to one of the senior project managers, projects tend to be divided into phases, with each phase considered as a mini project, especially in the case of long-duration or even large-scale developments. Planning is front-end loaded, whereby baseline schedules, work breakdown structures and resource plans are ready to satisfy a contractual time span, and sub-phases are time-boxed in this model.

There is, however, a variance in closure and learning practices. There are organisations in which organised lessons-learned workshops are performed, and the central repositories are managed by applications of the PMOs; on the other hand, there are organisations in which the central repositories are maintained by informal discussions and, therefore, organisational learning is limited. This lack of consistency limits the systematic implementation of the hybrid practices, which rely on feedback and continuous improvement.

Conventional project management is still prevailing, particularly when it comes to large infrastructure and government projects, because of regulatory conformity, consistent scope, and rigidity of the contract. Respondents pointed out that early design freezing, resistance to change and fixed baselines were applied to ensure cost and time certainty.

Agile is discreetly used in more uncertain projects like renovation, fit-out, marine works, and data centres and in most cases, it entails iterative review, short-cycle planning, and frequent client contacts. It is important to note that the agile terminology is hardly ever applied directly; instead, practitioners speak of flexible planning.

Practitioners view the major difference between traditional and agile/hybrid methods to be the balance of flexibility, control, and decision-making. The old methods focus on the sequential milestones and documentation, whereas the hybrid methods are based on overlapping work activities, the reduction of feedback cycles, and collaborative leadership.

The term hybrid project management was broadly characterised as a compromise between initial baselines and responsive re-planning in the running. Key enablers were found to include continuous learning and digital transformation. There were, however, senior practitioners who warned that there is too much emphasis on labels and that, in traditional project management, there has always been a high degree of adaptability, leading to a necessity to have more practical hybrid frameworks as opposed to strictly conceptual ones.

The reference frameworks were often referred to as PMBOK, ISO standards (including ISO 9001, ISO 45001, ISO 21500), PRINCE2 principles and FIDIC contracts. Several organisations have created in-house SOPs and their own project management systems based on combining these standards with agile practices. Project management teams and PMOs are also important in facilitating hybrid practices. Risk management also indicates a hybrid logic, the integration of past risk registers and risk contingencies, with the iterative reviews and change management during implementation.

BIM, ERP, Primavera, MS Project, and cloud-based collaboration tools were listed as the important enablers of HPM. Nonetheless, the rates of digital maturity are highly differentiated across organisations.

The key obstacles are the resistance to change, the lack of knowledge about agile principles, and the issue of fit between adaptive practices and the need to document the contract. The adoption requires successful leadership support, training, standardised templates and organisational culture to be successful.

With the growing complexity and digitalisation of the projects, hybrid forms will emerge that combine the old method of governance with the new growing flexibility that is more likely to take hold, should organisations invest in the development of capability and in the systematic application.

5.0 Findings and Results

The study's main findings and results are in line with the purpose of an HPM framework for airport projects.

5.1 Overview of the proposed HPM framework

The study's main outcome is an HPM framework for an airport project that is structured around the 49 PMBOK processes, which cover ten knowledge areas and five process groups. The framework uses a customisation approach on the process level, assigning a Traditional, Agile, or Hybrid project management strategy to each of 49 PMBOK processes, rather than assigning a single management methodology for the entire project lifecycle.

5.2 Basis for the management methodology assignment and rationale development

A cumulative analysis of literature study and industry professional interviews gives the justification for assigning project management techniques to PMBOK processes. Primary advice on the applicability of traditional, agile, and hybrid techniques under various situations of uncertainty, complexity, and governance requirements was taken from the literature review.

Interviews with industry professionals provided contextual information about how projects are handled and where control vs flexibility is important.

5.3 Consolidation of 102 Airport Planning Activities into 49 PMBOK Processes

102 airport-specific activities were identified from international airport planning manuals and regulatory guidance papers. These activities were categorised under the 49 PMBOK processes after a methodical analysis (Table 3). The process supported the choice to allocate methodologies at the process level rather than at every individual activity's level.

Table 3: Process Areas and Sub-Activities

S.no.	Process Area	Activities under those process areas
1	Develop Project Charter	Develop and Approve Project Charter and Initial Planning Proposal
		Define Project Objectives, Vision, and Success Criteria
2	Develop Project Management Plan	Identify Key Assumptions, Constraints, and Pre-Project Dependencies
3	Direct and Manage Project Work	Execute Airside Civil-Works Construction and Quality-Assurance Program
		Execute Terminal Building Construction and Fit-Out Management Plan
		Develop Air-Traffic-Control and Navigation Facility Construction Package
		Conduct Site Reconnaissance and Topographical Validation Surveys
		Implement Utilities and Electrical Infrastructure Integration Plan
		Deliver Fuel Farm and Hydrant Infrastructure Construction Plan
		Implement Utilities and Environmental-Services Infrastructure Delivery
4	Manage Project Knowledge	Execute Training, Capacity-Building, and Knowledge-Transfer Program
		Develop and Submit Final Project-Closeout Report and Master-Plan Documentation
5	Monitor and Control Project Work	Monitor and Control Project Work Using Performance-Measurement Techniques
6	Perform Integrated Change Control	Facilitate Integrated Decision-Making and Site Selection Approval Process
7	Close Project or Phase	Perform Regulatory Closure, Certification, and License-Acquisition Process
		Execute Project-Closure and Operational-Transition (ORAT) Management Process
8	Plan Scope Management	Develop Governance Framework and Policy Guidelines for Project Execution
		Plan Emergency Response Facilities and Safety Infrastructure Layout
9	Collect Requirements	Perform Current-State Assessment and Baseline Documentation
		Develop a Demand Forecasting Model for Passenger and Cargo Throughput
		Develop Space Program and Demand-Capacity Alignment Analysis
10	Define Scope	Translate Forecast Outputs into Design and Operational Planning Parameters
		Establish Design Capacity Metrics and Performance Baselines

11	Create WBS	Develop a Detailed Project Management Plan (Schedule, Scope, and Budget)
		Perform Alternatives Analysis and Design Optimisation Workshops
12	Validate Scope	Perform Detailed Design Development and Design-Review Process
		Perform Commissioning, Integrated-System Testing, and Validation Trials
13	Control Scope	Develop Land Use and Security Zoning Master Plan
		Perform Quality-Control and Design-Conformance Verification Process
14	Plan Schedule Management	Establish Strategic Planning Horizons and Preliminary Project Schedule Baseline
		Develop Airside Layout Plan and Airspace Management Framework
15	Define Activities	Perform Runway Design and Performance Optimisation Study
		Develop Terminal Complex and Landside Access Master Layout
		Develop Cargo Terminal and Landside Logistics Plan
		Design Apron Configuration and Aircraft Stand Optimisation Plan
16	Sequence Activities	Conduct Airfield Wind Analysis and Runway Orientation Planning
		Conduct Airfield Capacity Analysis and Runway Requirement Determination
		Optimise Stand Geometry and Apron Circulation Plan
17	Estimate Activity Durations	Conduct Site Reconnaissance and Topographical Validation Surveys
		Develop Conceptual Design Alternatives and Comparative Costing Models
18	Develop Schedule	Perform Quantitative Forecasting and Predictive Analytics for Capacity Planning
		Develop Implementation Phasing and Prioritisation Strategy
		Develop an Integrated Implementation and Delivery Management Plan
19	Control Schedule	Plan CNS/ATM and Air Traffic Infrastructure Requirements
20	Plan Cost Management	Develop Preliminary Cost Baseline and Financial Management Plan
		Implement Financial-Risk and Foreign-Exchange Management Plan
21	Estimate Costs	Perform Feasibility Study and Economic Viability Assessment
		Perform Landside Traffic Simulation and Curb Capacity Analysis
		Conduct Market Demand Analysis and Initial Forecasting Study
22	Determine Budget	Identify Potential Funding Sources and Develop Financing Strategy
		Establish Final Cost Baseline and Financial Control Plan
23	Control Costs	Implement Internal Roadworks and Transportation-Infrastructure Development
24	Plan Quality Management	Perform Regulatory and Standards Compliance Review
		Perform Structural Design and Pavement Capacity Analysis
25	Manage Quality	Design Check-in and Passenger Flow Optimisation Model
		Develop Baggage Handling System (BHS) Design Requirements and Simulation Plan
26	Control Quality	Execute Statutory Approval and Regulatory Compliance Management Process
		Conduct Internal and External Audit Management Process
		Conduct Emergency-Response Simulation and Continuous-Improvement Cycle

27	Plan Resource Management	Develop Organisational Structure and Define Roles & Responsibilities
		Develop Aircraft Grouping and Parking Configuration Strategy
28	Estimate Activity Resources	Develop Aircraft Mix Analysis and Fleet Utilisation Model
		Define Land Requirement and Prepare Land Acquisition Strategy
		Design Fuel Farm and Hydrant Distribution System Plan
		Develop General Aviation Infrastructure Master Plan
29	Acquire Resources	Assign Project Manager and Establish Leadership Authority
		Manage Land Acquisition and Property Transfer Process
30	Develop Team	Perform Maintenance Facility Siting and Risk Analysis
		Execute Ancillary Building Construction and Commissioning Program
31	Manage Team	Develop Operational-Readiness and Standard-Operating-Procedure Documentation
32	Control Resources	Deliver Apron and Airfield Infrastructure Construction Package
		Deliver Cargo-Handling Infrastructure and Systems Implementation
33	Plan Communications Management	Perform Gate Allocation and Apron Capacity Analysis
		Perform Operational Process Optimisation for Passenger Processing Facilities
34	Manage Communications	Develop Landside Traffic Circulation and Access Plan
		Integrate Ground Transport Planning into the Overall Mobility Master Plan
35	Monitor Communications	Perform Stakeholder Consultation and Community Engagement Analysis
36	Plan Risk Management	Conduct Needs Assessment and Define Project Scope Baseline
		Define Project Boundaries and Geographic Scope Statement
37	Identify Risks	Perform Route Network and Airline Demand Assessment
		Perform Desktop Site Screening and Alternative Analysis
38	Perform Qualitative Risk Analysis	Perform Risk Assessment and Airspace Safety Evaluation
		Conduct Social Impact Assessment and Community Risk Evaluation
39	Perform Quantitative Risk Analysis	Conduct Cost-Benefit and Financial Feasibility Analysis for Site Alternatives
		Execute Economic Evaluation and Project Selection Analysis
40	Plan Risk Responses	Develop Terminal Planning Concept and Functional Space Program
		Conduct Terminal Concept Evaluation and Final Selection Process
41	Implement Risk Responses	Perform Environmental-Mitigation Implementation and Monitoring Process
42	Monitor Risks	Perform Environmental Impact Assessment and Mitigation Planning Process
		Execute Environmental-Monitoring and Compliance-Tracking Program
43	Plan Procurement Management	Develop Financial Policy Framework and Funding Acquisition Plan
44	Conduct Procurements	Conduct Strategic Procurement and Service-Level Agreement Management
		Administer Construction Contract Management and Execution Control
45	Control Procurements	Develop ATC/AIS/Met Briefing Facility Layout Plan
		Perform Equipment Installation, Calibration, and Acceptance Testing
46	Identify Stakeholders	Conduct Stakeholder Identification and Engagement Planning Process
		Perform Ground Transportation Connectivity Study
47	Plan Stakeholder Engagement	Develop Concept of Operations (CONOPS) for Airside and Landside Systems

		Design Airside Taxiway Network and Service Road Layout Plan
48	Manage Stakeholder Engagement	Conduct Airfield Throughput and Delay-Reduction Simulation Study
		Design Support Infrastructure and Operational Facilities Master Plan
49	Monitor Stakeholder Engagement	Design Vehicle Parking Master Plan and Access Strategy
		Develop Airport Security Infrastructure Implementation Plan

Source: Author's compilation based on international airport planning manuals, regulatory guidance documents, and PMBOK framework

5.4 Distribution of activities under traditional, agile, and hybrid processes

There are certain trends in the type of activities assigned to each project management methodology when the entire activity list is studied. Regulatory approvals, contract administration, procurement planning, baseline scope definition, and formal risk identification are important parts of traditional methodology. Tasks are usually subject to external regulatory frameworks, allowing very little flexibility for alterations and requiring a lot of paperwork. While industry experts' perceptions emphasise the importance of control and predictability in these areas, the literature repeatedly associates such conditions with plan-driven project management approaches.

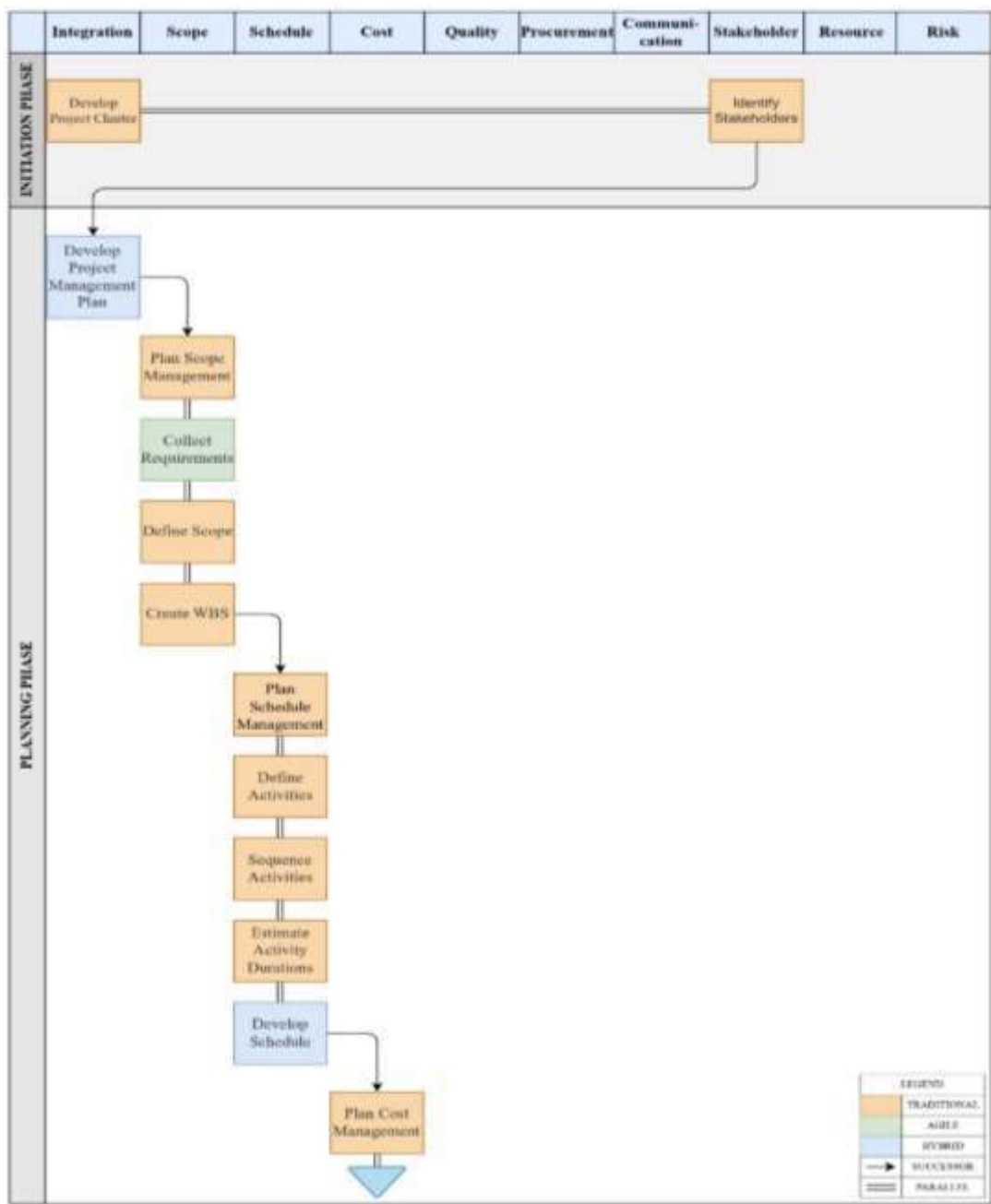
Stakeholder engagement, continuous information sharing, and changes based on ongoing feedback are all included in agile processes. Both academic literature studies and interview analysis show that iterative methods and adaptive planning increase the effectiveness of managing such dynamic activities in the airport project.

Hybrid management processes are activities that have structured planning elements with elastic implementation requirements. Examples are integrated schedule management, design coordination, interface management, performance monitoring, and change control. This necessitates compliance with project dynamics in real time, as well as compliance with pre-set project baselines. This classification highlights the importance of implementing various methodological approaches by demonstrating the way airport projects activities evolve during the project lifecycle.

5.5 Final framework output

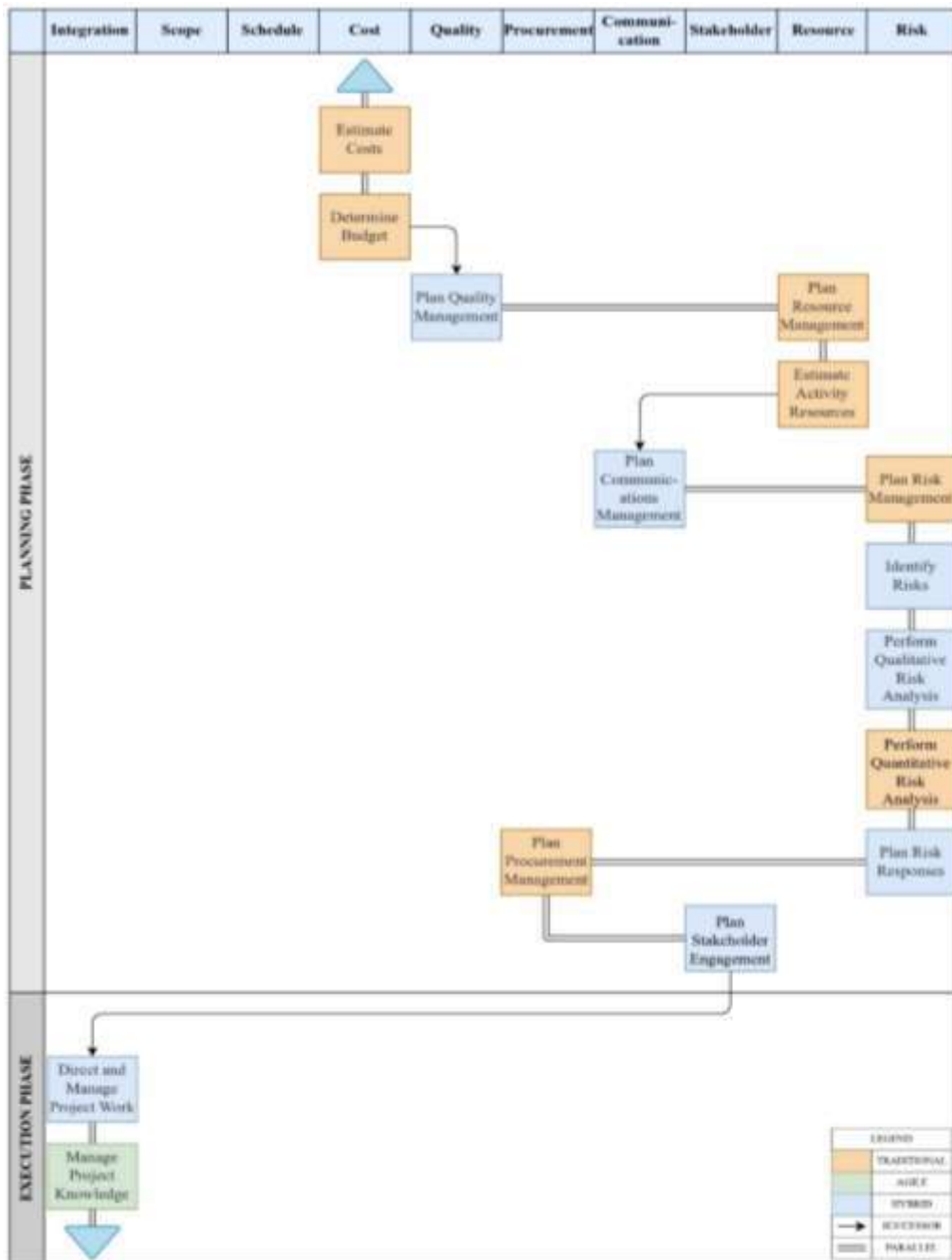
The main deliverable of this paper is the detailed HPM framework of airport projects that provides the recommended approach to management and a clear explanation of why each of the 49 PMBOK processes is recommended. The framework is an organised idea that aims at helping project managers to select appropriate project management methodologies in airport projects based on process characteristics and activity structure.

Figure 3: Proposed Hybrid Project Management Framework



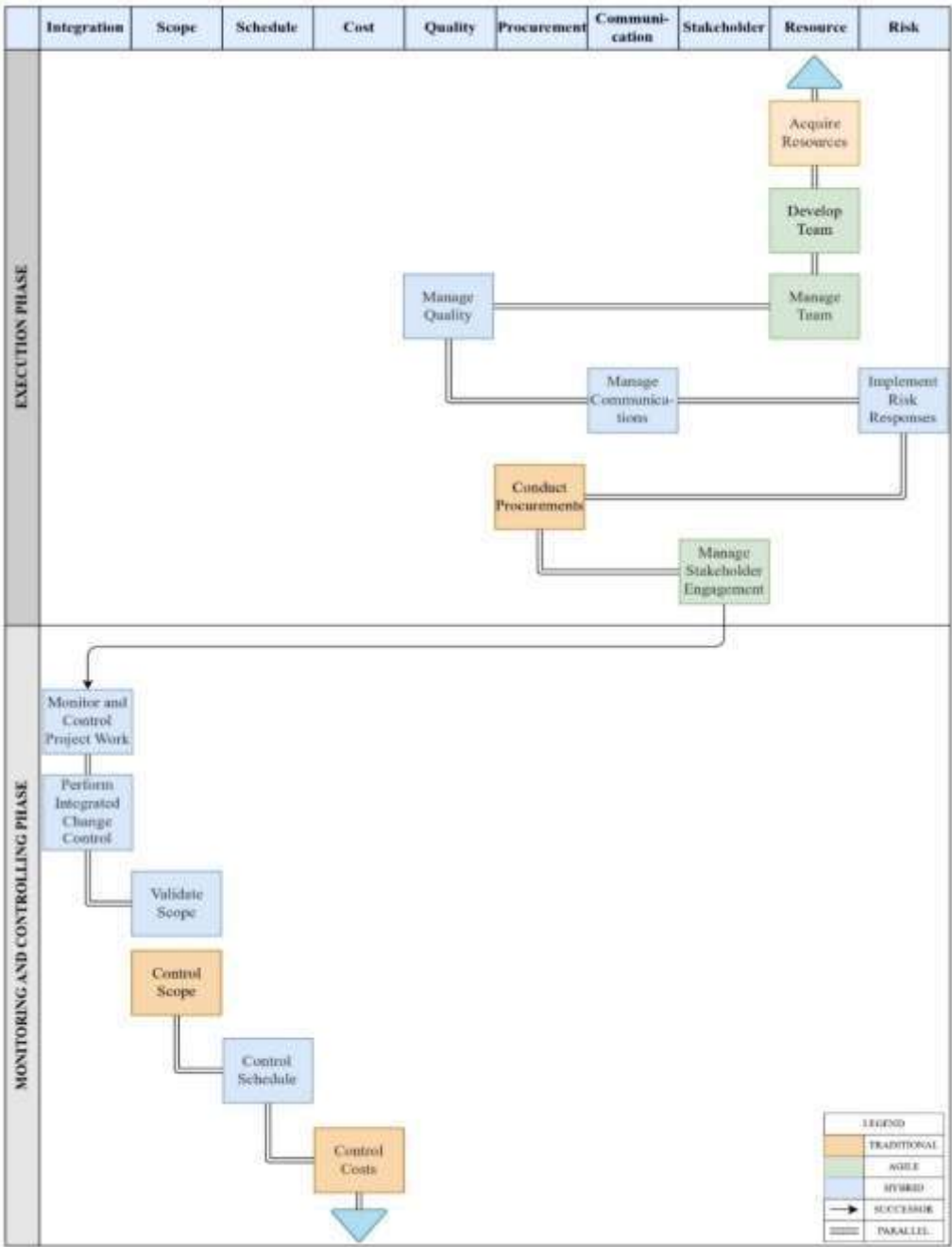
Source: Author's own work

Figure 4: Proposed Hybrid Project Management Framework (continued)



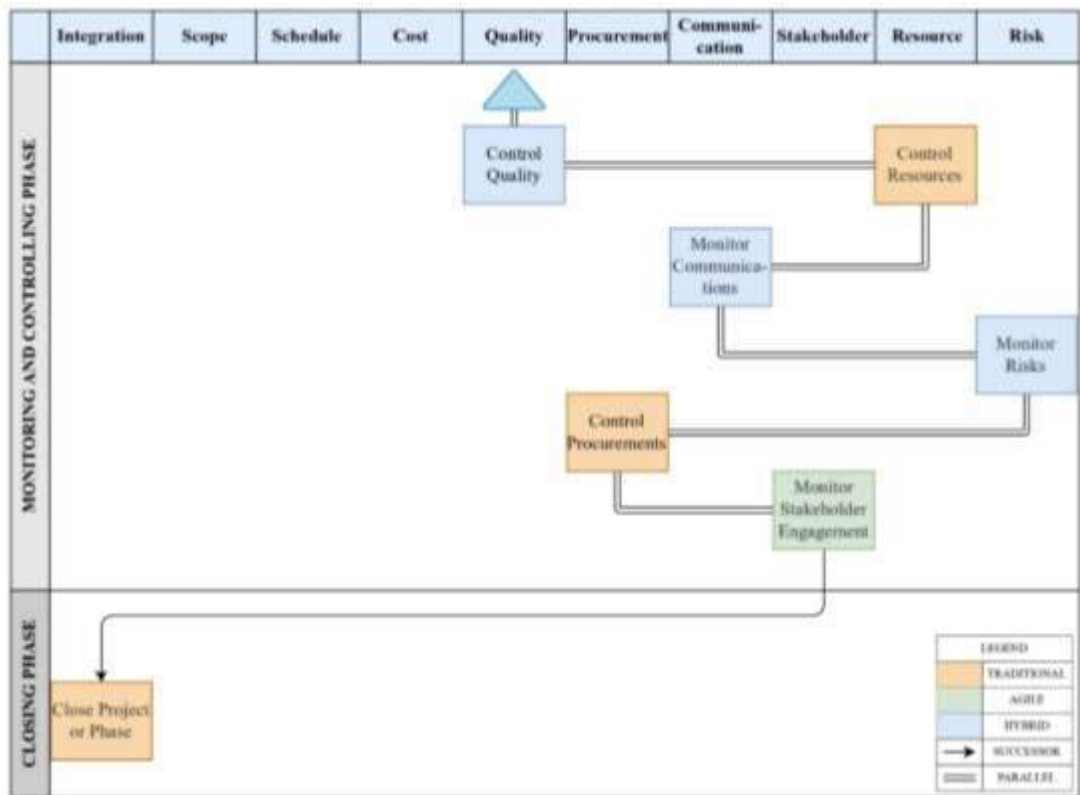
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Figure 5: Proposed Hybrid Project Management Framework (continued)



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Figure 6: Proposed Hybrid Project Management Framework (continued)



Source: Author's own work

6.0 Conclusion, Limitations and Future Research

This research paper presented an HPM system that is specifically designed to suit airport projects to address the shortcomings of adopting a single project management system to handle large-scale construction projects. The research points out that the intensity of regulation, stakeholders, and uncertainty are diverse in airport projects in terms of various project processes, and a systematic literature review and qualitative data regarding interviews with industry experts were analysed.

The findings indicate that different PMBOK processes in an airport project can gain from the specific strengths of traditional, agile, and hybrid project management approaches. The study proposes a structured framework for airport development projects by mapping 102

airport-specific activities to the 49 PMBOK processes and then assigning the appropriate management approaches at the process level.

The proposed framework suggests process-level methodology selection rather than a single uniform approach, allowing project managers to implement structured and controlled methods where outcomes are predictable and adaptive methods where change and iteration are unavoidable. In this way, the approach aligns industry-specific operational needs with project management principles. This study's main contribution is converting hybrid project management idea into a tailored framework for an airport project. The proposed framework gives a base for decision making which would be informed for complex projects. But this study is based upon the observations and experience of Industry professionals and literature review study. Future researchers can contribute by providing empirical evidence to strengthen this study.

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CHAPTER 23

A Study on Dynamic Resource Allocation for Construction Projects

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ABSTRACT

The construction industry is one of the backbones of national infrastructure that faces major challenges such as labor allocation, fragmented planning, and poor utilization of resources. The study aims at improving resource planning for complex residential projects by identifying bottlenecks in operations to minimise schedule delays and cost overruns. Initially, current resource allocation practices were reviewed to assess its impact on the project performance and avenues to improve resource allocation were identified considering technology based frameworks. The Study adopted a case study approach, which combines Primavera P6 for scheduling, resources levelling and track KPIs with Power BI to help practioners improve resource allocation. The framework combines hybrid simulation methodology using Discrete Event Simulation (DES) and System Dynamic (SD) approach, to understand workflow interdependencies and allows maintaining and monitoring of the project processes. Results indicate significant increase in the labor usage, improving on time delivery performance of the projects. The suggested model is valuable in terms of creating a replicable, data-driven project delivery mechanism.

Keywords: Resource allocation, Process improvement, Hybrid simulation (DES - SD), Project performance.

1.0 Introduction

The construction industry, known as one of the pillars of infrastructural development and economic growth, is a sector in a very uncertain environment, with high resource dependence and complicated coordination requirements. With the current growth of contemporary projects in size, technical complexity and dependencies, the call to control labour, equipment and materials with greater precision has grown.

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This is particularly important in high rise residential and mass infrastructural projects where the changing conditions of sites and the sequential nature of work processes means that nimble and data-driven decision-making is required.

However, as these demands change, numerous construction companies are still using stagnant scheduling processes, anarchic planning processes and manual control systems. The traditional methods have been notorious to react suitably to the real-time changes in the availability of labor force, productivity and the operational limitations. This leads to inefficient labour practices, workflow interruptions, schedule slippage and cost increase being common in the industry. These systemic challenges reinstate the necessity to have a more adaptive perceptive and analytically informed policy to the allocation of resources.

The new digital technologies, Building Information Modeling (BIM), artificial intelligence (AI), predictive analytics, Internet of Things (IoT) platforms and automated scheduling tools, offer significant opportunities to make the process more transparent and predictive and coordinate it more efficiently. Nonetheless, there is still a discrepancy in the practical use of these tools in the industry.

In attempts to fill these gaps, the current study utilizes an extensive digital framework involving the combination of Primavera P6 to schedule and level resources with Power BI to perform analytic visualization. Furthermore, a mixed simulation model based on Discrete Event Simulation (DES) and System Dynamics (SD) is taken to analyze the workflow dependencies and the resource long-term behavior. The study seeks to analyse the existing allocation activities, evaluate how optimization affects labour productivity and project performance, and develop evidence-based options to enhance resource management of the complex construction setting.

2.0 Literature Review

Construction projects are one of the key elements of the country's infrastructure development, but their implementation is often limited by poor resource allocation mechanisms, disorganized planning behaviours, and repetitive overruns. The problems become magnified in residential developments in large scale and high rise where conditions in the project environment include several stakeholders, interdependent activities and constantly shifting site conditions. The presence of multiple interests, long-term scope of the projects, and external regulation factors leads to a high level of uncertainty, thus making efficient project delivery more difficult (Caldas and Gupta, 2017; Mok et al., 2015).

The resources involved in construction such as workforce, material, machinery and time directly impact on project productivity and cost-efficiency. Out of them, labor and materials take a large portion of project spending, which in many cases amounts to more than

half of the total project costs (Sroka, 2021). Poor distribution of such resources will lead to wastage of time, workflow delay, and wasting of productivity which spreads over the project phases. Mok et al. (2015) also stressed that one of the basic managerial duties is the capability to match the availability of resources with the need to construct something.

Resource planning is also complicated by the fact that the procurement of materials is uncertain. The fluctuation of material price, quality, and availability has been cited as a major problem in fluctuating the schedule and increasing costs (Ibrahim and Elshwafy, 2021). Since the construction materials are usually obtained under the influence of several suppliers, strategic sourcing and supplier selection turns out to be the crucial factors of project success. The scholars have shown that informed sourcing choices might help decrease procurement risks and increase operational efficiency and competitiveness (Stanczyk et al., 2015; Ramanathan, 2017).

In order to solve the problem of supplier-related decisions, researchers first applied the deterministic model of optimization that includes linear programming and mixed-integer programming. One of the contributions that Ghodsypour and O'Brien (1998) made was to combine Analytical Hierarchy Process with linear programming to allow both qualitative and quantitative selection criteria. Later research made supplier selection into a multi-criteria decision-making issue, where cost, quality, reliability, and delivery performance should be assessed concurrently (Ho et al., 2010; Keskin et al., 2010). More recent studies have gone further to implement the methods with uncertainty using rough set theory, gray systems, evidential reasoning and multi-objective optimization models (Arabsheybani et al., 2018, 2019; Polat and Eray, 2015; Stević et al., 2017; Yazdani et al., 2019).

Similar trends in construction planning studies have also found an underlying weakness with the traditional scheduling behavior. Implementation of superior scheduling systems, including Primavera P6 has enhanced access to sequence of activities, identification of critical paths, and leveling of resources. However, there are a number of studies suggesting that the use of scheduling tools alone is not sufficient in responding to the dynamic characteristics of construction operations without the use of ancillary analytical and predictive methods.

This has led to the rise in the use of simulation-based methods in construction management as a decision support mechanism. DES is useful in reflecting variability of the processes and interaction of resources. System Dynamics is, conversely, appropriate to study the effects of workforce learning, rework cycles and policy impacts in the long term due to its emphasis on feedback and accumulative behaviour. Recent literature recommends the use of DES and SD together as it has been found to give a better insight on both the short-term performance on operations and the long-term pattern in the project. The application of key performance indicators with the help of digital analytics tools like Power BI has facilitated

real-time tracking of the labor usage, schedule variance, and productivity patterns, which allows taking the project under control in advance.

Although a lot has been researched in the field of optimization, scheduling, simulation, and sustainability, the prevailing literature focuses on researching these aspects in isolation. There is a lack of focus on creating an integrated, technology-based structure that can accommodate both dynamic resource allocation, scheduling, simulation modeling, and performance analytics in one setting of a construction project. In addition, such integrated solutions have not been empirically validated when used in high-rise residential projects.

To this end, there is a distinct gap in the existing research on the use of systematic, evidence-based resource management models in the management of complex construction projects. Closing this gap with the help of the Primavera-based scheduling, resource leveling, hybrid DES-SD simulation and KPI-based performance monitoring is associated with a high potential of the improvement of the level of labor utilization, the decrease of schedule delays, and the overall project delivery performance.

3.0 Objectives

1. To study the current practices and techniques used for resource allocation in complex construction projects.
2. To analyse how optimized resource allocation influences labour productivity and project performance.
3. To identify the challenges and barriers that limit effective resource allocation in construction environments.
4. To propose strategies and technological solutions to improve resource allocation and enhance overall project outcomes.

4.0 Research Methodology

4.1 Research design and case study approach

The research design used in this study is a case-study based research in order to analyze dynamic resource allocation in a high-rise residential project. The literature review that informed the methodology demonstrates that the traditional conservative approaches to planning are not sufficient to deal with the variability in labor, workflow dependencies, and schedule uncertainty within a complicated construction setting. According to the previous research, it is important to incorporate digital scheduling, simulation and performance analytics. In this case, the study suggests a technology-based model which brings together Primavera P6, simulation, and data analytics to facilitate dynamic decisions. The chosen high-

rise construction with its repetitive floor patterns and high labor utilization can serve as a realistic environment to prove the efficacy of the suggested model under the real conditions of the sites.

Figure 1: The Figure Illustrates the Process of Reviewing Methodologies Adopted in Existing Research Studies to Identify Gaps in Both the Literature and Real-world Practice



Source: Created by authors

Figure 2: Construction Optimization Models and Tools

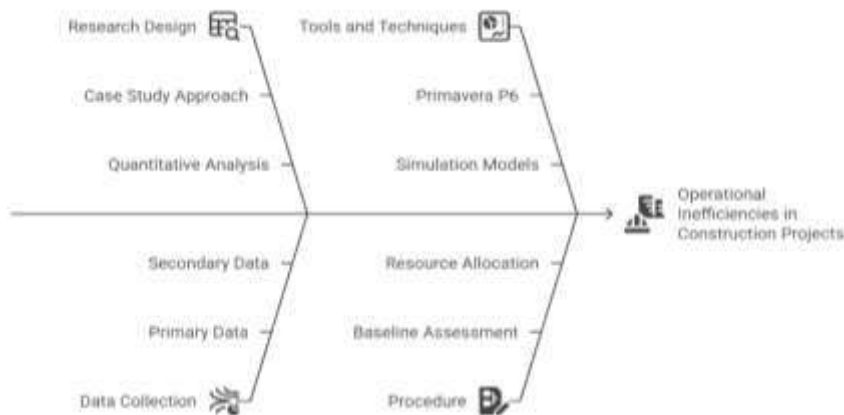


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4.2 Literature review data analysis

Data analysis in the given study is determined by the methodologies revealed in previous studies on the optimization of the construction workforce, which focus on applying the techniques of digital scheduling and dynamic analysis. In line with that, the project schedule was developed in Primavera P6, the labor resources were allocated as well as the critical activities and the workforce imbalance were identified with the help of resource loading and levelling.

Figure 3: Fishbone Diagram Explaining the Process of this Research Paper



Source: Created by authors

4.3 Step-wise research framework

The research approach has been organized into four consecutive processes creating a dynamic resource allocation model that is integrated and iterative.

Step 1: Literature-Based Approach to Method Choice and Framework.

The initial move was to undertake a review of previous studies on construction scheduling, resource optimization, simulation, and performance measurement. The literature review has aided the determination of the gaps in the methodology, the absence of the combination of scheduling platforms and simulation and analytics tools, in particular. Through these findings, the research structure was developed such that deterministic scheduling was used together with dynamic analysis in such a manner that operational level and system level was achieved.

Step 2: Project Scheduling and Resource Modelling with Primavera p6.

The second step involved creation of a detailed project schedule with the help of Primavera P6. The activities were organized in a Work Breakdown Structure (WBS) that

included all the key phases of the entire process of excavation to occupancy certification. The logical relationships, time durations, and milestones were stipulated depending on project documentation and site inputs. Required data fields such as planned dates, actual dates, resource assignments, costs, and progress parameters were configured.

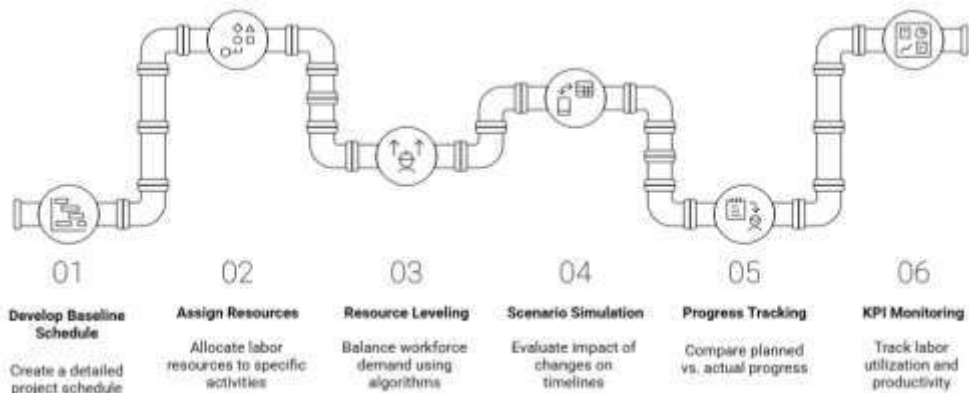
The allocation of labor and equipment resources to activities was done using standard productivity norms. To make it possible to compare actual progress and altered scenarios, a baseline schedule was set. The resource leveling features were implemented to determine the over-allocations, idle times, and peak manpower requirements.

Figure 4: This Template Acts as a Reusable Planning Framework, Allowing Professionals to Customise the Model for Similar Projects without Starting from Scratch

Layout: Classic Schedule Layout		Filter: All Activities						
Activity ID	Activity Name	Planned Start	Planned Finish	Actual Start	Actual Finish	Physical % Complete	Original Duration	Remaining Duration
Navi Mumbai Civil Works Projects		23-Nov-22 08:00 AM	08-Dec-25 11:12 AM	28-Nov-22 08:00 AM			793	342
Project Approval		23-Nov-22 08:00 AM	22-Mar-23 05:00 PM	28-Nov-22 08:00 AM	28-Mar-23 05:00 PM		86	0
A1230	Project Kick-off	23-Nov-22 08:00 AM	23-Nov-22 05:00 PM	28-Nov-22 08:00 AM	28-Nov-22 05:00 PM	100%	1	0
A1240	Appointment of Consultant	23-Nov-22 08:00 AM	28-Nov-22 05:00 PM	28-Nov-22 08:00 AM	03-Dec-22 05:00 PM	100%	5	0
A1250	Existing Building Structural Audit	30-Nov-22 08:00 AM	08-Dec-22 05:00 PM	04-Dec-22 08:00 AM	12-Dec-22 05:00 PM	100%	7	0
A1260	Preparation of Renovation Drawings	09-Dec-22 08:00 AM	29-Dec-22 05:00 PM	18-Dec-22 08:00 AM	18-Dec-22 05:00 PM	100%	8	0
A1270	MHADA Approval	21-Dec-22 08:00 AM	30-Jan-23 05:00 PM	19-Dec-22 08:00 AM	19-Jan-23 05:00 PM	100%	29	0
A1280	BMC IOD Approval	31-Jan-23 08:00 AM	13-Mar-23 05:00 PM	26-Jan-23 08:00 AM	26-Feb-23 05:00 PM	100%	30	0
A1290	Fire NOC	18-Dec-22 08:00 AM	05-Jan-23 05:00 PM	01-Mar-23 08:00 AM	18-Mar-23 05:00 PM	100%	15	0
A1300	Commencement Certificate (CC)	14-Mar-23 08:00 AM	22-Mar-23 05:00 PM	19-Mar-23 08:00 AM	26-Mar-23 05:00 PM	100%	7	0
Project Initialization		23-Mar-23 08:00 AM	14-Nov-24 05:00 PM	01-Apr-23 08:00 AM			431	66
A1000	Site Preparation	23-Mar-23 08:00 AM	12-Apr-23 05:00 PM	01-Apr-23 08:00 AM		0%	15	15
A1010	Site Mobilization	05-Sep-24 08:00 AM	11-Sep-24 05:00 PM	05-Sep-24 08:00 AM		0%	5	5
A1010m	Site Mobilization Completed		04-Sep-24 05:00 PM			0%	0	0

Source: Created by authors

Figure 5: Primavera Project Steps Needed to Develop the P6 Model



Source: Created by authors

Step 3: Active analysis via simulation methods.

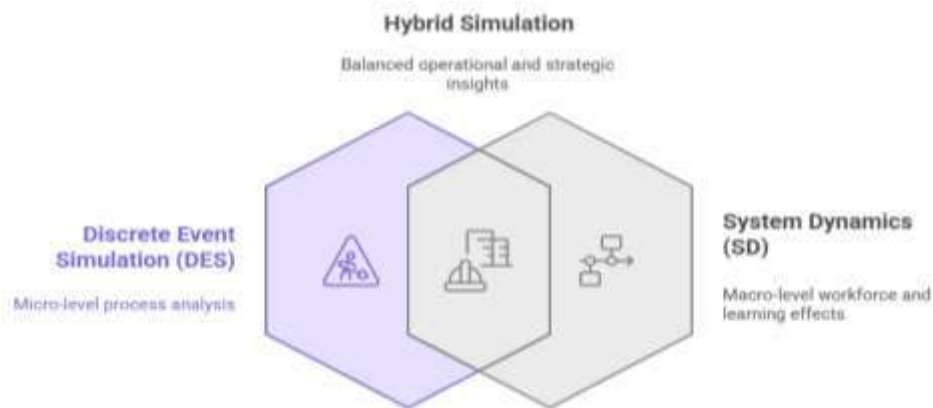
The third step to overcome the shortcomings of the static method of scheduling involved the adoption of a hybrid simulation approach.

The activity-level workflows, crew interaction and short-term disturbances including inspection delays, equipment breakdowns and productivity change were analysed using Discrete Event Simulation (DES).

System Dynamics (SD) was used to include long run feedback effects, e.g. the impact of labor shortages on productivity, rework and cumulative schedule delays.

The combination of DES and SD allowed us to obtain the full picture of both the short-term operational effects and the long-term project performance trends to make the decisions on healthy resource redistribution in the future.

Figure 6: Visual Presentation of Planning Processes at Micro and Macro Level Eliminates Major risks that Delay the Project. Holistically Combining the Decision Making Process with Physical Activities, keeping all Stakeholders in Loop



Source: Created by authors

Step 4: Decision Support and Performance Measurement.

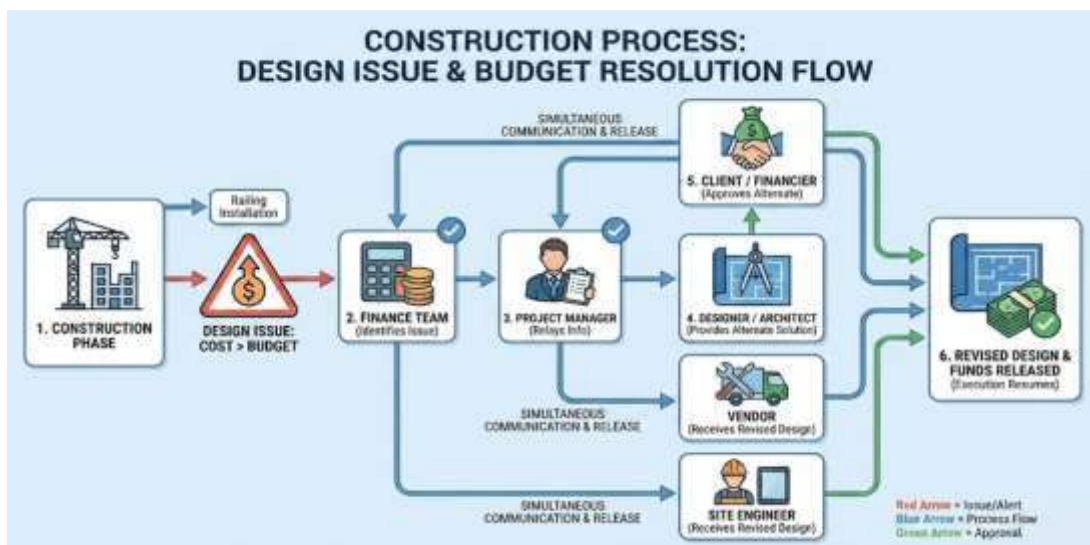
The Primavera P6 data is used to identify KPIs, such as the use of labor, materials, and equipment to create a successful decision-support dashboard. The dashboard would facilitate predicting the risk, analysis of the situation, and prior mitigation as it would emphasize the possible delays and constraints. KPIs visualized enable non-technical stakeholders to interpret project status within a very short time and act on it. Constant monitoring can guarantee the flow of work, avoid any delays related to slow feedback or incorrect resource management.

Figure 7: KPI - Based Roadmap for Dynamic Workforce Optimization



Source: Created by authors

Figure 8: How the Model Works- e.g. While Construction Progresses, A Design Issue Arises while Installing the Railing



Source: Created by authors

Step 5: RACI Framework- Stakeholder Responsibility Alignment

The RACI analysis shows that the PMC and Main Contractor are the main accountable and responsible parties throughout the majority of the construction phases, whereas consultants and MEP contractors are of vital importance in the coordination process during execution and completion. s

Approval-oriented stages fall under the authority of statutory bodies especially in pre-construction and OC procedures suggesting approval risks as external dependency. The RACI

framework enhances role demarcation and minimizes the coordination gaps, overhangs of responsibilities and improves schedule control in a complex high-rise project.

Table 1: RACI Framework on the Selected Case Study to Study Human Resource Allocation

Project Stage / Activity	Client / Developer	PMC	Main Contractor	Architect & Structural Consultants	MEP Contractors	Vendors / OEMs	Site Engineer	Statutory Authorities
Pre-construction approvals & mobilization	A	R	R	C	I	I	I	R
Excavation & dewatering	I	A	R	C	I	I	R	I
Piling & foundation works	I	A	R	C	I	I	R	I
Raft, plinth & ground floor	I	A	R	C	I	I	R	I
Podium, amenities & transfer slab	I	A	R	C	C	I	R	I
Typical floors (8th–44th, Mivan cycle)	I	A	R	C	C	I	R	I
Refuge floors & fire compliance	I	A	R	C	C	I	R	R
Terrace & above-terrace RCC works	I	A	R	C	C	I	R	I
Blockwork & internal plaster	I	A	R	C	C	I	R	I
Flooring, finishes & common areas	I	A	R	C	C	R	R	I
Lift installation & commissioning	I	A	I	I	C	R	R	C
OC documentation & NOCs	A	R	C	C	I	I	I	R
Final inspection & OC receipt	A	I	I	I	I	I	I	R
Resource planning & schedule control (Primavera)	I	A	R	C	C	I	R	I
Delay recovery & change management	C	A	R	C	C	I	R	I

Source: Created by authors

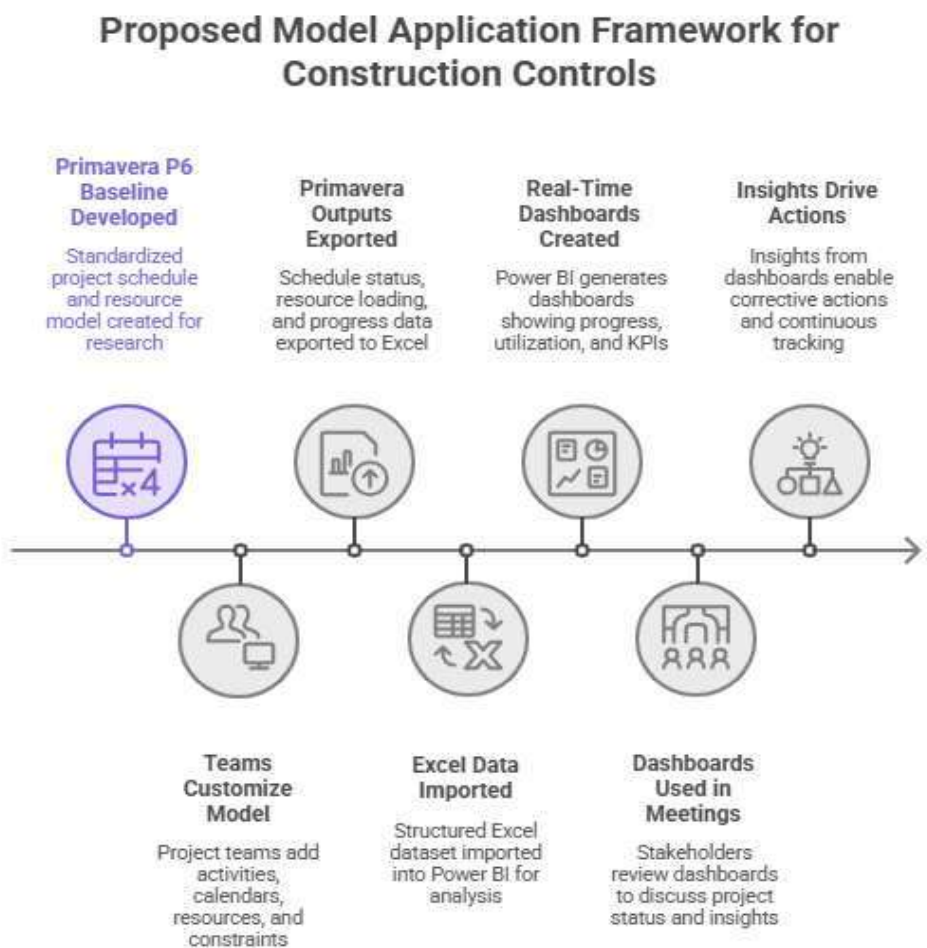
4.3 Assumption of the study

The study is based on the following assumptions:

- The model is based on the selected real life case study in Indian cities environment, and made for cluster, high-rise brownfield residential development.
- This helps us make a controlled, non-generic model, which caters to this type of project.
- Activity durations are derived from standard productivity rates adjusted for site conditions.
- Labor productivity varies due to congestion, learning effects, and external disruptions.
- Resources availability is finite and constrained by organizational and contractual factors.

- External influences such as weather and approvals introduce variability but are manageable through dynamic planning.

Figure 9: Steps Followed to Execute the Conceptual Idea, as per the Assumptions



Source: Created by authors

5.0 Data Analysis

5.1 Case study data analysis

During model development, critical challenges influencing this category of projects were systematically assessed. In alignment with the model assumptions and functional requirements, a structured approach to data analysis was implemented.

5.1.1 Project overview

The case study under choice is grounded on a project in Mumbai, Maharashtra. The project will comprise several high-rise towers developed in several rehabilitation (REHAB) and sale segments, with a height of each tower between G+42 and G+48. The project is planned to be broken down into three stages:

Phase 1: REHAB + Towers 1 & 2

Phase 2: Towers 3 & 4

Phase 3: Towers 5 & 6

Considering the magnitude and intricacy of construction, resource optimization, especially concerning labor productivity, workforce allocation, etc. is vital in resolving delivery schedules without compromising on quality and cost effectiveness.

5.1.2 Data collection and scope

In this case study, information was gathered on the site about two key finishing activities:

- *Gypsum Work*: All data contained number of laborers assigned, their productiveness rates and completion schedule.
- *Flooring Work (Tiling)*: The data consisted of the number of laborers involved, the material needed, labor productivity and efficiency in using the tile.

There were also provisional project schedules of tower stages completion. The workforce allocation, bottleneck and the influence of dynamic scheduling model are studied based on these datasets.

5.1.3 Workforce analysis

Gypsum Work: The labor team productivity variability was indicated by the data on the gypsum workforce. Mean outputs were compared to the project needs to approximate completion periods. It was noted that: Productivity was varying according to the level of skills and workforce disposition. Some of the floors had lagged behind because of the lack of fit between the manpower assigned and the work done. Optimal labor gang size was attained in balancing the speed and quality.

Flooring WorkL: The flooring data set was able to give information on the effectiveness of labor deployment and material use efficiency too. Others: pivotal conclusions were: The average daily/weekly productivity per worker ascertained realistic outputs. There were found cases of material wastage on the basis of erroneous tile cutting/placement, and resources inefficiency was associated with the missing gaps in workforce training. Causal relationships with other trades (e.g., waterproofing, MEP clearances) led to idle working hours, which highlighted the necessity of de facto allocation, as opposed to planned scheduling.

Table 2: Labour Work Tracking Sheet

Location	Date	Labor		Gypsum Plaster Done			Living	Kitchen
		Mason	Helper	M. Bed	Bed 1	Bed 2		
1705 (3BHK)	11-Jun-25	2	2	C				WIP
	12-Jun-25	2	2	C	P		WIP	WIP
	13-Jun-25	1	1	C	P	WIP	WIP	WIP
	14-Jun-25	1	1	C	WIP	WIP	WIP	WIP
	15-Jun-25	1	1	C	WIP	WIP	WIP	WIP
	16-Jun-25	1	1	C	C	WIP	WIP	WIP
	17-Jun-25	1	2	C	C	C	WIP	C
	18-Jun-25	2	2	C	C	C	C	C
Total	1 week	11	12					
1002 (2BHK)	21-Jun	1	1	C	WIP	NA	P	P
	22-Jun	Holiday						
	23-Jun	1	1	C	C	NA	P	P
	24-Jun	1	1	C	C	NA	WIP	P
	25-Jun	1	1	C	C	NA	C	WIP
	26-Jun	1	1	C	C	NA	C	C
Total	5 Days	5	5					

Source: Created by authors

Table 3: Project Timeline

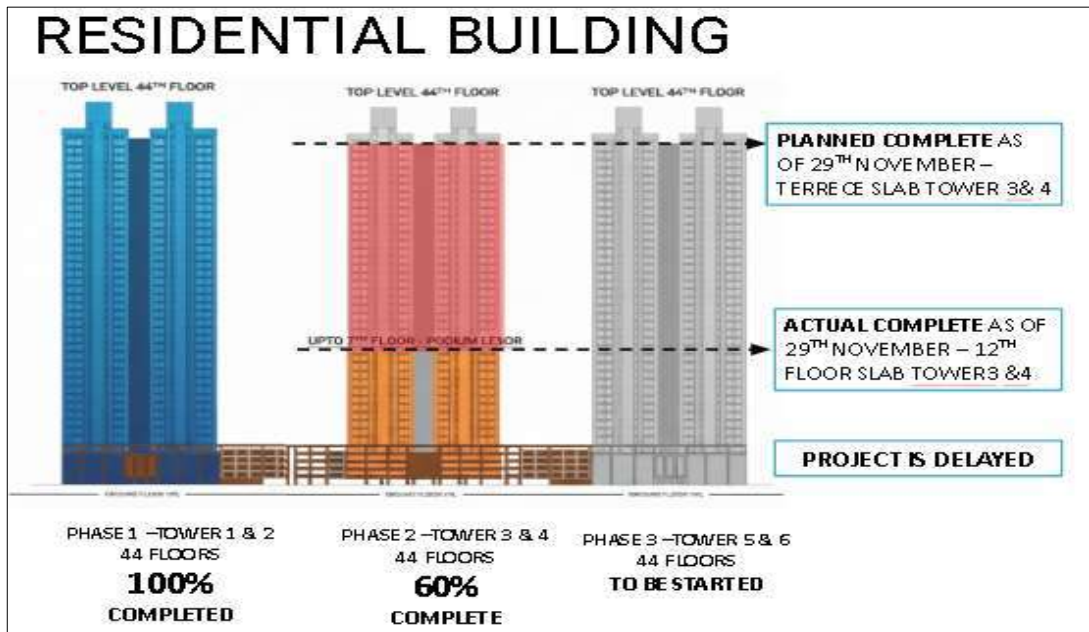
Phase 1				Phase 2			
Tower 1		Done		Tower 2		Done	
		Start Date	End Date			Start Date	End Date
OC Receipt- Full OC			26-Jan-26	OC Receipt- Full OC			19-Jun-26
Complete OC duration			26	Complete OC duration			26
OC Application- Full OC			27-Dec-25	OC Application- Full OC			20-May-26
Lift completion			01-Aug-25	Lift completion			22-Dec-25
Common area flooring completion			20-Sep-25	Common area flooring completion			10-Feb-26
Flat / Toilet Flooring/ Dado completion			27-Jul-25	Flat / Toilet Flooring/ Dado completion			17-Dec-25
Internal Plaster completion			23-May-25	Internal Plaster completion			13-Oct-25
Blockwork completion			23-Apr-25	Blockwork completion			13-Sep-25
Above Terrace RCC		15-Mar-25	19-Apr-25	Above Terrace RCC		05-Aug-25	26-Sep-25
Terrace		02-Mar-25	14-Mar-25	Terrace		23-Jul-25	04-Aug-25
42nd floor, Refuge Floor		17-Feb-25	01-Mar-25	48th floor		10-Jul-25	22-Jul-25
43rd floor		04-Feb-25	16-Feb-25	47th floor		27-Jun-25	09-Jul-25
40th floor		24-Jan-25	03-Feb-25	46th floor		14-Jun-25	26-Jun-25
39th floor		13-Jan-25	23-Jan-25	45th floor		01-Jun-25	13-Jun-25
38th floor		02-Jan-25	12-Jan-25	44th floor		19-May-25	31-May-25
37th floor		22-Dec-24	03-Jan-25	43rd floor		06-May-25	18-May-25
36th floor		13-Dec-24	21-Dec-24	42nd floor, Refuge Floor		23-Apr-25	05-May-25
35th floor, Refuge Floor		28-Nov-24	10-Dec-24	41st floor		10-Apr-25	22-Apr-25
34th floor		17-Nov-24	27-Nov-24	40th floor		30-Mar-25	09-Apr-25
33rd floor		06-Nov-24	16-Nov-24	39th floor		19-Mar-25	29-Mar-25
32nd floor		20-Oct-24	05-Nov-24	38th floor		08-Mar-25	18-Mar-25
31st floor		10-Oct-24	25-Oct-24	37th floor		25-Feb-25	07-Mar-25
30th floor		06-Oct-24	14-Oct-24	36th floor		14-Feb-25	24-Feb-25
29th floor		27-Sep-24	05-Oct-24	35th floor, Refuge Floor		01-Feb-25	13-Feb-25
28th floor, Refuge Floor		14-Sep-24	26-Sep-24	34th floor		21-Jan-25	31-Jan-25
27th floor		05-Sep-24	13-Sep-24	33rd floor		10-Jan-25	20-Jan-25
26th floor		27-Aug-24	04-Sep-24	32nd floor		30-Dec-24	09-Jan-25
25th floor		18-Aug-24	26-Aug-24	31st floor		19-Dec-24	29-Dec-24
24th floor		09-Aug-24	17-Aug-24	30th floor		10-Dec-24	18-Dec-24
23rd floor		23-Jul-24	08-Aug-24	29th floor		01-Dec-24	09-Dec-24
22nd floor		22-Jul-24	30-Jul-24	28th floor, Refuge Floor		18-Nov-24	30-Nov-24
21st floor, Refuge Floor		13-Jul-24	21-Jul-24	27th floor		09-Nov-24	17-Nov-24
20th floor		04-Jul-24	12-Jul-24	26th floor		31-Oct-24	08-Nov-24

Source: Created by authors

Tentative Timeline and Scheduling: The completion of towers was developed into a baseline timeline using project schedules. In the conventional static approaches to planning used in MS Project (MSP) and Primavera, the durations of activities, dependencies and manpower requirements were given.

Nevertheless, these tools also exposed: Critical delays in gypsum finishing which affects other tiling works. The under-use of work force in some stages with others being overworked. In this regard, we will implement dynamic resource allocation models. To enhance project efficiency, by relocating superfluous labor in the low priority areas to the late critical path tasks.

Figure 10: Explains the Case Study Timeline and Status



Source: Created by authors

5.2 Primavera analysis

The figure shows a delay mitigation system in a 44 storey high-rise building, which connects key milestones with possible delay causes, and intended delay mitigation strategies. It employs levelling of resources, logic optimization, and look-ahead scheduling in order to minimize the amount of idle time and bottlenecks. Monitoring also allows identifying problems in time, which supports getting the schedule under control and completing the project in time.

5.3 Development of a standardised primavera P6 project template

Following a detailed understanding of the case study, the project was translated into a primavera P6 model to develop a standardised sample template.

The P6 model can be customised and scaled by the organizations based on their requirements and needs. But the major milestones and baselines are considered as per a typical residential project of this scale.

Figure 11: Sample P6 Project Template

Layout: Classic Schedule Layout		Filter: All Activities							
Activity ID	Activity Name	Planned Start	Planned Finish	Actual Start	Actual Finish	Physical % Complete	Original Duration	Remaining Duration	
Navi Mumbai Civil Works Projects		23-Nov-22 08:00 AM	08-Dec-22 11:12 AM	23-Nov-22 08:00 AM			793	342	
Project Approval		23-Nov-22 08:00 AM	22-Mar-23 05:00 PM	23-Nov-22 08:00 AM	25-Mar-23 05:00 PM		86	0	
A1230	Project Kick-off	23-Nov-22 08:00 AM	23-Nov-22 05:00 PM	23-Nov-22 08:00 AM	28-Nov-22 05:00 PM	100%	1	0	
A1240	Appointment of Consultant	23-Nov-22 08:00 AM	29-Nov-22 05:00 PM	23-Nov-22 08:00 AM	03-Dec-22 05:00 PM	100%	5	0	
A1255	Existing Building Structural Audit	16-Nov-22 08:00 AM	08-Dec-22 05:00 PM	04-Dec-22 08:00 AM	12-Dec-22 05:00 PM	100%	7	0	
A1260	Preparation of Renovation Drawings	09-Dec-22 08:00 AM	28-Dec-22 05:00 PM	18-Dec-22 08:00 AM	18-Dec-22 05:00 PM	100%	8	0	
A1275	MHADA Approval	21-Dec-22 08:00 AM	30-Jan-23 05:00 PM	19-Dec-22 08:00 AM	19-Jan-23 05:00 PM	100%	29	0	
A1280	BMC IDO Approval	31-Jan-23 08:00 AM	13-Mar-23 05:00 PM	25-Jan-23 08:00 AM	26-Feb-23 05:00 PM	100%	30	0	
A1290	Fire NOC	16-Dec-22 08:00 AM	05-Jan-23 05:00 PM	01-Jan-23 08:00 AM	15-Mar-23 05:00 PM	100%	15	0	
A1300	Commencement Certificate (CC)	14-Mar-23 08:00 AM	22-Mar-23 05:00 PM	19-Mar-23 08:00 AM	26-Mar-23 05:00 PM	100%	7	0	
Project Initialization		23-Mar-23 08:00 AM	14-Nov-24 05:00 PM	01-Apr-23 08:00 AM			431	66	
A1000	Site Preparation	23-Mar-23 08:00 AM	12-Apr-23 05:00 PM	01-Apr-23 08:00 AM		0%	15	15	
A1010	Site Mobilization	05-Sep-24 08:00 AM	11-Sep-24 05:00 PM	05-Sep-24 08:00 AM		0%	5	5	
A1010m	Site Mobilization Completed		04-Sep-24 05:00 PM			0%	0	0	

Source: Created by authors

5.3.1 Data capture and schedule updating

In Primavera P6, the actual project progress is periodically updated in a schedule during project implementation. This includes:

- Update of activity start and finish.
- Percentage completion
- Cost and resource utilization.

Primavera P6 also guarantees a reliable and consistent way of data capture because Primavera P6 is accepted as robust in schedule control and reporting.

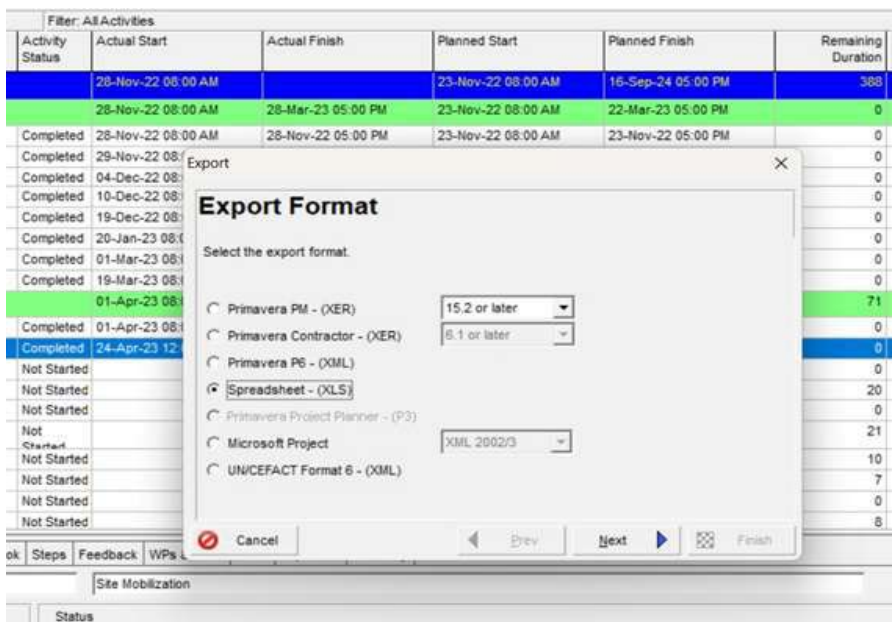
5.3.2 Data export from primavera P6

The information that is exported contains only the columns needed to perform the analysis like:

- Schedule status
- Cost information
- Earned Value parameters
- Details of resources allocation.
- Risk-related indicators

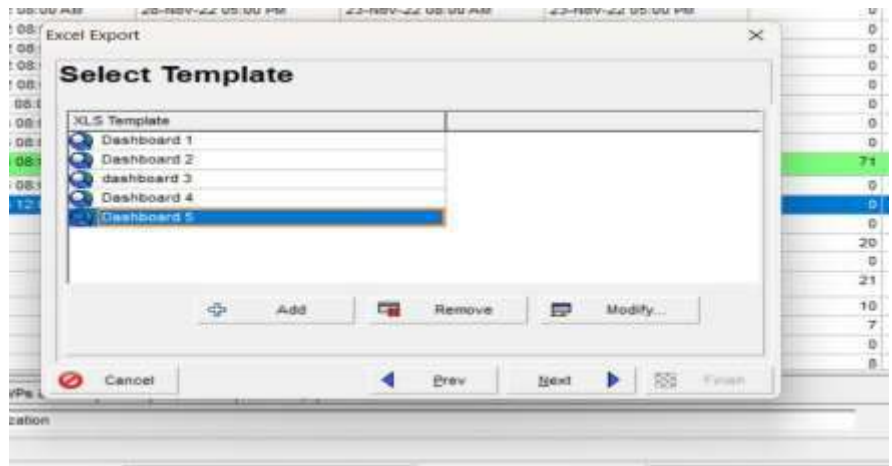
The step guarantees organized structured data to proceed with further analysis.

Figure 12: After Updating the Schedule, the Primes Project Data is Exported in Primavera P6 to Excel (XLS) File



Source: Created by authors

Figure 13: Dashboard Templates Models Already Made as per Required KPI's and Power Bi Dashboard Requirements



Source: Created by authors

5.3.3: Integration with Power Bi

The xls sheet is uploaded in Power bi and transformed into filterable data and dashboards are made.

Figure 14: Data from the xls File is Uploaded and Transformed, for Making Power Bi Dashboards

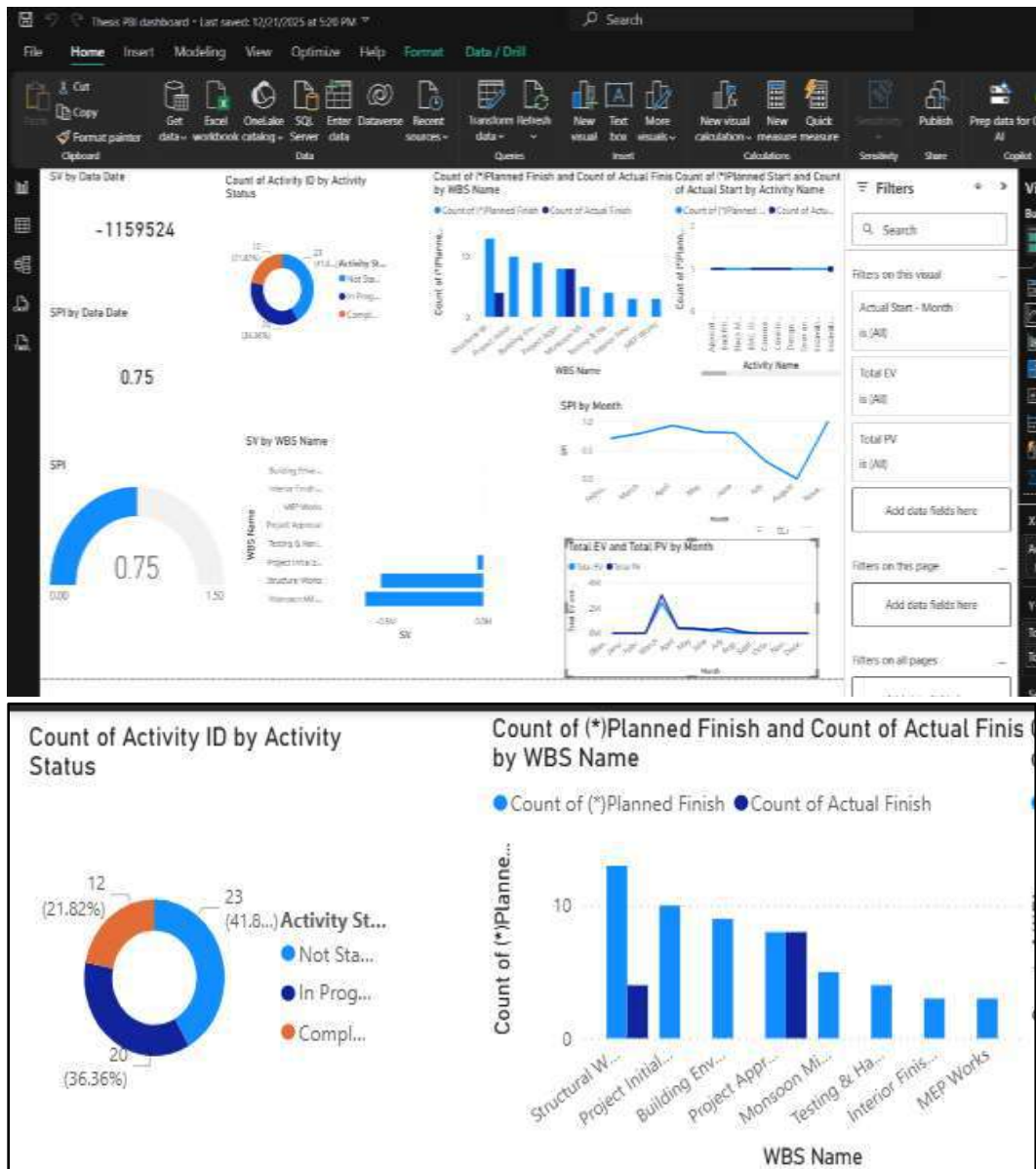
Activity ID	Activity Status	WBS Code	WBS Name	Budget At Completion(\$)	Actual Finish	Physical % Complete(%)	Activity Count	Free Float(\$)	Total Float(\$)	Critical
A1000	In Progress	NEWPRC1-1.1	Project Initialization	29400		0	1	0	0	Y
A1010a	Not Started	NEWPRC1-1.1	Project Initialization	0		0	1	0	0	Y
A1020	In Progress	NEWPRC1-1.1	Project Initialization	115700		100	1	0	0	Y
A1020a	Not Started	NEWPRC1-1.1	Project Initialization	0		0	1	0	0	Y
A1030	In Progress	NEWPRC1-1.1	Project Initialization	238160		0	1	0	0	Y
A1060	Not Started	NEWPRC1-1.3	Building Envelope	1700		0	1	0	0	Y
A1100	Not Started	NEWPRC1-1.3	Building Envelope	719700		0	1	0	0	Y
A1030	Completed	NEWPRC1-1.2	Structural Works	134800	25 April 2024	100	1	0	0	N
A1411	Completed	NEWPRC1-1.2	Structural Works	103380	07 May 2024	100	1	0	0	N
A1412	Completed	NEWPRC1-1.2	Structural Works	134800	17 May 2024	100	1	0	0	N
A1413	In Progress	NEWPRC1-1.2	Structural Works	134800		70	1	0	0	Y
A1425	In Progress	NEWPRC1-1.2	Structural Works	138000		80	1	0	0	Y
A1110	Not Started	NEWPRC1-1.4	MEP Works	4000		0	1	0	129	N
A1120	Not Started	NEWPRC1-1.4	MEP Works	3671900		0	1	0	129	N
A1130	Not Started	NEWPRC1-1.4	MEP Works	30032250		0	1	0	129	N
A1150	Not Started	NEWPRC1-1.5	Interior Finishing	68000		0	1	0	0	Y
A1160	Not Started	NEWPRC1-1.5	Interior Finishing	6600000		0	1	0	0	Y
A1170	Not Started	NEWPRC1-1.6	Testing & Handover	2000		0	1	0	0	Y
A1180	Not Started	NEWPRC1-1.6	Testing & Handover	2000		0	1	0	0	Y
A1190	Not Started	NEWPRC1-1.6	Testing & Handover	2000		0	1	0	0	Y
A1200	Not Started	NEWPRC1-1.6	Testing & Handover	0		0	1	0	0	Y
A1010	In Progress	NEWPRC1-1.1	Project Initialization	25800		0	1	0	302	N
A1210	In Progress	NEWPRC1-1.1	Project Initialization	139620		0	1	0	0	Y
A1220	In Progress	NEWPRC1-1.1	Project Initialization	23320		0	1	0	0	Y
A1230	Completed	NEWPRC1-1.7	Project Approval	200	28 November 2022	100	1	0	0	N
A1240	Completed	NEWPRC1-1.7	Project Approval	0	03 December 2022	100	1	0	0	N

Source: Created by authors

5.3.4 Dashboard design

- Dashboards are designed based on defined Key performance Indicators (KPI's) to ensure alignment with project objectives and performance measurement requirements.
- Each Dashboard provided focused insights into specific performance.
- Interactive visual elements such as filters (based on WBS), drill downs (based on days, weeks months) and trend analysis were incorporated to support real time monitoring, variance analysis and informed decision making by project stakeholders.

Figure 15 & 16: Using the P6 data, The dashboard shows SPI is designed, which has KPI cards showing SPI - i.e. 0.75 which means the project is behind schedule. (if SPI is less than 1), schedule variance based on the WBS, Activity status shows which activity is completed, in progress, or not started. Planned finish vs actual finish. Etc.

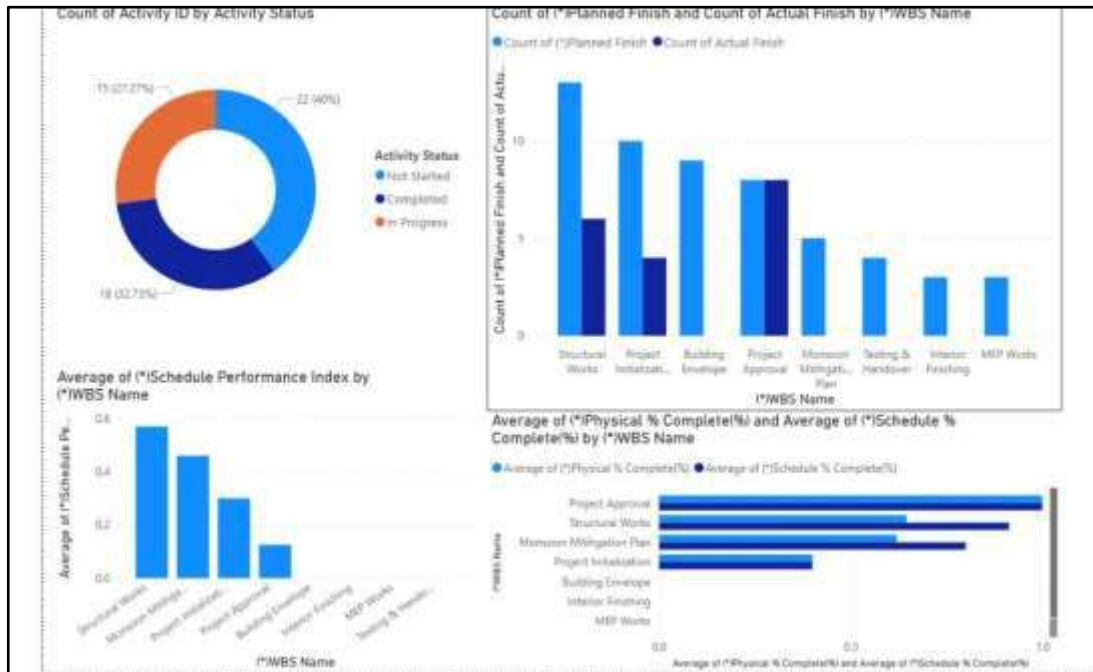


Source: Created by authors

5.3.5 Continuous updates

The Excel files are connected to Power BI, in which the predefined data models and dashboards are already developed.

Figure 17: Shows the Activity Status Donut Chart, Planned vs Actual Finish Clustered Chart, SPI as per each WBS Column Chart, etc.



Source: Created by authors

This data derived from P6 will get updated as the manager/ in charge updated the data and over rights the XLS file. After overwriting the data in power Bi needs to be refreshed, to get an updated chart.

5.3.6 Stakeholder communication and reporting

The visual dashboards also translate complicated project information into understandable charts, KPI, and filters to ensure information is easily comprehended by all stakeholders.

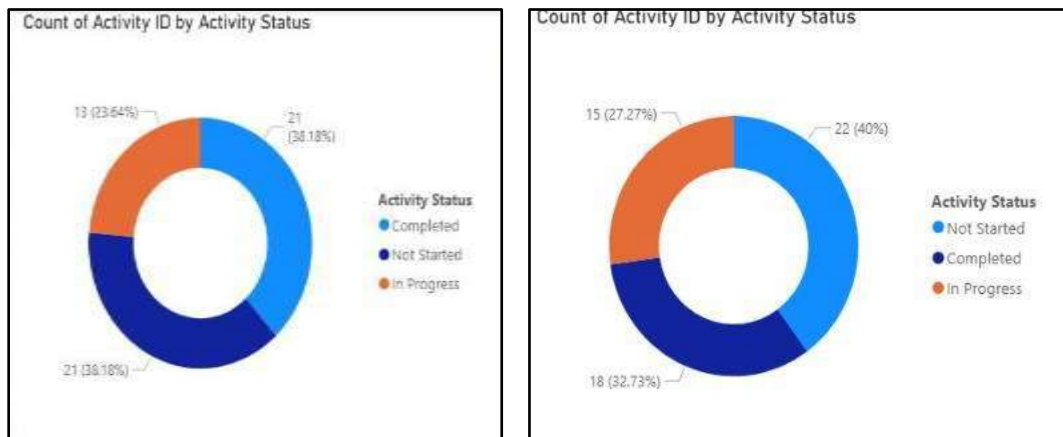
Project managers can:

- Webcast share boards between teams and levels.
- Create updates on progress on a daily or even hourly basis.

- Enhance accountability and transparency.

This greatly increases the speed and accuracy with which the information flows to assist in identifying the issues faster and taking corrective measures.

Figure 18 and 19: Show before and after Updating the P6 Model



Source: Created by authors

5.3.7 Decision-making support and project control

The model helps in real time monitoring of performance, whereby the project managers can:

- Early detect schedule delays.
- Determine cost overruns and resource wastage.
- Monitor variances on track.
- Be timely, informed and data-based.

This reinforces proactive project management as opposed to problem-solving.

5.3.8 Both value and practical benefits of the model

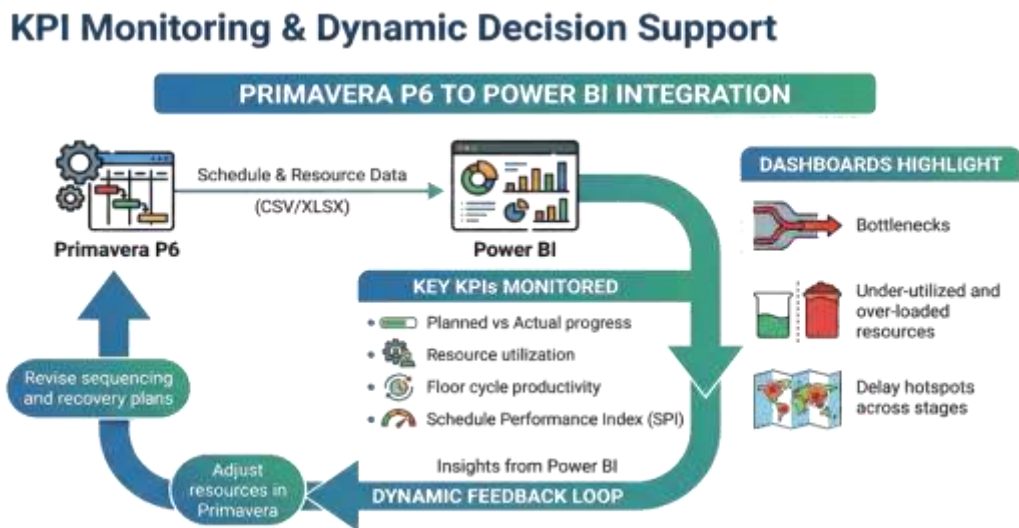
The proposed model will have the following benefits to project managers and planning professionals:

- Minimizes project set up and reporting time.
- Removes duplicate modelling and transformation of data.
- Enhances the efficacy and efficiency of planning as well as monitoring.
- Increases the level of coordination among the planning, execution and management teams.
- Facilitates scaling to different projects.

6.0 Key Finding

This study demonstrates that the combination of Primavera P6 and Power BI offers a scalable and data-driven planning and controlling Primavera P6 model in high-rise residential projects. In comparison to traditional systems, which are based on fragmented and delayed information, the suggested framework gives an opportunity to track everything in near real-time with the help of KPI-based dashboards. The performance of the schedule, use of labor, productivity, and delay recovery are key indicators that are used to detect the bottlenecks at an early stage. Also facilitating using the interactive dashboards is the scenario based decision making which enhances efficiency, saves planning time and increases control in the project lifecycle.

Figure 20: Primavera P6 to Power BI Integration



Source: Created by authors

The model assists organisations to gain improved control over complicated construction projects by offering a ready-to-use, versatile, and automated planning and reporting system and conserving a lot of time and effort.

6.2 Stage-wise delay drivers and primavera P6 based mitigation strategies

The stage-by-stage analysis of the high-rise project reveals that the project delays are interrelated due to the approval, resource, and coordination problems instead of sing-song activities. Statutory approvals and site preparations led to early delays as these factors were easier controlled by following the progress of approval milestones in Primavera P6.

Delay in substructure and podium was attributed to equipment, new construction processes and reinforcement planning, which was enhanced by the comprehensive WBS and levelling of resources. Repetitive floor cycles (Mivan) were handled through modelling crane, labor and inspection dependencies in order to identify early breaches. Delays at finishing stage (primarily caused by procuring and documentation of Occupancy Certificate) were minimized through observing statutory milestones.

Table 4: Simulation Table reflecting DES + SD

Area	P6 Feature Used	Purpose	Result
Planning & Baseline	Create Multiple Baselines	Compare progress over time	Identify slippage instantly
Critical Path Control	Run CPM Weekly	Locate delay-causing activities	Early intervention
Resource Optimization	Resource Leveling & Histograms	Avoid over/under allocation	Balanced workforce
Monitoring	Activity Steps + Physical % Complete	Track detailed task-level progress	Real-time visibility
Forecasting	Predictive Analysis	Predict impact of delay	Adjust sequencing
Risk Management	Risk Register & Float Tracking	Identify and quantify potential delays	Plan contingency
Performance Evaluation	SPI/CPI (Earned Value)	Quantify schedule efficiency	Data-driven control
Reporting	S-Curve & Layout Reports	Visual management updates	Transparent communication

Sr.No.	Stages	Delay Factors	Solutions	Effect
1	Start of Construction	Delay in statutory approvals (Commencement Certificate, RERA registration, NOCs). Funding delays from promoters or investors. Mobilization of contractors, machinery, and labor. Delay in site handover from client/owner. Site access issues, encroachments, or land disputes.	Define pre-construction WBS (approvals, mobilization, procurement). Use baseline start date to monitor slippage in statutory approvals. Apply constraints (Finish on or Before) for key approvals. Add activity codes for responsibility (Client/Contractor). Include early warning milestones like "Mobilization Complete".	visually see which approval is blocking construction start and manage float accordingly.
2	Excavation	Delay in approval for excavation from authorities. Equipment breakdown (excavators, dumpers). Hard strata or unforeseen soil conditions. Monsoon interruptions or dewatering issues. Safety non-compliance halting work. Delay in muck disposal or dumping permissions.	Link excavation sequence with logical dependencies to avoid idle time. Add lag durations for dewatering during monsoon. Maintain equipment resource calendars to track downtime. Use activity steps for layer-wise excavation progress tracking. Monitor productivity using earned value analysis (EVA) .	Prevents idle time for downstream activities (e.g., raft foundation).
3	Foundation Pile (Piling Works)	Machine availability and mobilization delays. Pile load testing delays. Design changes due to unexpected strata. Cement, steel, or bentonite shortage. Safety inspection delays. Poor productivity due to congestion or restricted working hours.	Assign critical resources (pile rigs, crane) and apply resource leveling. Add activity codes for test piles vs production piles. Set milestones for test approval before full mobilization. Create lookahead schedules (weekly) for pile installation to monitor output.	Improves sequencing, ensures pile productivity meets planned cycle.
4	Foundation Raft	Reinforcement bending/fixing delays. Shuttering and formwork shortages. Delay in raft concrete pour sequence and curing. Equipment breakdown (pumps, vibrators). Concrete batching plant supply interruptions.	Use sub-activities (rebar, shutter, pour, curing) under a parent activity. Apply crew resource tracking to ensure continuous labor flow. Set activity relationships (FS + lag) for each pour sequence. Use resource histogram to plan rebar & concrete needs.	Accurate tracking of cycle time, early identification of poor performance.

5	Foundation to Plinth (Backfilling)	Poor compaction or soil quality issues. Rainwater stagnation delaying compaction. Delay in retaining wall construction. Testing and inspection hold points.	Assign weather calendars to simulate monsoon delays. Define inspection milestone (e.g., "Plinth Inspection Clearance"). Link testing labs as resources to check availability.	Prevents further structural works from being delayed by paperwork.
6	Plinth Approval	Delay in submission of documents to consultants/local authorities. Non-conformance observations during inspection. Rework for structural or service alignment.	Add document submission activity linked to plinth completion. Maintain document approval log in P6 under deliverables. Use flag milestones for "Approval Received" before next stage.	
7	Ground Floor (Conventional)	Delay in material delivery (formwork, concrete, steel). Labor shortage or crew underutilization. Coordination delays between civil and MEP services. Design revision or mismatch with foundation layout.	Define procurement activities (steel, formwork) with lead time. Apply resource assignment for each trade (civil, MEP). Use "activity steps" for detailed tracking of slab, column, beam. Add lookahead filter for the next 2 weeks to plan dependencies.	Overlapping activities ensures no idle time between trades.
8	1st Level to 7th Level (Podium + Amenities + Refuge)	Complex formwork systems at podium level. Integration of MEP, firefighting, and waterproofing. Heavy reinforcement congestion. Delay in PT (Post-tensioning) work for slabs. Waterproofing and podium landscaping coordination. Amenity block design changes.	Link civil + MEP + waterproofing activities using FS and SS logic. Assign Activity Codes for multi-discipline tracking. Run Critical Path Analysis (CPA) weekly to see bottlenecks. Add resource curves to match manpower peaks.	
9	Transfer Slab (2nd Level & 3rd Level)	Complex shuttering and staging design. Delays in rebar detailing and PT cable installation. Long curing time and strength gain delays. Quality check hold points from consultants.	Use "Resource Loading" for formwork and reinforcement gangs. Include lag time for curing (minimum 7 days). Add inspection milestone for consultant clearance before next cycle. Use baseline comparison to measure cycle variance.	Enables precise monitoring of heavy structural tasks and shift coordination.
10	8th Floor – 44th Floor (Typical Mivan Floors)	Delay in Mivan formwork cycle (ideally 7-day or 10-day cycle). Inadequate number of Mivan sets. Concrete supply disruptions. Rebar congestion and alignment issues. Lifting and crane breakdowns. Safety stoppages. Delay in inspection and approval for next pour. Poor coordination between civil and service sleeves. Labor productivity variations.	Create repetitive activities using "Copy Activity + Increment Logic" for each floor. Set resource calendar to maintain 7-day Mivan cycle. Link precedence as FS between consecutive floors. Use Global Change function to update multiple floor sequences quickly. Track productivity variance through earned value metrics (SPI, CPI). Add crane and hoist resources with limits to avoid double booking.	Allows predictive control of high-rise cycle time; one floor delay triggers early corrective action.
11	Refuge Floors (14th, 21st, 28th, 35th, 42nd)	Change in design due to fire compliance. Delay in finishing works and waterproofing. Special fireproof materials lead time. Extra inspection from fire and structural consultants.	Create inspection milestones for each refuge level. Maintain approval logs as separate WBS. Assign float monitoring to track potential delay absorption.	Keeps tower progress aligned with statutory safety checks.

12	Above Terrace RCC & Terrace Works	Delay in parapet wall, machine room, and waterproofing. Solar panel or mechanical equipment coordination. Delay in finishing and service installations.	Add sub-activities : parapet, waterproofing, solar, MEP plant room. Apply SS relationships where trades can overlap. Assign calendar exceptions to track night shift work if needed.	Controls last structural stages that often impact finishing and handover.
13	Blockwork Completion	Shortage of AAC blocks or sand. Slow productivity due to vertical working heights. Delay in layout approval. Rework due to mismatch with MEP sleeves. Weather impact on curing.	Link blockwork start after Mivan de-shuttering + curing lag. Assign blockwork teams as resources with productivity norms. Use progress update fields (% Complete Type: Physical) for accurate tracking.	Prevents rework and ensures material flow continuity.
14	Internal Plaster Completion	Delay in material supply (sand, cement, plaster mesh). Dependency on electrical and plumbing chasing completion. Labor shortage. Quality rework due to cracks or poor surface.	Add logic ties with plumbing and electrical chasing completion. Use WBS-level filters to monitor delay in finishing sequence. Assign crew productivity rates to calculate accurate duration.	Reduces rework and plaster-to-finishing conflicts.
15	Flat/Toilet Flooring & Dado Completion	Tile procurement delays (imported tiles lead time). Improper leveling and waterproofing issues. Rework due to cracked or uneven tiles. Plumbing or sanitary fixture delay.	Link procurement with construction activities (FS + lag for delivery). Define float limit to identify near-critical delays. Track progress using activity steps (Waterproofing > Screed > Tile).	Smooth workflow coordination between procurement and execution.
16	Common Area Flooring Completion	Delay in marble/granite supply. Coordination with railing, lighting, and facade works. High workmanship rework due to aesthetic issues.	Use inter-discipline linking between finishing, facade, and railing. Create constraint milestones like "Facade Completion Before Flooring Start". Regular baseline updates to analyze rework impact.	Ensures coordination of aesthetic and structural finishes.
17	Lift Completion	Delay in shaft readiness and alignment. Late delivery from OEM (KONE, Schindler, etc.). Power supply availability for testing. Inspection and commissioning delays.	Link Lift Installation FS to "Lift Shaft Plaster Completion". Assign OEM resource with limited availability. Add testing milestone under Mechanical Completion WBS. Use " Activity Codes " to segregate vendor scope.	Keeps vendor work in sync with civil readiness.
18	OC Application (Full OC)	Delay in submission of completion drawings & NOCs. Pending statutory compliances (fire, STP, lift, environment). Delay in as-built documentation. Local authority inspection scheduling.	Create WBS: Statutory Approvals with all required NOCs as activities. Assign responsible departments (Fire, STP, Lift, Environment). Apply milestones (OC Applied, OC Inspection, OC Received). Use progress thresholds to track approval readiness.	Ensures readiness and avoids last-minute paperwork delays.
19	OC Receipt – Full OC	Delay in authority processing. Pending clearance certificates (Water, Drainage, Fire, Lift, Environment). Minor rectification works flagged during inspection.		
20	Complete OC Duration	Delay in internal coordination between departments. Paperwork and audit delays. Delay in obtaining occupancy certificates for both towers simultaneously.		

Source: Created by authors

6.3 Stakeholder responsibility alignment

The Findings: An Online Decision Support Cycle.

This approach is able to convert the Primavera formal planning features to a dynamic, data-driven, and continuously optimized system of managing its workforce. Through the

closed feedback loop between the planning, simulation and execution processes, project teams can have unprecedented visibility and control over the decision of resource allocation.

6.4 Conclusion

The proposed model offers the following advantages to project managers and planning professionals:

- Reduces time taken in project set up and reporting.
- Removes redundant data modelling and data transformation processes.
- Enhances the efficacy of planning and tracking.
- Improves the collaboration among planning, execution and management teams.

Allows scaling in use in numerous projects. By providing a ready-to-use, flexible, and automated planning and reporting framework, the model helps organisations achieve better control over complex construction projects while saving significant time and effort.

This paper finds that the model aids in making decisions based on data by converting fixed schedules into an adaptive control system, such that data presented by dashboards directly influence corrective action and recovery planning.

In general, the framework increases transparency, better coordination among the stakeholders, and allows taking control of the project, which makes it a viable and reproducible solution to high-rise and other large-scale construction projects.

6.5 Recommendation

Going by the results of the present study, it is advisable that construction organisations should implement a data-intensive resource and project management model that incorporates scheduling software like Primavera P6 along with data analysis tools like Power BI. Visibility of project progress, labour usage and productivity are much enhanced by the early development of standardized scheduling templates and the development of structured resource plans. Regular KPI monitoring, such as schedule performance, costs, and cycle productivity, should be institutionalised with dashboard-type reviews that allow the correction to be taken in good time and ensure proactive project control. Scenario analysis and responsibility-based planning also increase coordination among the stakeholders and as such, delays and inefficiencies in high-rise developments are minimized.

Based on this base, future developments of the model can include the use of Industry 4.0 advanced technologies like drones to track progress, an IoT-based machinery monitoring tool, and a 4D and 5D visualisation tool based on BIM. Incorporation of predictive analytics and simulation would also help to make decisions under uncertainty in a proactive manner, which would help to make project delivery more resilient and efficient.

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CHAPTER 24

Artificial Intelligence in Project Scheduling: A Comprehensive Review of Techniques, Applications and Future Opportunities

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ABSTRACT

The growing complexity of modern construction projects demands efficient scheduling to meet time, cost, and quality goals. Traditional methods like Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), and Gantt charts, though widely used, struggle to handle uncertainties, dynamic conditions, and limited resources. This study reviews both conventional and Artificial Intelligence (AI)-based scheduling approaches to evaluate their effectiveness in construction project management. A comprehensive literature review of traditional methods identifies their strengths in simplicity and proven reliability but also highlights limitations in adaptability and resource optimization. Emerging frameworks such as the Fuzzy-GERT model, Repetitive Scheduling Method (RSM), and BIM-based scheduling have attempted to improve flexibility and precision. The paper further examines AI-driven techniques—Machine Learning (ML), Deep Learning (DL), Genetic Algorithms (GA), Reinforcement Learning (RL), and Fuzzy Logic—that enhance prediction, optimization, and automation. Integration with Building Information Modeling (BIM) and the Internet of Things (IoT) demonstrates promising potential for intelligent scheduling systems. Ultimately, the study compares both traditional and AI-based methods, offering insights into selecting suitable scheduling approaches based on project characteristics and emphasizing the future integration of AI with conventional techniques for adaptive and efficient project scheduling.

Keywords: Artificial Intelligence, Project Scheduling, Optimization, Traditional Scheduling methods.

1.0 Introduction

Delay, cost increase, poor resource use, and schedule change persist in construction as a result of the complexity of project, fluctuating site conditions, unpredictable productivity

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and change of design, which makes ineffective scheduling a key contributor to poor performance in infrastructure and building projects. Despite the simplicity that they are valued with, the traditional methods of planning such as Gantt charts, CPM and PERT are largely deterministic and reliant on human judgment. Therefore, they struggle to cope with resource constraints, space-temporal conflicts, and real-time fluctuation particularly in large-scale earthwork projects that often undergo numerous revisions that lead to incompetent and costly schedules.

Due to the recent advancements in AI, intelligent, data-driven, and flexible scheduling solutions are now feasible. Especially in equipment-intensive processes such as earthworks, such techniques as machine learning, genetic algorithms, reinforcement learning, and simulation-based optimization are effective at addressing challenging scheduling problems, optimizing resources, and reducing the project duration and cost.

Intelligent scheduling can be improved by using AI with BIM, sensors, and simulation platforms by automated WBS generation, AON modeling, and optimization via simulation. Nonetheless, there is a complexity of implementation, data accessibility, and lack of comprehensive and combined frameworks that hinder practical application, and studies remain scattered.

Thus, this review paper aims to provide a complete and systematic analysis of AI use in the construction schedules. Specifically, the research examines the flaws of traditional scheduling systems, collects AI-based scheduling protocols that appeared in the literature, and considers practical implementations, compares AI-based scheduling systems with traditional ones, and recommends future research directions to developing intelligent project scheduling systems.

2.0 Literature Review

2.1 Traditional project scheduling methods

The ease of use, transparency and simplicity of traditional methods of scheduling such as CPM, PERT, Gantt charts and RSM make them easy to apply. They aid in determining essential tasks, project estimation, tracking progress and repetition of project management. Nevertheless, they are largely deterministic and rely on the manual sequencing limitations and preset lengths of activities, which limits their ability to deal with project complexity and variability. (Fahihi, et.al,2014) Scheduling based on CPM often does not take into account dynamic spatial and time limitations of equipment intensive activities such as earthworks. The frequent adjustments of schedules that highly depend on human judgments reduce responsiveness and increase the potential of making bad decisions

2.2 Artificial intelligence techniques in project scheduling

To avoid the disadvantages of traditional scheduling, researchers research AI-based project scheduling approaches that enable flexible decision-making, deal with uncertainty, and optimize multifaceted constraints.

2.2.1 Machine learning

Machine learning can be used to support data-driven scheduling by predicting the time periods of activities, based on the characteristics of delays. These techniques make forecasts more precise by using information about previous projects; however, the success of these techniques relies entirely on the quality and accessibility of such information. (Alikhani et al.,2023)

2.2.2 Genetic algorithms

Genetic algorithms are widely applied to schedule optimization, and they are effective to search for a high-dimensional solution space to improve the project duration, cost, and resource efficiency. The ASCE literature reveals that the heuristic CPM-based scheduling systems are worse than GA- and swarm-intelligence-based scheduling techniques, especially when combined with simulation. (Jeonghoon Lee et al.,2018)

2.2.3 Reinforcement learning

Reinforcement learning allows systems to communicate with the environment of the project and acquire optimal rules by modeling scheduling as a sequential decision-making process. Frameworks based on RL are highly promising in adaptive and real-time scheduling, yet often have a high processing power and training cost (Mingshu Li et al.,2024)

2.2.4 Fuzzy logic

It is due to uncertainty, fluctuation of productivity, risk levels, and linguistic reasoning that fuzzy-based scheduling is more resilient than deterministic approaches although there are interpretability and scalability problems since this kind of scheduling considers them during the scheduling process. (Sarrah Dahmani & Jmal,2011)

2.2.5 Deep learning

Deep learning extends machine learning by modeling complex nonlinear interactions and has shown promise in large-scale prediction and pattern recognition for scheduling performance, though its application in construction scheduling is still in early stages. (Hatami et al.,2022)

2.3 Applications of AI in project scheduling

In the construction of buildings, there are several significant scheduling processes that have been approached using AI means.

2.3.1 Delay prediction

The AI-based models allow proactive intervention compared to reactive control; the previous data is used on the project and the site to make a much more accurate forecast of schedule delays. (Alikhani et al.,2023)

2.3.2 Resource optimization

Artificial intelligence (AI) has tremendous potential in constrained scheduling by automating WBS creation, using AON networks, and optimising with simulation to create conflict-free plans that reduce effort, duration of project and project cost by a significant margin (Jeonghoon Lee et al.,2018)

2.3.3 Risk-aware scheduling

Risk-aware scheduling is achievable by modeling numerous situations and optimizing under uncertainty making AI achieve more flexible and reliable project schedules. (Egbedion, 2024)

2.4 AI integration with BIM and IoT

AI application and integration with BIM and IoT is directly connected to digital and paper-based building methods. The combination of AI, BIM and sensing technologies enhances construction scheduling by offering automated WBS, optimum sequencing, and real-time schedule updates which is dynamic and requires minimal human involvement. (Golparvar-Fard et al.,2023)

2.5 Literature gaps summary

Despite the huge progress, there are still significant research gaps. The existing literature is often constrained by its focus on specific kinds of projects in general or AI methods in particular. The barrier to the industry implementation is the complexity of models and the associated data requirements, and it does not provide numerous studies comparing the AI-based and traditional approaches to scheduling. The need to have standard and scalable scheduling systems is also exacerbated by the fragmented interaction with BIM, IoT, and decision-support systems. (Fouad Amer et al.,2021).

2.6 Application of AI techniques in construction project scheduling

Table 1 compares the main functionalities of AI and AI-aid scheduling techniques, i.e., WBS generation, sequencing, resource optimization, conflict resolution, and adaptability. The traditional simulation models and optimization methods (GA, PSO) address some of the requirements but they are not flexible or learning based. In general, the authors come to the conclusion, which is scientifically proved, that hybrid AI scheduling systems are required since no single strategy suffices.

Table 1: Comparison of Main Functionalities of AI and AI-aid Scheduling Techniques

AI Technique / Method	WBS Generation	Activity Sequencing	Resource Optimization	Conflict Resolution	Time Optimization	Cost Optimization	Schedule Automation	Real-Time Adaptability
Flow Network Optimization	✓	✓	✓	✓	✓	✓	✓	
Genetic Algorithm (GA)		✓	✓	✓	✓	✓		
Particle Swarm Optimization (PSO)		✓	✓		✓	✓		
Discrete Event Simulation (SDESA)			✓	✓	✓	✓	✓	
Automated WBS & AON Generation	✓	✓		✓			✓	
Resource-Constrained CPM (AI-assisted)		✓	✓	✓	✓			
Expert Systems (Knowledge-based)		✓						
Neural Networks (Reviewed)					✓			✓
Hybrid AI Models (AI-CPM / AI-BIM / Simulation-Optimization)	✓	✓	✓	✓	✓	✓	✓	✓

Source: Created by authors

3.0 Research Methodology

3.1 Review methodology

Databases used: The literature review utilized peer-reviewed scholarly materials, such as the ASCE Library (18 publications), the ScienceDirect (22 papers), and the Google

Scholar (5 additional sources). The ASCE Library was particularly useful in the case of research on resource-constrained scheduling, AI-based planning, automated WBS generation, and AON network modeling.

Keywords and Search Strategy: A keyword-based search used AI, scheduling, and optimization terms, applying AND/OR operators to capture interdisciplinary construction and scheduling research.

Inclusion and Exclusion Criteria

Inclusion Criteria

- Peer-reviewed journal articles and conference proceedings.
- Research on construction project scheduling, planning or sequencing.

Exclusion Criteria

- Research that does not deal with timetable of construction or planning.
- Articles that are only concerned with cost estimation or safety not related to scheduling. Opinion or editorial or non-peer-reviewed articles.
- Redundant research in databases.

This screening was done to be consistent with the structured automation and optimization strategies outlined in the uploaded ASCE literature.

Time Span of the Review: The review covers studies from 2000–2024, highlighting the transition from CPM-based scheduling to AI-driven, simulation-based, and automated planning, supported by foundational WBS, AON, and resource-constrained scheduling literature.

3.2 Case study selection method

Type of case study: A real-life case study approach analyzed literature-reported AI-based scheduling implementations using peer-reviewed journals, conferences, and industry-validated research, without collecting primary project data.

The case study data sources: A phased roadmap is recommended, starting with CPM-based AI optimization, progressing to BIM and simulation integration, and advancing to AI with digital twins and sensors for real-time adaptive scheduling.

Methodological consistency: The case study was chosen as it is closely related to the goals of the review and represents:

- Construction conditions are equipment intensive.
- Active interactions of resources.
- The necessity of automated and flexible scheduling.

This consistency will guarantee that the insights based on the case study will be directly related to the comparative analysis and findings of the review.

4.0 Data Analysis

Even though it was a review paper, systematic data analysis was undertaken to determine patterns and trends based on peer-reviewed articles, conference papers, and case studies on AI in construction scheduling. The research makes records of frequently used AI methods, fields of application, perceived advantages, and frequent implementation issues.

4.1 Classification of reviewed literature

The primary strategy for scheduling and AI technology used for literature categorization was automated and optimized literature scheduling. For the literature collected, there was a clear movement away from scheduling that was deterministic to frameworks that incorporated automation and optimization.

Table 2: Classification of Scheduling Research Approaches

Scheduling Approach	Representative Techniques	Relative Frequency
Traditional methods	CPM, PERT, Gantt charts	Moderate
Optimization-based	GA, PSO, linear programming	High
Simulation-based	Discrete-event simulation, SDESA	High
Learning-based AI	Machine Learning, Reinforcement Learning	Emerging
Hybrid systems	BIM–AI, simulation–optimization	High

Source: Created by authors

4.2 Frequency of AI techniques used in scheduling research

The most frequently employed AI techniques and methods are optimization algorithms as indicated in the analyzed publications, due in part to their overall effectiveness and interpretability in the resource-constrained environments.

The main points are as follows

- Genetic Algorithms (GA) serve as the preeminent AI methodology for optimizing construction scheduling
- Simulation-based optimization tools (SDESA, for instance) are often interfaced with AI for managing dynamic resource interactions
- ML techniques serve predominantly for predictive tasks, in particular, forecasting delays
- Reinforcement Learning continues to be restricted to the experimental and design automation domains due to the excess data and training it entails.

4.3 Project scheduling AI application areas

The reconstructed literature was subjected to additional scrutiny encompassing the broad functional deployment of the AI techniques in the scheduling continuum.

The prevalent functional application areas include:

- Automated work breakdown structure (WBS) generation • Activity sequencing and precedence modeling
- Resource allocation and leveling
- Conflict-free scheduling under spatial and temporal constraints
- Resource-constrained scheduling optimization

The ASCE case study exemplifies AI-enabled conflict-free sequencing of haul jobs and optimized resource assignment, thus overcoming the shortcomings of superintendent-driven CPM schedules.

4.4 Reported benefits of AI-based scheduling

From previous studies, the following benefits of AI Scheduling have been recorded:

- Shortened the duration in which projects can be completed
- Improved the management and distribution of company resources
- Removed conflicts that would best be described as spatial or temporal
- Increased flexibility to [site] conditions that may change
- Less need for manual or expertise

4.5 Challenges and limitations identified

The study finds that there are some major barriers to the AI-based scheduling, including biased inputs, low interpretability, workflow integration issues, and insufficient individuals knowledgeable in AI. ASCE recommends the resolution of issues via transparent simplified processes with the emphasis on AI methods, which are reliant on the simulation and optimization techniques.

4.6 Trend mapping and analysis

- Early: studies that utilized heuristic optimization and CPM enhancement
- Middle: The use of simulation-based scheduling
- Exploring integration of AI, BIM, and learning-based techniques in recent studies

5.0 Findings / Results

5.1 Comparative performance of traditional and AI-based scheduling methods

The discussion reveals that artificial intelligence solutions always perform better than traditional approaches to scheduling, particularly in complex and dynamic projects. AI-based tools are more flexible and optimizing as compared to deterministic classical technologies.

Table 3: Performance Comparison of Scheduling Approaches

Performance Criterion	Traditional Scheduling Methods	AI-Based Scheduling Methods
Adaptability to changes	Low	High
Handling uncertainty	Limited	Advanced
Resource optimization	Moderate	High
Automation level	Manual	Semi to fully automated
Scalability for large projects	Moderate	High

Source: Created by authors

These results indicate that while traditional methods remain effective for stable and small-scale projects, AI-based scheduling offers significant advantages for complex construction scenarios.

5.2 Dominant AI techniques in project scheduling research

The analysis reveals that some AI methods are more commonly used in construction scheduling studies because they offer a balance between computational speed and the optimization potential.

Key findings include:

- Genetic Algorithms (GA) and Machine Learning (ML) are the most common methods of AI application in scheduling studies.
- GA is applied mostly to the resource-constrained scheduling and optimization problems.
- Use It ML methods are typically used in prediction of delays, estimation of productivity, and pattern recognition.
- Reinforcement Learning and Deep Learning are new, yet not as widespread because of excessive information and computational demands.

5.3 Application trends in AI-based scheduling

The literature review has identified a number of overriding areas of use of AI.

Major application areas identified:

- Schedule delay and performance risk prediction.
- Labor, equipment and material allocation optimization.
- Activity sequencing and work breakdown generation, which is automated.
- Uncertainty-based and risk-conscious scheduling.

Resource optimization and automated planning are the most studied and practically implemented areas of application among them.

5.4 Practical implementation of AI-based scheduling

Although the technical benefits are proven in research studies, AI-based scheduling systems have not been applied in real-life yet.

Observed findings include:

- The majority of AI-based scheduling applications are limited to pilot projects, simulations, or controlled case projects.
- Industry adoption is impeded by complexity of implementation, dependency of data and unskilled individuals.
- Construction practitioners still find the use of traditional tools like CPM and commercial scheduling software important.

Such discrepancy between business and scientific studies reveals the necessity of scalable and user-friendly AI scheduling solutions.

5.5 Effect of BIM-AI integration on the reliability of scheduling

The combination of AI and Building Information Modeling (BIM) and digital construction systems contributes greatly to the reliability of schedule and extended practicality.

Key results show that:

- The data of BIM allows work breakdown and sequencing to be done automatically and correctly
- AI optimization enhances the schedule robustness by removing both spatial and temporal conflicts.
- Independent BIM-AI systems facilitate the introduction of real-time schedule updates, as well as informed decision-making.

5.6 Summary of key findings

The review concludes that the AI-based scheduling is more flexible and more optimized in the context of uncertainty, compared to the traditional methods. Genetic algorithms and machine learning dominate the current research but are still not utilized in practice. The BIM-AI integration enhances schedule accuracy and hybrid systems that integrate traditional and AI-based approaches can provide a way forward in the future.

6.0 Case Study: AI-Based Project Scheduling in Earthwork Operations

This case study investigates the comparison of AI-based scheduling and the traditional methods in an equipment-intensive earthwork infrastructure project.

6.1 Case background

Project type: The given case study containing a relatively large infrastructure earthwork project involving dump trucks, compactors, and excavators is suitable to evaluate

the AI-based scheduling due to its high equipment dependency, dynamic space-temporal interactions, and fluctuating productivity.

Scheduling challenges: Following the traditional methods the project was faced with some serious scheduling issues including conflict of resources between excavation and carrying machines, poor haul sequencing due to ignorance of the geographical boundaries and numerous human schedule amendments due to the change in site conditions. CPM timelines involved significant role in heuristics and experience to lead to inefficient utilization of equipment and a longer project timeline.

6.2 AI technique applied

Algorithm / system used

- Automated Work Breakdown Structure (WBS) generation,
- Creation of an Activity-on-node (AON) network
- Resource-constrained critical path scheduling
- The optimization by the use of the Genetic Algorithm (GA)
- Discrete-event performance evaluation.

Data Inputs

The AI-based scheduling system took into account the following inputs:

- Types, quantities and rates of productivity of equipment
- Automatically generated project layout activity definitions
- Distance of transportation and space restrictions.
- Resources and restrictions on operations.

6.3 Comparison with traditional scheduling

The AI-based schedule was directly compared to a traditional CPM-based schedule that was developed using common project management software

Table 4: Comparison of Traditional and AI-Based Scheduling Approaches

Parameter	Traditional CPM Scheduling	AI-Based Scheduling
Schedule preparation	Manual	Automated
Handling resource conflicts	Limited	Optimized
Equipment utilization	Moderate	High
Adaptability to changes	Low	High
Schedule flexibility	Low	High
Time efficiency	Lower	Improved
Cost efficiency	Moderate	Improved

Source: Created by authors

By creating schedules free of conflicts, allocating equipment optimally, and cutting down on needless idle time, the AI-based method showed improved performance.

6.4 Results and retrospectives

Outcomes: The AI-based scheduling framework was implemented, and it was observed that,

- The general time taken on the project was reduced.
- Efficiency in the utilization of equipment was enhanced.
- Spatial and temporal conflicts were eradicated.
- Dependence on manual planning skills was reduced. the ability to evaluate the different scheduling alternatives was enhanced.

The results confirm that AI-based scheduling has a significant benefit compared to traditional CPM-based planning in the context of equipment-intensive construction projects. (Li & Du 2017), (Fouad Amer et al.,2021)

Lessons Learned: Some of the key lessons of the case study are as follows:

- There is reduced human bias and planning through automation.
- AI scheduling works very well with dynamic and resource-intensive operations.
- The integration of simulation and optimization improves schedule dependability.
- AI implementation is only possible with data quality and structured inputs.

7.0 Conclusion & Implications

7.1 Conclusion

Using a mixture of traditional methods, AI-dedicated approaches, areas of application, and a real-world case study, this review explores the topic of artificial intelligence in construction project scheduling. CPM, PERT and Gantt charts continue to be applicable in simple projects, but cannot support the complexity, uncertainty and resource constraints of modern construction. The AI-based scheduling, specifically the optimization and simulation-based models, offer more flexibility, optimization, and resolve conflicts in a better way. Learning-based approaches allow predictive scheduling, but again, it is limited due to computing and data needs. As the case study illustrates, the application of hybrid AI-solutions, in particular, in equipment-intensive projects, has a significant positive impact on the reliability of the schedules, time efficiency, and cost performance.

In the figure, the AI opportunities in the field of construction scheduling, including automated planning, optimization of resources, delay forecasting, and decision support, are mentioned. The new trends are digital twins, IoT, and BIM. The key barriers include cost, quality of data, experience, and interpretability; in order to implement it in practice, the next generation of research should focus on standardization, scalability, and explainable AI.

Figure 1: Opportunities, Challenges, Emerging Trends, and Open Research Issues in AI-Based Construction Project Scheduling



Source: Created by authors

7.2 Academic implications

The review brings organization to the body of knowledge by categorizing AI techniques and their applications in construction scheduling. To bridge the theory-practice divide, future research will have to make the large-scale and real-world validation more of a priority compared to all simulation-based research and explore combining AI-based scheduling with digital twins, real-time sensing technologies, and BIM-driven decision-support systems

7.3 Industry implications

The findings provide certain recommendations on how AI can develop to be used in construction scheduling. The biggest construction and infrastructure projects, projects related to earthworks, and complex and resources-demanding processes are the most appropriate ones to address with AI-based scheduling. Despite a relative lack of historical information, optimization-based AI can quickly become more efficient, reducing the amount of effort needed to plan manually and utilize better resources. With the help of integrating AI and BIM, they are further able to obtain accurate, real-time, and field-level scheduling.

8.0 Recommendations

The conclusions of this extensive evaluation and the lessons learned with the help of the illustrative real-life example allow to suggest several recommendations to help the successful implementation of artificial intelligence-based project scheduling in the construction industry and its further development.

8.1 Development of hybrid AI–CPM scheduling frameworks

AI must be used to supplement the scheduling that is based on CPM, not to replace it. Hybrid AI-CPM models allow allocating resources automatically, resolving conflicts, and dynamically updating as a result of merging traditional critical path visibility with AI-based optimization and simulation. Researchers and developers should focus on user-friendly hybrid solutions that can interoperate with the existing project management systems

8.2 Construction professionals training and capacity building

The deficit of technical knowledge and practical training of the experts in the construction field is one of the largest hindrances to AI-based scheduling. Companies are supposed to invest in special training involving AI principles, AI-created schedule reading, and the way AI technologies can be integrated with project management and BIM systems

8.3 Implementation of pilot projects

Pilot projects that involve limited settings should be used to test AI-based scheduling systems before they become widely used. Pilot installations enable organizations to determine the constraints of the system and the data requirements of the system as compared to traditional solutions.

8.4 Standardization of construction data for AI applications

Introducing AI scheduling in tasks with repetitive cycles, heavy equipment is useful in building trust. To offer AI-based solutions the ability to be interoperable with BIM systems and project management systems to enable scalable dependent scheduling solutions, effective adoption requires high-quality demonstrative construction data including WBS, activities, sequencing, and resources which are standardized.

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CHAPTER 25

Integrating Lean and Circular Economy Principles to Enhance IGBC Certification Process

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ABSTRACT

Sustainability in construction is a key global objective, and integrating Lean Construction with Circular Economy principles into the green building certification framework offers a transformative opportunity. This research focuses on embedding these principles within the IGBC certification system to enhance sustainability in high-rise residential projects. The study aims to develop a conceptual framework that systematically integrates Lean and Circular Economy principles into the IGBC green building certification process for high-rise residential developments. The methodology follows a structured approach, beginning with a comprehensive literature review to identify key Lean Construction and Circular Economy parameters relevant to IGBC standards. A comparative analysis of existing IGBC-certified projects evaluates their sustainability performance against Lean and Circular Economy benchmarks. This research contributes significantly to the Indian building sector by introducing a systematic framework to enhance sustainability and operational efficiency in IGBC-certified buildings. The integration of Lean and Circular Economy principles promotes resource optimization, waste minimization, and improved cost management. The findings serve as a guide for policymakers, developers, and certification bodies, facilitating the incorporation of these principles into India's green building strategies and advancing the nation's sustainable development initiatives.

Keywords: Lean construction, Lean and circular economy, lean and sustainability, IGBC.

1.0 Introduction

The construction business industry is very important with respect to the economic development, urbanization and social wellbeing but it is also among the most resource consuming and the most environmentally devastating industries worldwide.

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The high-rise residential projects, especially in countries which are fast urbanizing like India are linked with high consumption of materials, energy and water, as well as huge amounts of construction and demolition garbage. Green building certification systems have developed in answer to these problems, as organized systems that can be used to inform sustainable construction (Aristizábal-Monsalve et al., 2022; Weinheimer, 2016). In India, the Green house rating system proposed by Indian Green Building Council (IGBC) has gained popularity as a system of encouraging residential buildings to be environmentally friendly.

Although IGBC certification offers overall checklist-based sustainability method, in practice, its application is usually compliance focused and not performance oriented. Meeting minimum requirements or being selective to the credits that are easier to reach can produce developers who are often interested in achieving overall sustainability potential of projects. This has especially been marginal in high-rise residential properties, where the lack of integration in project delivery, decision-making on its sustainability at a later stage, and the lack of co-ordination between the design and construction personnel make the green strategies less effective. This has led to the situation where a large number of projects are certified without effective resource optimisation or environmental performance. Both Lean Construction (LC) and Circular Economy (CE) principles have been called to focus on in their turn as the alternative to ineffective ways of handling the issues of construction.

The idea of production serves as the basis of Lean Construction and was first introduced by Koskela, with its main focus on removing non-value-adding processes, decreasing variability, and enhancing improvement on the project lifecycle. Its main emphasis is in enhancing efficiency of its processes, the reliability of its planning, and its coordination with its stakeholders (Khodeir & Othman, 2018; Ogunbiyi, 2014; Chen et al., 2024). Circular Economy, in its turn, encourages the regenerative model of resource utilisation through the focus on material reuse, recycling, life-cycle thinking and closed-loop systems in the planning, development, upkeep, maintenance and demolition of structures. The research attempts to show how process-based and resource-based approaches can be mutually reinforcing in certification results through direct mapping of the integrated Lean-Circular ideas onto the mandatory requirements and credits in the credentials provided by the Integrated Green Building Certification.

In line with this, the research question to be used in the main research is: What is the most effective way to combine Lean Construction and the principles of the Circular Economy and achieve better effectiveness and results of the IGBC Green Homes certification process of high-rise residential buildings?

By providing this answer, the study adds a systematic approach that would enable the filling of the gap between theory, certification systems, and the actual project implementation. The results are also meant to assist the developers, consultants and policymakers to enhance

sustainability performance without jeopardizing constructability, cost efficiency and operational viability (Benachio et al., 2021; Salibi et al., 2022; Wibowo & Ammar, 2025). This paper fills this gap and presents a proposed integrated conceptual framework of Lean and Circular in line with:

1. To assess the conceptual interaction between Lean and Circular Economy principles with IGBC certified buildings.
2. To propose a process map for incorporating Lean and Circular Economy concepts for enhancing the outcome of IGBC Green Existing Buildings.
3. To validate the proposed framework through expert feedback and practical insights from stakeholders involved in sustainable construction.

2.0 Literature Review

The literature review delves into the theoretical and practical bases in order to deployment of Lean Construction alongwith Circular Economy concepts for sustainable building certification schemes, namely the Indian Green Building Council (IGBC). Initially, it looks at the application of Lean principles, which were initially meant for manufacturing, to increase project efficacy and cut waste in the construction industry. Likewise, it discusses the contribution of Circular Economy principles in the area of conserving materials and sharing the materials in a closed-loop manner throughout the building lifecycle. The research points out a worldwide trend that is increasingly adopting the integration of these two techniques to deliver more eco-friendly building outcomes.

Table 1: Literature Review Table

Paper Title	Name of Author(s)	The Year of Publication	Journal/ Conference	Abstract	Summary
The Process of Green Building Certification: An Examination Regarding Lean Principles	Nina Weinheimer	2016	24th Annual Conference of the International Group for Lean Construction (IGLC), Boston, USA	This paper examines the procedure of DGNB certification of Green Building, analyzes inefficiencies, and proposes Lean principles to improve them. It reveals sources of waste and shows how Lean can enhance sustainability.	Explores inefficiencies in the German DGNB certification process and shows how Lean Thinking's 5 principles can optimize it. Emphasizes customer value, waste reduction, and continuous improvement.
ISO and Lean Can Contribute to a Culture of Continuous Improvement	Christy P. Gomez, Hashima Hamid	2018	26th Annual Conference of the International Group for Lean Construction	This study investigates whether ISO QMS alone ensures continuous improvement (CI) and argues that integrating the Last Planner System	Reveals that ISO-certified firms have only moderate CI maturity. Advocates using Lean tools like LPS under the TFS framework to better

			(IGLC), Chennai, India	(LPS) significantly boosts maturity involved for construction planning.	establish a CI culture in construction organizations.
Improving Green Building Project Management Processes through the Lean Approach	Alessandro Orsi, Tariq S. Abdelhamid, Eugenio Pellicer, Ignacio Guillén- Guillamón	2021	Lean Construction Journal	Applies Lean principles to design-stage issues in four European green building projects. Identifies process waste and proposes improvements aligned with sustainability goals.	Offers a Lean-based framework to optimize project management in green buildings using case studies. Aligns LEED/BREEAM certifications with Lean waste-reduction strategies to enhance efficiency and performance.
Lean Diagnosis for Chilean Construction Industry: Towards More Sustainable Lean Practices and Tools	José L. Salvatierra, Luis F. Alarcón, Angela López, Ximena Velásquez	2015	23rd Annual Conference of the International Group for Lean Construction (IGLC), Perth, Australia	Diagnoses Lean implementation across 10 Chi-lean construction firms using surveys, interviews, and site visits. Identifies barriers like poor training and lack of leadership and varying use of the Last Planner System.	Highlights challenges in sustaining Lean practices in Chile. Recommends focusing on leadership, training, cultural alignment, and comprehensive Lean adoption beyond just the LPS tool.
Lean and the Circular Economy: A Systematic Literature Review	José Geraldo de Oliveira Rangel Salibi, Ana Laura De Souza Medina Rodrigues, Pedro Augusto Bertucci Lima, Fernando Bernardi de Souza	2022	Journal of Lean Systems, Vol. 7, No. 4, pp. 23– 46	This paper explores how Lean principles can support circular economy (CE) via an organized review of literature review. It identifies overlapping the concepts of waste reduction alongwith resource reutilization, proposing a concept known as “Circular Lean.” Lean tools like 5S and VSM are highlighted for their relevance to CE practices such as eco-design and the 6Rs.	Provides a foundation for integrating Lean and CE, suggesting that both concepts share sustainability goals. Introduces “Circular Lean” to merge material and energy reutilization strategies, emphasizing continuous improvement and closed-loop systems in production
Interactions between Lean Construction Principles and Circular Economy Practices for the	Gabriel Luiz Fritz Benachio, Maria do Carmo Duarte Freitas, Sergio Fernando Tavares	2021	<i>Journal of Construction Engineering and Management</i> (ASCE	Investigates how Circular Economy alongwith Lean Construction interact within construction. Through content analysis, this study finds 74 interactions (70 positive, 4 negative) between CE	Establishes a comprehensive interaction matrix between LC and CE concepts in the built environment. Concludes that combining these approaches enhances

Construction Industry				practices and LC principles. Key insights include LC's focus on non-value-adding activities and CE's off-site construction emphasis.	sustainability and construction efficiency, though research is still emerging and requires standardization and incentives
Integrating Lean Construction with Sustainable Construction: Drivers, Dilemmas and Countermeasures	Yunxin Chen, Dong Qiu, Xiaomin Chen	2024	<i>Sustainability</i> , MDPI	This review examines synergies and conflicts between Lean Construction (LC) and Sustainable Construction (SC). It identifies drivers like cost reduction and waste minimization, alongside dilemmas, disagreements over worker welfare and environmental compromises are examples. It proposes using Dynamic Capabilities (DC) to mitigate these issues and develop an integration strategy.	Analyzes 654 papers using qualitative and bibliometric methods. Suggests integrating LC and SC improves efficiency and sustainability, and promotes DC (like organizational learning and adaptability) as key enablers for better LC–SC synergy in practice. Offers a strategic framework for implementation.

Source: Author's compilation based on previous studies

3.0 Research Methodology

3.1 Structure and Approach towards Research

Through qualitative exploratory strategy combined with an embedded case study methodology is the basis of this research. The goal is to investigate the potential strategic integration using ideas from the Circular Economy (CE) and Lean Construction (LC) to improve high-rise residential structures sustainability performance and point score in the IGBC certification system. The study aims to respond to the pivotal question:

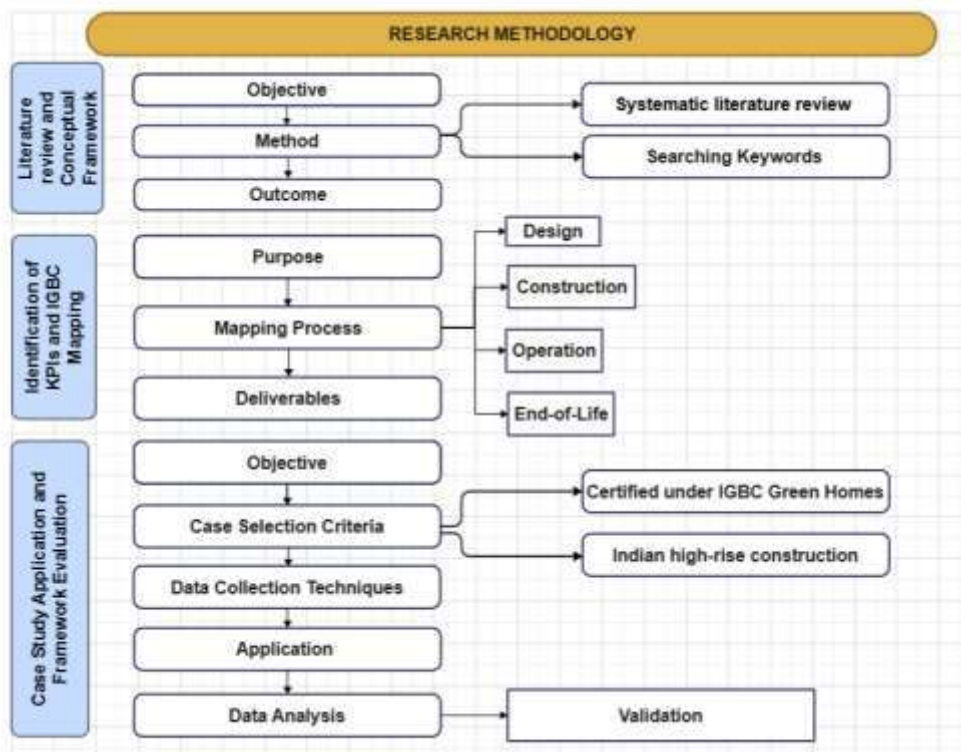
How can Circular Economy and Lean Construction principles be merged to leverage the sustainability effectiveness and impact, and efficiency of the IGBC certification process, for high-rise residential projects?

The proposed study follows a case-based analytical and framework-development strategy to study the applicability Circular Economy (CE) and Lean Construction (LC) procedures, as they can methodically be applied towards IGBC v3 Green Home Rating System. The research design is exploratory in its approach because it aims at developing

organized conceptual links between management concepts, sustainability practices and certification requirements. The study also forms and uses conceptual matrices as methodological tools to test the data instead of using the statistical test.

3.2 Methodology flowchart

Figure 1: Proposed Methodology



Source: Created by authors

3.3 Lean-circular integrated concepts development

Lean Construction aims at enhancing the efficiency of the processes by removing waste, decreasing variability and increasing coordination whereas Circular Economy aims at enhancing the resource efficiency through reuse, recycling, consideration of the life-cycle and closed-loop. The fact that sustainability issues in the residential construction business are caused by process and resource inefficiencies, therefore, makes this study combine between the LC and CE ideas into a single analytical definition.

Eight Integrated Lean -Circular Concepts (C1-C8) have been created as a result of synthesising construction management and sustainability literature. These ideas are the analytical basis of the study and represented with the help of the Integration Logic Matrix.

3.4 Framework development

3.4.1 Circular economy × lean construction integration logic matrix

Lean Construction and Circular Economy are usually introduced as several approaches in management of construction research. Lean Construction can be aimed to enhance reliability of planning, minimize the waste of processes, and optimize the workflow, whereas Circular Economy is oriented on responsible usage of resources, reusing materials, and minimizing the environmental impact of the whole building life cycle.

Table 2: Integration Logic Matrix: Lean Construction × Circular Economy

Code	Integrated Lean-Circular Concept	Lean Construction Basis	Circular Economy Basis	Integration Rationale
C1	Waste elimination & material reuse	Elimination of material waste, rework, excess inventory	Reuse and recycling of materials	Lean prevents waste generation; CE retains material value
C2	Life-cycle thinking & value optimisation	Value stream mapping across project stages	Life-cycle assessment and durability	Integrates process value with long-term resource value
C3	Design for adaptability, flexibility & disassembly	Simplification and standardisation of design	Design for disassembly and reuse	Lean simplicity enables circular reuse strategies
C4	Process transparency, planning & control	Last Planner System, visual management	Resource tracking and documentation	Enables traceability and accountability
C5	Resource efficiency in energy & water systems	Reduction of energy and water losses	Closed-loop water and renewable energy systems	Supports operational sustainability
C6	Localisation & reduced transportation impacts	Logistics optimisation and reduced movement	Local sourcing and reduced embodied carbon	Reduces emissions and supply-chain dependency
C7	Human wellbeing, safety & social responsibility	Respect-for-people principle	Social sustainability and healthy materials	Addresses social dimension of sustainability
C8	Continuous improvement, innovation & learning	Kaizen and feedback loops	Circular innovation and regenerative practices	Supports adaptive and future-ready projects

Source: Developed by authors

As a practical method of construction, particularly residential construction, the two methods are frequently used hand in hand and not separately. The lean principles assist in the minimization of unnecessary activities and wastes of materials in the process of planning and implementation, and the Circular Economy practices deal with what occurs to materials at the use, reuse, and disposal stages. It is this inherent overlap of application that will bring the two concepts of Lean Construction and Circular Economy together in this study in a unified conceptual framework.

In a bid to describe this integration, a Lean-Circular integration logic matrix was created. The matrix provides the alignment of the individual Lean concepts with the respective practices of the Circular Economy and the reason of treating the two as one intertwined entity. They are not supposed to be a convergence of theories at the conceptual level, but are aimed at being a mirror of the way sustainability-oriented construction practices are practiced in practice on the site and throughout the building life cycle.

Table 2 presents the Integration Logic Matrix used in this study. The matrix explains how Lean Construction principles and Circular Economy practices are combined and why they are treated as integrated concepts.

The utilization of the Concept Relationship Matrix as the second methodological tool, which illustrates the mapped integrated Lean-Circular concepts (C1-C8) versus the mandatory requirements and credits of IGBC Green Homes v3.0 in total. The matrix describes the conceptual alignment through binary presence-absence logic.

Table 3: Concept Relationship Matrix: Lean-Circular Concepts × IGBC Green Homes

IGBC Credits	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8
1. Sustainable Design (SD)								
Local Building Regulations		✓	✓	✓				
Soil Erosion Control	✓	✓		✓	✓		✓	
Natural Topography & Vegetation		✓	✓		✓	✓	✓	
Heat Island Effect		✓	✓		✓			✓
Passive Architecture		✓	✓		✓			✓
Universal Design			✓	✓			✓	
Green Parking Facility				✓	✓	✓		
Access to Amenities				✓		✓	✓	
Construction Workforce Facilities	✓			✓			✓	
Green Education & Awareness				✓			✓	✓
2. Water Conservation (WC)								
Water Efficient Fixtures	✓	✓		✓	✓			
Rainwater Harvesting	✓	✓		✓	✓	✓		

Landscape Design		✓	✓		✓	✓	✓	
Irrigation Management	✓	✓		✓	✓			
Recycle & Reuse of Wastewater	✓	✓		✓	✓			✓
Water Quality		✓		✓	✓		✓	
Enhanced Rainwater Harvesting	✓	✓		✓	✓	✓		✓
Water Metering		✓		✓	✓			✓
3. Energy Efficiency (EE)								
HCFC-Free Equipment	✓	✓		✓	✓			
Minimum Energy Performance		✓		✓	✓			
Enhanced Energy Performance		✓	✓	✓	✓			✓
Alternate Water Heating		✓		✓	✓			
On-site Renewable Energy		✓		✓	✓	✓		✓
Efficient Common Equipment	✓	✓		✓	✓			
Energy Monitoring System		✓		✓	✓			✓
4. Materials & Resources (MR)								
Waste Segregation	✓			✓				
Green Procurement Policy	✓	✓		✓		✓		
Structural Optimisation		✓	✓					✓
Certified Green Products	✓	✓		✓		✓		
Local Materials	✓					✓		
Eco-friendly Wood	✓	✓				✓		
Alternative Construction Materials	✓	✓	✓			✓		✓
C&D Waste Management	✓	✓		✓				✓
Organic Waste Treatment	✓	✓		✓				✓
5. Resident Health & Wellbeing (RHW)								
Minimum Daylighting		✓	✓		✓		✓	
Ventilation Design		✓	✓		✓		✓	
No Smoking Policy				✓			✓	
Enhanced Daylighting		✓	✓		✓		✓	✓
Enhanced Ventilation		✓	✓		✓		✓	✓
Cross Ventilation		✓	✓		✓		✓	✓
Connectivity to Exteriors		✓	✓				✓	
Low VOC Materials	✓	✓					✓	
Physical Wellbeing Facilities				✓			✓	
6. Innovation & Design (ID)								
Innovation	✓	✓	✓	✓	✓	✓	✓	✓
Exemplary Performance	✓	✓	✓	✓	✓	✓	✓	✓
IGBC Accredited Professional				✓				✓

Source: Developed by author with reference from IGBC Green Homes v3.0

3.5 Role of the matrices in the overall methodology

The Integration Logic Matrix constitutes the principal conceptual part of the framework, while the Concept Relationship Matrix applies this basic building block by connecting the combined Lean-Circular concepts to the IGBC certification requirements. The combination of these two matrices represents the principal methodological contribution through this research and permits the methodical analysis through potential for certification improvement in the sections that follow.

4.0 Data Analysis

4.1 Purpose and analytical approach

The objective through this data analysis is to discover how the Integrated Lean Circularity framework, created using the Integration Logic Matrix and Concept Relationship Matrix, shows in an actual IGBC-certified high-rise residential project. The analysis is directed towards spotting the Lean-Circular concepts that are present in the project and assessing how they correspond to the IGBC Green Homes v3.0 credits that have been achieved. This part of the study evaluates the way in which the Integrated Lean-Circular framework is realized through several IGBC-certified high-rise residential projects. A comparative case study approach is used to analyse the integration of the two methodologies across different certification levels which results in greater analytical strength and less project-specific bias.

The analysis is grounded in:

- the Integration Logic Matrix (Lean × Circular), and
- the Concept Relationship Matrix (Lean-Circular × IGBC Green Homes v3.0).

4.2 Overview of case studies

Table 4: Profile of Selected IGBC-Certified Case Studies

Case Study	Location	Building Type	IGBC Certification Level	Primary Sustainability Focus
Joyville Hinjewadi	Pune	High-rise residential	Gold (Pre-certified)	Energy and water efficiency
Rohan Abhilasha	Pune	High-rise residential	Platinum (Pre-certified)	Integrated sustainability practices
5 Maidan	India (Urban)	High-rise residential	Gold / High Gold	Compliance-driven green measures

Source: Developed by author from project documentation

Three high-rise residential projects certified under the IGBC Green Homes framework were analysed:

- Joyville Hinjewadi, Pune - IGBC Green Affordable Housing, *Gold (Pre-certified)*
- Rohan Abhilasha, Pune - IGBC Green Affordable Housing, *Platinum (Pre-certified)*
- 5 Maidan, Pune - IGBC certified residential project representing mid-to-high certification performance

These projects were selected to capture variation in certification outcomes, scale, and maturity of sustainability implementation, enabling comparison of Lean-Circular integration patterns across different performance levels.

4.2 Comparative presence of integrated lean–circular concepts

Using the Integration Logic Matrix, the presence of Integrated Lean - Circular Concepts (C1-C8) was examined across all three projects.

Table 5: Comparative Presence of Integrated Lean–Circular Concepts

Integrated Concept	Joyville	Rohan Abhilasha	5 Maidan
C1 Waste elimination & material reuse	Moderate	Strong	Moderate
C2 Life-cycle thinking & value optimisation	Moderate	Strong	Moderate
C3 Design for adaptability & disassembly	Limited	Moderate	Limited
C4 Process transparency & planning	Moderate	Strong	Limited
C5 Resource efficiency (energy & water)	Strong	Strong	Moderate
C6 Localisation & reduced transport impacts	Moderate	Strong	Moderate
C7 Human wellbeing & social responsibility	Strong	Strong	Strong
C8 Continuous improvement & innovation	Limited	Strong	Limited

Source: Author's analysis based on Integration Logic Matrix

4.3 Alignment with IGBC credit categories

The Concept Relationship Matrix was then used to evaluate how the presence of integrated concepts translates into IGBC credit performance.

Table 6: Lean - Circular Alignment with IGBC Credit Categories

IGBC Category	Dominant Lean-Circular Concepts	Observed Pattern Across Case Studies
Sustainable Design	C2, C5, C7	Strong design-stage alignment, limited adaptability focus
Water Conservation	C4, C5	Consistently strong across all projects

Energy Efficiency	C2, C5, C8	Higher certification linked to monitoring and optimisation
Materials & Resources	C1, C6, C8	Clear differentiation between Gold and Platinum projects
Resident Health & Wellbeing	C7	Uniform performance, limited differentiation
Innovation & Design	C8	Key differentiator for higher certification

Source: Author's analysis based on Concept Relationship Matrix

4.4 Comparative credit realisation trends

To further clarify differences in certification outcomes, credit realisation trends were analysed qualitatively.

Table 7: Comparative IGBC Credit Realisation Patterns

Credit Category	Joyville	Rohan Abhilasha	5 Maidan
Sustainable Design	Moderate - High	High	Moderate
Water Conservation	High	High	Moderate to High
Energy Efficiency	High	Very High	Moderate
Materials & Resources	Moderate	High	Moderate
Resident Health & Wellbeing	High	High	High
Innovation & Design	Low - Moderate	High	Low

Source: Author's interpretation based on IGBC documentation and matrices

5.0 Impacts and Conclusion

5.1 Conclusion

Through above paper which is intended at discussing incorporation of Circular Economy alongwith Lean Construction (LC) principles, as they are applicable to high-rise residential buildings to improve the effectiveness of the IGBC Green Homes Rating System. Instead of considering Lean and Circular approaches as similar sustainability practices, the study generated and implemented an integrated Lean-Circular framework, which is operationalised using an Integration Logic Matrix and a Concept Relationship Matrix that is consistent with IGBC Green Homes v3.0.

The results indicate that the achievement of the higher IGBC certification results is not motivated only by the implementation of the personal green technologies or the measures of compliance. Rather, improvement of accreditation is highly associated with the level of integration of process efficiency with resource efficiency throughout the project lifecycle.

The projects with a higher level of certification demonstrate a wider and deeper implementation of the integrated Lean-Circular ideas especially in the convention of process transparency, material circularity, and continuous improvement.

The comparative analysis of three IGBC-certified residential case studies also confirms that though the energy efficiency and water conservation actions are well developed and consistently applied to projects, they mostly assist in meeting minimum certification criteria. Conversely, the categories like Materials and Resources and Innovation and Design are very important in distinguishing between the Gold and Platinum outcomes. They are the categories that can be best benefited through combined Lean-Circular application since they need to be planned together, have their waste systematically reduced, documented, and learn instead of being subject to a single design intervention. Overall, the study supports the central hypothesis that integrating the ideas and principles of Lean Construction and the circular economy improves the IGBC certification process by lessening the disconnect between sustainability mindset, implementation, and performance checks.

5.2 Theoretical implications

This study has added to the current mass of knowledge by making Lean-Circular integration go further than the conceptual debate on sustainability and reach the area of formal green building certification systems. Though the interaction of Lean and sustainability or Lean and Circular Economy were examined previously in individual studies, this paper illustrates that such a combination can be designed and implemented on a developed rating system. Concept mapping to analyze the interdisciplinary interaction in construction management research using integration and relationship matrices is a methodological approach that can be duplicated. The study closes a major gap in the relationship between sustainability theory and certification practice by integrating Lean-Circular ideas into the very framework of the credit structures of IGBC.

5.3 Practical Implications

The results of this study are numerous and significantly impact the stakeholders involved in IGBC certified residential projects:

- The real estate development community and property owners can consider the major lesson learned through this research as the opportunity to achieve the highest level of certification without the need for redesign and applying expensive technologies. The union of Lean and Circular makes this possible.
- The project managers and construction personnel will know the importance of process transparency, workflow efficiency, and continuous monitoring in receiving sustainability credits, thanks to the research outputs.

- IGBC - certified auditors and consultants will be able to follow the proposed model as a guided procedure to pinpoint areas in which the best designs are still losing or can lose the battle, particularly in areas related to material management and innovation documentation.

6.0 Limitations

The study's restrictions are that it does not use performance measurement (quantitative) but rather conceptual mapping and case study analysis. Although the framework is quite insightful in terms of the analysis, the next phase of research might involve longitudinal performance data, interviews with stakeholders, or statistical validation on a broader sample of projects.

Future studies may also be done on how the proposed framework applies to other building typologies and certification systems or how digital tools like BIM could be used to facilitate Lean-Circular integration in certification-based projects.

The extension of the research should be on the validation of the Lean-Circular framework proposed, based on quantitative performance indicators on a larger sample of IGBC-certified projects. The longitudinal research of a post-occupancy performance may help to explore more profoundly the advances of Lean-Circular integration over the course of time. Additional research can be also done on how the framework can be applied in other building typologies and green building rating systems.

7.0 Recommendations

In accordance with inference of this research and implementation of the integrated Lean-Circular model to IGBC-certified high-rise residential buildings, the following recommendations can be offered to the most important stakeholders of residential buildings planning, design, construction, and certification.

7.1 Project developers and owners

Project developers must not just use an approach that is more focused on compliance to IGBC certification but instead embrace the use of Lean -Circular principles as one of the components of their overall project delivery approach. With prior adoption of Lean planning and Circular resource strategies, coordination between design and construction teams can be enhanced, wastage of materials can be minimized, and the life-cycle performance could be improved. Promoters are urged to incorporate the Lean-Circular goals in project briefs and project contracts in order to have uniform implementation throughout the project lifecycle.

7.2 Design team and consultants

The Lean and Circular thinking should be combined by architects, engineers, and sustainability consultants at the initial design stages. The decisions covering design must be based on flexibility, efficient design, and material optimisation in addition to end-of-life recovery and re-use. Records of Lean-Circular integration by the consultants should be made in written reports to the IGBC as part of IGBC Innovations and Exemplary Performance credits to enhance the certification results.

The Lean Construction tools that should be embraced by the construction teams include a dependable planning, the workflow coordination and the continuous monitoring so that the sustainability measures that were identified during the design phase are achieved on the ground. The implementation of the Circular Economy practices, including organised construction waste management, material recovery, and local sourcing would contribute greatly to the performance in Materials and Resources credits. Data collection and documentation should also be emphasized to assure the certification verification.

7.3 IGBC and policy stakeholder

IGBC can look into reinforcing its message on integrated process-based sustainability strategies as the part of its certification. Project teams could be persuaded to be more holistically-sustainable through the introduction of Lean-Circular thinking into training-programmes, best-practice manuals, and evaluation standards. Realisation of integrated management frameworks in Innovation and Design credits would also encourage continuous improvement and innovation.

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CHAPTER 26

Integrated Smart Water Infrastructure Planning for PCMC

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ABSTRACT

Climate change and rapid urbanization are exerting unprecedented stress on urban water infrastructure in emerging cities. This study investigates the challenges in the water supply system of the Pimpri-Chinchwad Municipal Corporation (PCMC), Maharashtra, India, and proposes an Integrated Smart Water Infrastructure (ISWI) framework to enhance system efficiency, sustainability, and resilience. Using a mixed-method approach that combines a systematic review of global best practices with insights from an interview with a PCMC Sub City Engineer, the research identifies key issues such as high non-revenue water (NRW), pipeline leakages, irregular supply, and inadequate real-time monitoring. The literature review emphasizes the potential of technologies like SCADA, IoT sensors, Advanced Metering Infrastructure (AMI), and Digital Twins for predictive maintenance and leak detection. Although PCMC has initiated smart metering and SCADA in select zones, challenges such as outdated infrastructure, water scarcity, and financial constraints hinder full-scale adoption. The study recommends phased implementation of smart technologies with robust cybersecurity and data analytics to achieve continuous water supply and long-term water security.

Keywords: Smart Water Infrastructure, Urban Water Management, PCMC, SCADA, Sustainable Cities.

1.0 Introduction

The purpose of this study is to analyze the current water supply and management system used in the Pimpri-Chinchwad Municipal Corporation (PCMC) and to come up with an integrated smart water infrastructure planning model that can help to increase efficiency, minimize wastages of water and improve the reliability of the services.

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Water is among the most important resources that support urban life, economy, and health of people. The stress on the available water supply systems is accumulated as urban areas grow and a more substantial population is known to be in place. Most urban water systems were developed decades ago with lower populations and less demand patterns, which is seen in the older water distribution systems of such cities as Mumbai, Chennai, Kolkata and Delhi which had originally been planned with much smaller urban populations and less per capita demand. Such systems are nowadays finding it hard to handle the escalating consumption, ageing infrastructure, and climatic change, as well as rising demands of reliable and fair service delivery. Consequently, the problem of water leakages, wastage, uneven distribution and interruption in supply has become a common problem in the urban local authorities.

The prevailing system of water supply was traditionally based on manual control of water supply systems, regular inspection of supply systems, and reactive maintenance. Although such ways were satisfactory several years ago, nowadays they are insufficient in the crowded urban setting. The manifestation of high non-revenue water, and inefficient use of available resources were caused by delays in leak detection, poor visibility in real-time consumption as well as the lack of integrated decision-making. Current water management in urban areas needs to be transitioned to proactive and non-reactive systems that are able to forecast issues and aid effective planning.

As a way of addressing these issues, the idea of smart water infrastructure has become very popular across the globe. Smart water systems combine digital technologies because they include sensors, automated control, real-time data platform and analysis tools to monitor a water network around. By enabling utilities to monitor flow and pressure, identifying irregularities in advance, predicting demand, and enhancing operational efficiency, these systems enable utilities to monitor their systems. In addition to its efficiency, smart water infrastructure contributes to the long-term sustainability of the water infrastructure due to its minimization of water loss, increased reliability of services, and resilience to disruptions.

Tecnological developments in India have worsened the water stress conditions in numerous urban centers whereby population growth, growing industries, and a lack of locally available water resources have exerted strain and strain on pre-existing water supply networks causing chronic water shortages and scarcity, particularly in the summer seasons. Municipal corporations are prone to seasonal shortages, reliance on scarce water resources on the surface, and losses in infrastructure. The use of smart technologies to enhance urban services, such as water supply and management, is under the focus of government initiatives as the Smart Cities Mission. Nevertheless, to make smart water systems successful, special planning of the systems would be necessary that should take into consideration the local circumstances, institutional resources, financial viability, and stakeholder alignment.

The Pimpri-Chinchwad Municipal Corporation (PCMC) is a fast developing urban and industrial area, where management of water has taken a new dimension. As the population increases, residential developments expand and the industrial demand also increases the water supply system at PCMC is having difficulties in terms of leakage losses, non-revenue water, seasonal scarcity and unfair distribution. Though there are the first steps in the digital monitoring and automation, the necessity to have a uniformed approach to the planning of smart water infrastructure is still present.

The study being targeted at the designing of a comprehensive smart water infrastructure planning model of PCMC. The research question is to review the current water management, detect the gaps in the systems, and evaluate how smart technologies and data-based solutions could be used to enhance efficiency, reliability, and sustainability. Through the interconnection of the knowledge obtained in research around the world and realities of operation in the country, the study aims at making practical recommendations that can help PCMC transform into a smarter and more resilient urban water system.

2.0 Literature Review

Increased population growth, climate uncertainty, and the old structure have led to a significant interest in urban water management as an academic and policy-oriented topic of research. A number of researches point out that traditional water supply systems that heavily rely on manual monitoring and regular repairs are no longer suitable in the modern urban settings. These concerns are identified by a number of scholars on the international and local levels. To illustrate, Mankad and Arolkar highlight that, traditional water systems lack good leakage control, effective monitoring, and real-time data which restricts effective decision-making in Indian cities, whereas Parkhe demonstrates that urban and Tier II cities in India have a severe issue of water wastage, ineffective monitoring and a ineffective distribution as a result of old-fashioned and manually managed systems.

Researchers claim that, in most cases, these traditional systems lead towards high non-revenue water, slow response to water wastage, and poor transparency in operations. To counter the effect of these outbreaks, smart water systems have been advanced as a promising solution, the digital technologies that are incorporated include real-time sensors, automated control systems, and central data platforms. According to existing literature, these systems can enhance visibility throughout the water network in a major way, as well as help utilities to transition to practices based on reactive maintenance to proactive and preventive management.

The other valuable topic in the literature is associated with robustness and stability of smart water infrastructure. In the article by Mankad and Arolkar, titled Smart Water

Metering Implementation, the authors note that even though IoT-based water systems can enhance monitoring and control, such systems also present security issues when it comes to the system and communication reliability as well as data management in large urban and heterogeneous networks. In the same manner, in their review article, Zapata-Sierra et al. (2024) identified the communication, cybersecurity, and system integration as a significant research topic in the field of smart water, which demonstrates a rise in interest towards operational and cyber threats in intelligent infrastructures.

Resilience of smart water studies also posit that an appropriate method of implementation must be balanced embracing physical infrastructure, decision system, information systems, and stakeholder involvement. The usage of technologies like SCADA, constant internet control, and innovative metering infrastructure is extensively addressed as facilities that help in making decisions in real-time and responding promptly to the situation not only in the normal functioning process but also in emergency cases. Nevertheless, researchers warn these systems may not be resistant to technical breakdowns and malicious cyber actions without the proper level of redundancy, system risk analysis, and interagency response mechanisms. This literature provides a clear elucidation of the need to incorporate resilience planning and technological improvements on urban water systems.

According to the recent researches, smart metering, predictive analytics, and digital twin technologies play a vital role in enhancing the performance of the water management system and the water demand. Smart meters can minimize the use of water because timely and clear feedback to the users is given, however, long-term effect is maintained because of the constant interaction. On the utility level, digital twins contribute to the increased accuracy in demand forecasting and the possibility to identify the problems early on and eliminate leakage and pressure loss, among others. Nevertheless, some situations concerning the data quality, integration of the systems, and high cost of implementation remain to be troublesome, particularly in the prospering city centers.

Overall, the literature emphasizes that successful smart water infrastructure requires adaptation to local contexts, supported by strong governance and capacity building.

3.0 Research Methodology

This research study focuses on smart water infrastructure planning and scope and applicability using a qualitative and exploratory method in the context of Pimpri-Chinchwad Municipal Corporation (PCMC). The methodology aims to build on the understanding of smart water systems, resilience and digital water management presented in the existing literature and to anchor the analysis by the context of the local urban area. A systematic review of peer-reviewed journal articles, government publications, municipal reports and

policy documents was conducted to learn about global best practices and technological trends in smart water management. Particular emphasis was placed on those studies that address real time monitoring, demand management, system resilience, and predictive maintenance as these themes are directly pertinent to the challenges faced by PCMC.

To ensure that the findings from around the world fit to our local context, the research uses secondary data relating to PCMC's water supply system, including official reports from the municipality, any statistics made available to use, and efforts documented to do with water sourcing, treatment, and distribution. Moreover, interviews with the representatives of the water department in PCMC provided secondary insights that help to gain a practical picture of operation challenges, the current system of limitations related to infrastructure, and the current digital programs. These interactions helped bridge the gap between existing theoretical frameworks that were discussed in the literature as against the practical reality of municipal water management in a rapidly growing urban region like Pimbri-Chinchwad.

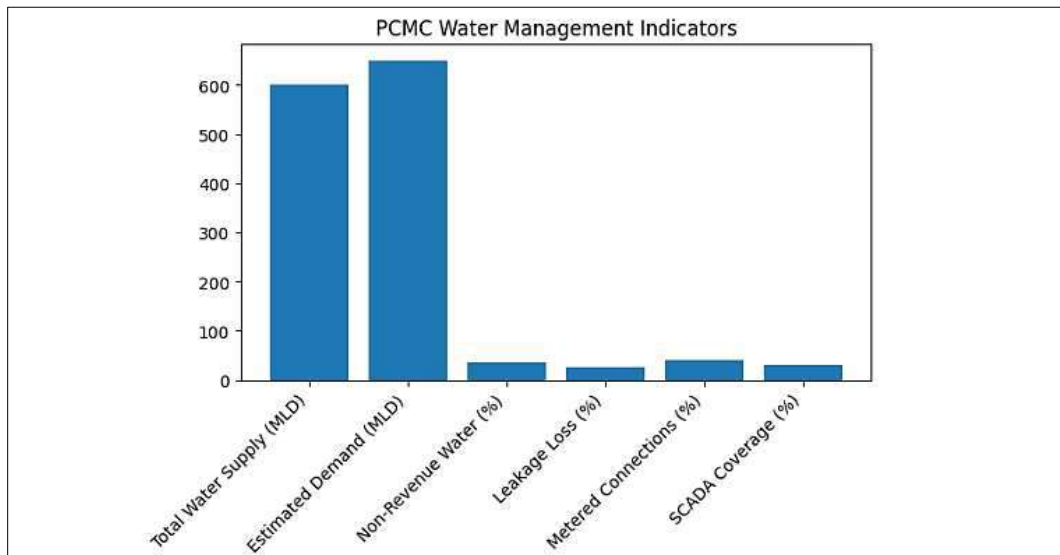
The data collected had been analyzed using thematic approach to identify the key gaps between existing water management practices in PCMC and the capabilities provided by smart water infrastructure. Themes such as non revenue water, leakage detection, demand variability, limitations in monitoring and institutional readiness were examined with respect to smart technologies highlighted in the literature. This strategy made it possible to establish a unified view in planning which would take into account technological achievability and local government limitations. The methodology guarantees that recommendations of the study are context specific, practical and consistent with the long-term goal of PCMC to develop a more efficient, resilient and sustainable urban water supply system.

4.0 Data Analysis

The analysis of the data shows that at present PCMC provides about 600 MLD of water, which is the potential demand of the water of about 650 MLD that is short by an estimated 50 MLD. To a large extent this supply-demand gap is coped by emergency means like water tanker mobilization, redistribution on a temporary basis in areas with high supply, and augmented reliance on deep-drilled borewells in high summer. Nonetheless, these emergency measures add to the operational expenses and cause access inequalities because the supply of tankers is uneven and is often prioritized or strictly impacted by circumstance. Almost 35 percent levels of non-revenue water and a 25 percent level of leakage losses also exacerbate this shortage, whereby a considerable amount of treated water is squandered. Also, PCMC does not have real-time visibility of flows and losses because it has approximately 40 percent connections metered and little over 30 percent of the network covered by SCADA. The present gap-management practice reveals that existing gap-management strategies are

reactive and inefficient hence substantial interest in an integrated smart water infrastructure approach capable of reduce losses, build up a better monitoring facility, and a more resourceful approach to demand.

Figure 1: Key Water Management Performance Indicators of PCMC



Source: Created by authors

Table 1: Key Water Management Indicators – PCMC

Parameter	Value
Total Water Supply (MLD)	600
Estimated Water Demand (MLD)	650
Non-Revenue Water (%)	35
Leakage Loss (%)	25
Metered Connections (%)	40
SCADA Coverage (%)	30

Source: Created by authors

5.0 Findings/Results

The results presented in this paper are obtained through the research of secondary data on the system of water supply in PCMC with references to the information obtained with the help of municipal reports and talking to the authorities. The findings are given in a manner that demonstrates major operational loopholes, existing states of utilizing smart technology,

and where smart water technology infrastructure can enhance enormous performance of the systems. The results are explained in accordance with the aims of research and themes that were observed in the literature review.

5.1 Water supply–demand gap and system efficiency

According to the analysis, PCMC is now delivering about 600 MLD of water, and the estimated amount of required water is about 650 MLD per day meaning that there is an ongoing gap between supply and demand. This deficit is aggravated in summer seasons subjecting the distribution system to more stress thus resulting to intermittent supply in some regions. The existence of such a gap proves previous literature statements that urban water stress cannot be attributed only to lack of water availability but also to distribution inefficiencies and limitations in the management of demand.

5.2 Sources of non-revenue water

When the breakdown of NRW is further considered, leakage losses occur as the biggest element, and is over two-thirds of the total NRW. Coding and the consumption of unauthorised advertising and measurements add a smaller, though significant, amount. This distribution brings out the structural nature of the losses as opposed to behavioural/billing related issues. Leakage losses are the leading causes of water loss according to the domination; therefore, this implies that aged pipelines and delayed detection systems are among the major causes of water loss. This observation complements the literature that argues out the significance of real-time monitoring and proactive maintenance as a means of minimizing physical losses in the water networks.

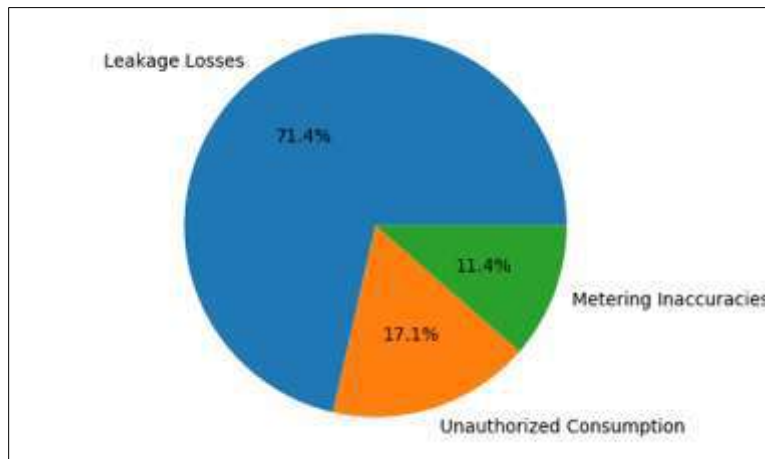
5.3 Status of smart technology adoption

The results further show that there is partial and unbalanced adoption of smart technology in PCMC. Only an approximate 40 percent of the connections are metered and SCADA has a coverage of approximately 30 percent of the distribution system. Along with the fact that these initiatives are good moves towards digitalization, they are limited in terms of scale which limits the capacity of the system to offer real time visibility and coordinated control. As it was emphasized in the literature review, the entire effect of smart water systems is weakened and the effectiveness on the resilience and operational efficiency of water systems is restricted due to fragmented implementation.

On the whole, the findings indicate that PCMC experiences the problem characteristic of fast urbanization cities such as high NRW, infrastructure depreciation, and poor digitalization. The results support the idea that an all-encompassing smart water

infrastructure strategy is necessary that can integrate the aspects of network-wide monitoring, data-informed decision-making, and the local phased efforts strategies.

Figure 2: Composition of Non-Revenue Water in PCMC



Source: Created by authors

6.0 Conclusion

The study will answer the question and relevance of the need to have an integrated smart water infrastructure planning plan in the Pimpri-Chinchwad Municipal Corporation that considers the increasing stress on urban water, the deterioration of the infrastructures, and the escalating demands. The evaluation highlights that PCMC also experiences unremitting supply demand imbalance, excessive non-revenue water and excessive leakages-all contributing factors to reduction of efficiency and reliability of the current system of water supply. In addition to that, the real-time monitoring and informed decision-making are further impeded by partial metering coverage and partially implemented SCADA.

These results reinforce the support that the existing predicaments regarding the water management in PCMC are not just influenced by the accessibility of water, but are predominately brought about by the lack of effectiveness in distribution, latency in leak identification, and fragmented digital application. Despite the first steps provided in the smart water management, no fully integrated and network-based approach will allow making the use of such technologies to be beneficial. This strengthens the importance of a proper planning framework that brings together technological upgrades, institutional coordination, data integration and capacity building.

This paper claims that the smart water infrastructure is more than a pure technological solution to a problem but rather a component that will form the foundation of proactive management, demand forecasting and safeguarding against seasonal and operational uncertainties. This way, the gradual approach of implementation, adapted to the local environment and aided by the competent governance, could help PCMC in the gradual reduction of non-revenue water, enhancement of service stability and efficiency, as well as optimization of resource utilization.

This study brings the contextual aspect as it aims at the circumstances of the particular area of the Pimpri-Chinchwad Municipal Corporation that is marked by a rapid population increase, a rise in industrial water requirements, seasonal crises, the deterioration of infrastructure, and incomplete digitalization. Instead of using generalized smart water models, the research establishes smart infrastructure planning as specific to the institutional and financial capabilities and the operational issues of PCMC.

The results show that the best practices of the world (real-time monitoring, advanced metering infrastructure, predictive maintenance, and data-driven decision-making) can be successfully adjusted to local realities when followed in a gradual and adaptive fashion. This combination approach, through its alignment of international smart water strategies with the ground-level conditions of PCMC, provides a convenient reference framework concept in other urban local agencies, intending to transition to more efficient, resilient, and sustainable urban water supply systems.

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CHAPTER 27

Real Estate Regulation Act (RERA): A Study of Its Implementation with Specific Reference to Maha RERA

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ABSTRACT

The Real Estate (Regulation and Development) Act, 2016 was a major regulatory step in changing how regulatory bodies handle the real estate sector in India, and the Maharashtra Real Estate Regulatory Authority (MahaRERA) is one of the most ambitious state regulatory bodies. This study discusses the impact of MahaRERA in Maharashtra, particularly the enforcement of the regulation by orders, judgments, and circulars of the Authority. Based on secondary data from MahaRERA annual reports and a methodological review of the individual project-related orders issued by the Authority and Adjudicating Officers, the study assesses the effects of enforcement mechanisms on promoter behaviour, project compliance, and consumer protection. It has been shown that the large application of speaking orders, penal actions, awards of interest and compensation and clarificatory circulars by MahaRERA has been essential in promoting transparency, enhanced accountability and institutionalisation of regulatory discipline in the industry. The paper also highlights the changing jurisprudence of MahaRERA, which shows how interpretive consistency and judicial administrative circulars have created less ambiguity and increased adherence. Although the results related to enforcement have been mostly favourable, issues of prolonged project completion and order-related performance remain. This article contributes to the regulatory impact of literature because it contains an enforcement-based evaluation of RERA's implementation in Maharashtra.

Keywords: Real estate regulation, MahaRERA, RERA implementation, Regulatory orders, Enforcement.

1.0 Introduction

The adoption of the Real Estate (Regulation and Development) Act, 2016 (RERA), was a transformative move in the regulation of the real estate industry in India, as it provided

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better accountability statutes, disclosure requirements, and a dedicated adjudication system for real estate sector. The RERA implementation in Maharashtra through the establishment of Maharashtra Real Estate Regulatory Authority (MahaRERA) since May 2017 provided one of the most prolific enforcement settings in Indian states. Over time, MahaRERA has not only become a registration authority but also a quasi-judicial regulator, the decisions of which, orders, and circulars, have had a significant influence on market participant behaviour.

This paper analyses the effect of the MahaRERA between 2017 and 2025, with a specific intention to focus on the regulatory enforcement of the Authority, as revealed by orders and judgments made by the Authority and the Adjudicating Officers, and general as well as project-specific circulars issued at any given time. Instead of regarding RERA implementation as a compliance project quantified by the number of registrations or aggregate disposal rates, this study considers MahaRERA as an enforcement body, the jurisprudence of which has gradually delimited the rights and duties of promoters, allottees, and real estate agents.

The regulatory power of MahaRERA manifests itself most evidently in its orders covering late projects, conditional extensions, project revocation and de-registration, freezing and supervision of specific bank accounts, and the payment of interest, penalties, and compensation. These orders often extend well beyond the resolution of disputes to mandate governance mechanisms in projects, such as compulsory reporting of project progress, escrow management, appointment of professionals, and schedules for obtaining statutory approval. Simultaneously, MahaRERA published a set of administrative circulars and process guidelines, including project disclosures, advertising standards, quality assurance, agent registration, self-regulatory organizations, and digital compliance systems, by which regulatory expectations were standardized throughout the sector.

A review of these orders and circulars shows a changing philosophy of enforcement. The first years of implementation are characterized by a careful, facilitative approach to ensure that legacy projects come under the regulation framework, whereas subsequent years are characterized by a more assertive regulatory stance, which comprises a more rigorous examination of documentation, forfeiture of non-compliant projects, and the strengthening supervisory measures in high-risk cases. This development underscores the way in which the enforcement strategy of MahaRERA has been modified to suit market behaviour, judicial interpretation, and practical considerations in the completion of projects and the redressal of consumers grievances.

The primary aim of this research is to examine the impact of the enforcement tools of MahaRERA, such as judicial orders, adjudicative decisions, and regulatory circulars, on the behaviour of promoters, project governance, and consumer protection within Maharashtra in a period to 2017-2025. This study attempts to fill the empirical gap in the limited research

on the enforcement of RERA and regulatory jurisprudence by systematically analysing the content, reasoning, and remedial structures of the orders of MahaRERA. A grounded approach to translating statutory intent into operational control in the real estate industry is possible by focusing on orders.

2.0 Literature Review

With the Real Estate (Regulation and Development) Act, 2016, a growing body of scholarly and policy-focused research has emerged on its effects on transparency, accountability, and consumer protection in the Indian real estate industry. To a great extent, early scholarship viewed RERA as a structural reform and concentrated on the statutory requirements of the system, including the mandatory registration of projects, escrows, and disclosure. However, such studies find that RERA is more of a corrective measure to overcome chronic information asymmetry, diversion of funds, and delays, which characterized the pre-RERA housing market. Empirical estimates carried out in a large number of states show that the level of buyer awareness through the introduction of regulatory powers and mandatory disclosure affects the behavior of promoters in relation to advertising and documentation practices.

Later works considered other factors, such as implementation, instead of statutory intent. As pointed out by several researchers, the effectiveness of RERA differs by state based on institutional capacity, administrative design, and intensity of enforcement. Although the number of registrations and complaints rose drastically after 2017, researchers warn that aggregate metrics do not provide the quality of the regulatory intervention on their own. One theme replicated in this literature is that the outcomes achieved by RERA are more influenced by the presence of the law than by how state authorities operationalize enforcement through adjudication, penalties, and procedural directions. This observation is especially pertinent in the context of Maharashtra, where MahaRERA embraced a digital-first strategy and increased adjudicatory procedures.

There is a parallel line of literature that studies dispute resolution in the context of RERA and how regulatory authorities, adjudicating officers, and appellate tribunals play a role in it. RERA judgment analysis has been concerned with the changing interpretation of essential provisions, including the applicability of RERA to pre-Act agreements, the calculation of interest and compensation, force majeure claims, and the extent of extensions granted to delayed projects. These studies observe that regulatory orders and judgments have increasingly brought out ambiguities in the Act and thus expectations and compliance strategies among promoters. Nonetheless, a larger portion of this scholarship is doctrinal,

which is the examination of individual landmark judgments, as opposed to the systematic study of patterns within a body of numerous regulatory orders.

A few empirical and policy-based studies have examined the alternative dispute resolution mechanisms implemented under RERA, particularly conciliation mechanisms. The conciliation model in Maharashtra has attracted the interest of scholars because of its apparently cool experimentation with regulatory dispute resolution, and papers report high settlement rates and reduced litigation costs. According to these authors, conciliation, with the support of a regulatory authority, can become a great compliance tool rather than merely a dispute-settlement mechanism. Nevertheless, most existing literature considers conciliation results as an adjunct to formal enforcement without incorporating them into a larger strategy that includes supervisory orders, conditional extensions, and revocation actions.

In the context of regulatory theory, those who dwell on responsive regulation and enforcement literature say that current regulators adopt a gradual combination of instruments, ranging from persuasion and negotiated compliance to coercive penalties. Administrative orders are not merely case-specific results in this structure; they are important instruments of governance that convert legislative will into administrative control. Regulatory design and content of regulatory orders, such as reporting requirements, conditional approvals, and monitoring mechanisms, research on infrastructure, environmental regulation, and financial regulation demonstrate that the behavioral effect of statutory penalties alone is frequently smaller than the behavioral effect of regulatory design and content of orders. The extension of this lens to real estate regulation implies that orders and circulars are important in interpreting how RERA operates in practice.

Although the literature on RERA has increased, there are two obvious gaps. First, there is little empirical work that considers regulatory orders and circulars as the main data to examine the behavior of enforcement over time. Second, there is a paucity of studies that systematically attribute the nature of orders, including conditional extensions, account-freezing directions, or registration revocations, to more general implications in project governance and consumer protection. Most of the work done is based on descriptive statistics or random instances of cases, and the comprehensive logic behind regulating hundreds of regular orders by various authorities, such as MahaRERA, remains untapped.

This study addresses this gap by adopting an orders-centered approach to the operation of MahaRERA between 2017 and 2025. This study contributes to the literature on RERA implementation and regulatory enforcement by focusing on the content, arguments, and remedial frameworks of regulatory orders and circulars. By doing so, it transcends compliance metrics to examine how enforcement is constructed, expressed, and institutionalized within the daily process of making regulatory decisions.

3.0 Research Methodology

A qualitative-descriptive research methodology, with a small measure of rudimentary quantitative summarization, is applied in this study to analyze regulatory enforcement by MahaRERA using its publicly available orders, judgments, and circulars. This analysis was conducted for the period between 2017 and 2025, which is the period of operation of MahaRERA since the Real Estate (Regulation and Development) Act, 2016, became operational in Maharashtra. This study is based entirely on secondary data available on the official MahaRERA website. The principal ones are project-level orders made by the Authority and Adjudicating Officers, general and project-specific circulars, and the information provided on registered projects in the form of status updates and comply directives. These records constitute the heart of empirical data according to which the mode of enforcement of MahaRERA is considered to be.

This is a systematic review and categorization of MahaRERA orders as the methodology. First, the orders were organized over time to observe changes in the regulatory approach over time. They were then sorted according to their regulatory dominance, such as conditional extensions of project schedules, cancellation or deregistration of projects, penalties, giving interest or compensation to allottees, freezing or monitoring of specified bank accounts, and consenting compliance-related instructions. Circulars were examined individually to understand how MahaRERA sanctioned regulatory practice and demystified procedural regulation throughout the sector.

The reasoning, conditions, and directions in the orders were examined with the help of a content analysis. Special focus was placed on the themes of recurring enforcement issues, such as promoter tracking mechanisms, disclosure, compliance schedules, and non-compliance consequences. The representative orders were discussed in close view to understand how MahaRERA considers consumer protection, completion of projects, and the discipline of the regulator in various factual conditions.

To determine the impact, this study examines visible regulatory effects in the form of the type of relief that is awarded, the intensification of enforcement efforts, and the change in the direction of more stringent supervisory and coercive orders. The analysis does not seek to make a causal measurement based on statistical modelling; rather, it aims to identify patterns of enforcement and regulatory intent through the decisions of MahaRERA.

The methodology is appropriate for the goals of the study because it will enable a grounded approach to how MahaRERA functions in practice through its daily regulatory activities. Although the analysis is constrained with regard to publicly available data and does not involve any primary surveys and interviews, the sheer number of orders and circulars

gives the analysis sufficient insight to assess the role of MahaRERA as an enforcement agency and its influence on the real estate industry in Maharashtra.

4.0 Data Analysis

MahaRERA has been able to dispose of a significant number of complaints that it received over time. Table 1 shows the number of complaints resolved by the MahaRERA over time. It can be seen that the number of complaints resolved has been increasing over time, indicating the rising regulatory ability to resolve consumer grievances. There was some amount of stagnation in the number of cases resolved during 2021-2023, which was an aftermath period after the Covid 19, as the pandemic has affected very sphere of economic activity, including real estate development and allied activities. However, the Authority was able to resolve a large number of complaints – more than 6,000 cases – by the end of last year i.e., 2025. The total number of complaint resolutions at more than 20,000 cases also reflects the regulatory capacity built by the MahaRERA overtime.

Table 1: Resolution of Complaints by the MahaRERA

Year	Number of Complaints Resolved	Increase in per cent
2020	1,630	-
2021	2,207	35.40
2022	2,627	19.03
2023	2,792	6.28
2024	4,775	71.02
2025	6,945	45.45
TOTAL	20,976	

Source: MahaRERA Reports

Data narration reveals a definite annual change in the enforcement practice by MahaRERA between 2017 and 2025. In the initial stage (2017 -2019) the regulator aimed to establish institutional arrangements and promote compliance by providing guidance and conciliation. Much of the orders and circulars of this era are in the constructive and process-setting style: establishing conciliation benches, standardizing disclosure forms, and encouraging professional practice as against instant penalties. The language of most of the early orders focused on transparency, outreach to stakeholders, and capacity building, and the remedies recommended tended to be procedural (e.g., guidance on conciliation or compulsory disclosure forms) rather than coercive. This created some early pushing in by promoters and agents and assisted in getting many legacy projects under regulatory scrutiny.

During the pandemic years (2020-2021), the regulator went in a new direction. Various relief-based directions were issued by MahaRERA in a series of pragmatic directions, which, in effect, halted the strict application of statutory timelines. Circulars and orders provided temporary registration and compliance deadline extensions, force-majeure invoked where necessary, and hearings and conciliations shifted online to allow movement and site constraints. These pandemic regulations placed more emphasis on continuity and legal certainty for promoters and allottees and expressly retained basic protections for buyers; extensions were widely permitted but with the instruction to keep records and follow the terms specified where necessary. In the case of projects that had completion commitments in the lockdown period, the regulator offered time-limited and structured relief without compromising the procedural protection of the interests of allottees.

Since 2022, a more prescriptive enforcement has shifted towards. Orders become longer and more detailed and routinely include supervisory conditions that must be satisfied by promoters to receive an extension or prevent de-registration. The most common are routine progress reports, independent engineer appointments, escrow or bank-account supervision, completion guarantees, and the affirmative consent of a specified percentage of allottees to additional extensions. The drafting is rights-sensitive: extensions are strictly conditional, and protections of homebuyers, including the preservation of escrow discipline and their right to receive interest or compensation, are restated many times. During this stage, show-cause notices and formal punishments for disclosure and advertising violations are also more frequently used. The enforcement of non-updating of the project status and other breaches of procedures increased, and the regulator started to publish the list of the non-compliant projects and the formal penalty orders to prevent repeat violations. These trends denote a change in facilitation to firm supervision.

In the latter period, two interrelated innovations are remarkable. First, MahaRERA incorporated more powerful monitoring in the design. Some orders mention systematic monitoring of advertising and disclosure standards and determine specific enforcement measures in case violations are detected. This operationalized a change in the ad hoc mode of detection to a regular compliance check, allowing faster show-cause proceedings and punishment triggers. Second, the Self-Regulatory Organisation (SRO) framework, which was mentioned above, was deployed as an enforcement supplement: some circulars and orders inquired that SROs help with promoter education, audits, and peer-level discipline, whereas other orders referred issues to SROs for pre-review before regulators followed up. This combination of enforcement by law and self-regulation by industry is a pattern in orders that have been issued since 2019 and has become more noticeable since the pandemic relief measures were lifted.

The regulatory record indicates these changes in terms of their quantity. There was a peak in the period of the pandemic of extensions of the blanket and relief in the process, but then the following years record higher numbers of conditional extensions, which were granted only after more rigorous examination. Alongside the trend of conditional approvals, there has been an increase in formal enforcement actions: advertising and disclosure breaches are fined, and the number of projects that are put under supervisory conditions or de-registration proceedings is on the rise. The recovery effort and show-cause orders have increased, and a larger percentage of their 2022-2025 orders include multi-line remedial packages (monitoring, milestones, escrow controls, and consumer-facing remedies) as opposed to single-line directions. This is an indication of a more holistic strategy of enforcement, one that incorporates coercive and supervisory aspects of altering promoter's behavior.

Altogether, the documents issued by MahaRERA orders and circulars suggest a three-phase path: (i) institution-building and enabling (2017-2019), (ii) relief-based responding during COVID (2020-2021), and (iii) recovery to aggressive, situation-based enforcement (2022-2025). The later time is marked by fully detailed orders that bind extensions and discretion to actual monitoring obligations, escrow control and consumer protection, and a more obvious use of penalties to enforce habitual compliance. The following trends indicate that MahaRERA is no longer focused on creating administrative infrastructure but has deployed a progressively more sophisticated enforcement toolkit between settlement and supervision and punitive action to enhance project governance and safeguard allottees.

5.0 Findings

The results show that the regulatory regime of MahaRERA has significantly changed since its founding. The initial years were devoted to establishing the compliance framework, whereas the subsequent years were dedicated to strict enforcement. During the initial year (2017-18) of the implementation of RERA, promoters mostly compiled and registered projects: more than 16,000 projects and 14,000 agents were registered in the same year. The Authority received 2,229 cases during the 2017-18 period (2018 caseload statistic), and closed 1,273 cases, thus the Authority had a growing caseload; the initial focus on the Authority was on project registration. Indicatively, the late registration of the ongoing projects was punished (to up to Rs. 200,000 or more in fees) to make sure that the deadline was met. In 2017-18, many of the projects were already on the way (as reported in the annual report of MahaRERA) and only approximately 4,000 out of 20,560 projects registered in 2017-18 were completed. The existence of this gap meant that a significant proportion of projects needed to be continuously monitored. Other steps to enhance quality control and accountability of construction were also implemented by MahaRERA like the introduction of a mandatory

Quality Assurance Certificate (Form 2A), which will be filled in by site engineers every quarter in late 2018. These initial measures indicate that in 2017-19 the strategy of MahaRERA was to provide groundwork such as registering projects, registering projects with delays, and quality inspections in place and handle thousands of complaints in accordance with the new law.

With regard to the promoter compliance behaviour within the context of this initial registration, the promoter adherence proceeded under two overlapping pressures, viz. RERA deadlines, and subsequently the external interruptions. Since the year 2018, there have been numerous developers who failed to complete the projects according to the initial schedules, which resulted in frequent extensions requests under Section 7(3) of the Act. According to the 2020 report of MahaRERA, it received approximately over 10,000 cases each year by that time, and it disposed of nearly 74 percent of those cases (8,162 cases of 11,026 received). The influx of filings can be attributed to the increased awareness of the customers about RERA and the list of uncompleted projects. Outreach and compliance surveys were done - for instance, in mid-2020 the MahaRERA was sending monthly reminders to promoters whose registrations or filings were overdue - yet many projects continued to be behind statutory milestones.

As COVID-19 began, the issue of compliance became worse. In its 2020 section, From the Desk, MahaRERA specifically documents that due to lockdowns, the construction activity of all real-estate projects came to a halt that affected all the stakeholders, including promoters, real-estate agents, allottees etc. The Authority responded with an emergency measure: the period of project validity was become six months longer in case of any project that would expire after mid-March 2020, and the timeframes of statutory filing were eased. Practically, MahaRERA recognised that several delays were out of control of promoters, and in advance, it did not wish to punish them due to stoppages caused by the pandemic. These indicators show that most promoters followed the rules when provided with flexibility in 2020 (e.g. most promoters accepted extensions and resets of the timeline instead of officially challenging them).

But with the restoration of order the latent compliance problems again began to surface. By 2021 and 2022, promoters were requesting massive deadline extensions, often attributed to COVID related delay, unavailability of funds or new regulations. As an example, 2023-25 orders provide promoters with the reasons of shortage of labor in the pandemic and even new environmental or safety regulations. They were normally granted extensions by MahaRERA but with strict conditions. In 2023, the promoter of a project received two additional years, on condition of preparing comprehensive schedules (PERT/CPM charts), monthly progress reports to MahaRERA and to allottees, and updating its publicly accessible project page with any new Occupancy Certificate. Nevertheless, as of 2025, a one-year

extension was granted when the developer was obliged to publicly post occupancy certificates of the previous stages to the public portal and commence intensive monthly reporting. These instances demonstrate a wider trend: although extensions were granted, promoters were required to make available detailed project-management plans and enhanced transparency, which basically augmented their compliance obligations. According to the trend, although promoter deadline-meeting remained a challenge, the regulator diverted attention to tools of accountability to ensure the projects were still on track.

Notably, MahaRERA also ensured that promoters who attempted to evade their responsibilities were also brought to book. Another case in point is an order of 2025 that denied the demand of a developer to deregister a portion of a residential tower in a larger development. MahaRERA indicated that under RERA partial deregistration is forbidden since registration implies the promise of the promoter to complete and deliver the whole approved project. In reality, the developer could not simply leave unsold flats, the Authority demanded that the entire scope should be maintained. Similarly, when a new building complex was attached to an existing registration, MahaRERA only made extensions to the new parts and did not change the original schedule. This carefully chosen extension ensured this addition of scope did not allow promoters to avoid previous promises. These judgements send a strong signal; compliance with promoters now has a stronger legal repercussion-MahaRERA will not divide or water down registered functions at the bequest of a promoter.

As far as the adaptation of implementation plan concerned, the enforcement strategies of MahaRERA became much refined over the period of 2017-2025. The first two years were dedicated to the implementation of processes: adoption of e-filing, paperlessness, establishing a conciliation forum, and consistently processing complaints. As an example, in 2018-19 the Authority sorted approximately 4218 of 6719 complaints. At that point, MahaRERA blended its central adjudication with promotion efforts promoter association meetings monthly and awareness campaigns to identify unregistered projects with the people. Registration was principally enforced by penalties, which were either the consequence of adjudication, or imposed to enforce the registration deadline; as indicated in the annual reports, those promoters who failed to make their registration were regularly fined and had to make a retroactive registration.

With time, enforcement became more systematic. MahaRERA had implemented tools to standardize the behavior of promoters by 2019-2020. In 2019, it started certifying Self-Regulatory Organizations (SROs) to supervise groups of promoters, the purpose of which was to achieve higher professionalism and uniformity. It also established periodic audits (such as the requirement of an engineer to submit Form 2A) and introduced a compliance-monitoring system (software-based). The annual report of 2020 contains a specific calendar: on fixed days of every month, automated lists of the projects requiring

updates or the ones expiring soon are created and reminder emails are sent to the corresponding promoters. This demonstrates a change of ad-hoc enforcement to proactive monitoring: MahaRERA began actively monitoring whether promoters updated their data and filings.

The COVID pushed the enforcement to the limit. Initially, the strategy of MahaRERA was flexible- extension of deadlines. However, starting in 2021 the focus shifted back to accountability. As an example, though the pandemic disruptions increased project timeframes, MahaRERA increased them by several months instead of the complete relief promoters insisted on, with explicitly that aim so that the Authority could inspect project progress more closely. It also denied extensions when they were not acceptable (e.g. denying a further extension despite the promoter not having the allottee consent of two thirds, on the basis that refusal to grant an extension were prejudicial to allottees). New internal processes came into force in 2022²³: MahaRERA reports that since April 2022, cross-disciplinary review (technical, legal, and financial) has to take place before any application is approved. The Authority went to an extent of publicly rectifying its own officer who made a mistake in registering a project signaling some sense of accountability in the regulator. It observed in 2023 in order that better institutional checks than those in place after 2022 circulars existed to prevent errors during registration. This is an indication that there is a transition of the building capacity into the quality control of the system itself.

By 2024 25 more strict enforcements in practice had taken place. Almost all extensions approvals were conditional: in addition to meeting a new deadline on completing construction, promoters were required to e-mail all permits when they were available and provide PERT/CPM/BAR charts and monthly progress reports to MahaRERA as well as allottees. In one of its high-rise cases, MahaRERA actually obliged that 100 per cent of subsequent sales proceeds be deposited into a special escrow account as an escrow control, a critical measure, which is equivalent to post-2022 rigor. Meanwhile, the public orders of MahaRERA put more stress on consumer interests: extensions are availed directly to safeguard allottees, or even to execute, rather than to compensate for non-compliance. These narrative utterances, together with the factual circumstances, are indicative of an obvious approach: rather than lightening the enforcement in difficult periods, MahaRERA condones delays at the expense of increasing the various requirements on developers.

To sum up, compliance on promoters following the implementation of RERA has varied with high registration compliance but at times, slow in delivery. The implementation of MahaRERA changed its focus, and, instead of supporting the new regime (registering projects, educating stakeholders), turned into active regulation. The Authority increased its pressure by 2022 25: requiring detailed reporting, disallowing deregistration loopholes and pressuring compliance with penalties. This tendency can be observed in both the information

in the case and annual reports. As an example, the number of case disposals increased by 1,273 to above 8,000 in 2017-18 and 2019-20, respectively, and the language of the MahaRERA orders became more official. Practically, this translates into the fact that promoters have more explicit and more stringent responsibilities now than they had during the initial years of RERA - a tendency which has been compounded by the subsequent policy changes of 2020. The collective impact is that, even though the advent of RERA created a friendly compliance atmosphere in the early days, by the mid-2020s, enforcement has been entrenched on accountability: extensions have been made conditional and audited and part of compliance will not be welcomed. Such changes - particularly the intensification of tightening in the registration of the MahaRERA toolkit after 2022 - imply that the latter is now using its enforcement arsenal to make sure that promoters fulfil their obligations to homebuyers.

6.0 Conclusion

Since 2017 until 2025 MahaRERA emerged as an institution-building regulator to an enforcement-oriented entity applying a wide array of tools - orders, conditional extensions, supervisory directions, escrow controls, conciliation and penalties to ensure that the behaviour of promoters is consistent with their statutory obligations. The period till 2021 has been characterised by more aggressive, conditions-based enforcement binding discretion to monitoring and remedial requirements, which demonstrates that the first years of the policy were characterised by registration, transparency and conciliation; the pandemic years by pragmatic relief without loss of core buyer protections; and afterwards by stronger enforcement tied to monitoring and remedial obligations. The records of the orders level indicate that MahaRERA does not consider extensions as formalities: extensions are systematically associated with PERT/CPM schedules, monthly progress reporting, independent supervision, escrow discipline and, where necessary, escrow restrictions or proportionate penalties. Such a combination of procedural rigour coupled with a narrowly focused sanctioning has enhanced adherence to disclosure requirements, escalated the cost of routine non-reporting, and enhanced regulatory pressure against promoters. Such inferences are based on the authority report summary and the authority corpus of decision and as such trace the transition between facilitation and assertive oversight.

7.0 Recommendations

- Enhance financial control implementation. Enforce and operationalise strong escrow monitoring through provision of more explicit standard operating procedures to the banks

and indications of Swiffer remedial actions (temporary freezes, diversion approvals can only be made on confirmed milestones). Formal guidelines amongst MahaRERA and banks will lessen the delays in executing account-level instructions and enhance the recovery of sums owed to the allottees.

- Conditional extensions should be more performance-based. Keep providing relief of time where reasonable but standardise the minimum set of provisions (detailed CPM schedules, independent engineer verification, escrow release triggers and a public milestone dashboard). Where needed, demand third party performance guarantees (bank guarantees or insurer products) to support long extensions.
- Enhance independence, institutionalise and empower SROs. Outreach should be performed with SROs, peer audit and initial compliance checks, it is necessary to make the SRO activities transparent to MahaRERA, and de-recognition requirements should be clear to avoid capture. SROs are not to be applied in replacement of statutory enforcement, but rather they should be used as a first line of corrective education and monitoring.
- Increase and hasten non-litigious dispute settlement. Increase the conciliation bench model using professional mediators, and regular settlement schedules and couple the results of conciliation with binding orders in such a way that settlements become enforceable and not informal.
- Enhance cross agency coordination. Combine the project status information of MahaRERA with the municipal building approval and utility certification systems to avoid regulatory arbitrage. Coordinated checklists and common dashboards with urban local bodies would also ensure that there is minimum time wastage by statutory approvals that the promoter had no control over.
- Increase transparency and dashboards. Make project data (percentages of progress made that are machine-readable, time-driven, and time-series) publicly available and have straightforward signs of projects that are high-risk. The public visibility gives reputational incentives and aids the allottees and financial institutions in making informed decisions.
- Quicken the appellate and review. Reform procedures (time limited appeals, backlog benches), promote short form orders to address basic technical questions in order to cut down on pendency, and put a greater deterrent impact on first instance orders.
- Combine quality assurance and skill building requirements. Keep on with Form 2A quality certificate roll-out, on-site training and qualified master-trainer programme; make quality certification conditional on preferential regulatory treatment (e.g. simplified processing of consistently compliant promoters).

- Issue a periodical enforcement impact report. Periodically (at regular intervals) published a brief enforcement report summarising orders, compliance rates, sanctions recovered and successful remediation case studies. This will assist in bringing policy on a level and reducing similarity with any other published text through original, authoritative statements of impact.
- Encourage access to anonymised orders -level research. Empower researchers to work with a sanitized and well-documented orders dataset to determine causal effects and systemic bottlenecks; ex-post data will assist them in tightening the enforcement design through the years.

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CHAPTER 28

Optimizing Traffic Signal Management using Artificial Intelligence and Internet of Things: A Case Study-Based Approach

Nia Naman, Nikita Gedam** and Saurabh Mhatre***

ABSTRACT

Transitions in the dynamical features of vehicular traffic, e.g., due to varying occupancy or capacity of the road, constitute a prominent class of phenomena which one would like large-scale models with many interacting agents to be able to explain. The Traffic Congestion Index (TCI) values also indicate that India's road network which spreads across more than 6.6 million kms, carries almost 85 percent of passenger and close to 71 per cent of freight traffic adding to choke-up the already-overloaded urban corridors which were operating way beyond their design limits. The increase in the number of vehicles, from 21 million (1991) to over 142 million (2011), has only added to traffic on the roads leading to delays, wastage of fuel and environmental pollution. Therefore, this research study aims at using AI and IoT to optimize traffic flow in real time to address these issues. Advanced intelligent traffic management systems powered by artificial intelligence-driven analytics and IoT sensor networks have the potential to enable real-time data capture, adaptive signal timing, and predictive traffic flow control, which will ultimately enable an improvement in traffic flow, easing congestion, and improved urban mobility and also helps traffic police and other stakeholders.

Keywords: Traffic Signal Optimization; Artificial Intelligence; Internet of Things; PCU Analysis; Smart Cities.

1.0 Introduction

1.1 Urbanization and traffic congestion challenges

Rapid urbanization has become one of the most evident global trends of the twenty-first century and has had a considerable impact on the transportation demand in the metropolitan areas.

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The United Nations predicts that urbanized cities will host almost 68% of the world by 2050, which will trigger a significant increase in the number of vehicles on the roads and their use (United Nations, 2022). In places like India which are not developed, an increase in urban traffic is further exacerbated by the mixed traffic conditions, poor road infrastructure and the lack of alternative mass transportation. All these have led to sustained traffic jams, further travel delays, fuel usage, and high greenhouse emissions.

Traffic congestion has been reported to be one of the greatest economic and environmental issues resulting in loss of productivity and a lot of air pollution in the cities. Research has shown that delays caused by congestion can raise fuel consumption by 30 per cent directly affecting the sustainability objectives of urban areas (Zhou et al., 2020). Conventional traffic management schemes cannot keep up with variable demand trends, peak hour traffic and mixed car stocks, and thus congestion management is becoming an extremely challenging issue in fast-growing cities.

1.2 Conventional traffic signal system limitations

Traditional traffic signal systems are mostly founded on fixed or semi-actuated control systems, which work on the principles of previously defined signal cycles and phase separation. Although these systems are comparatively easy to use, they do not have the capacity to dynamically react to real-time traffic changes. There are also fixed-time signals which can lead to poor green time utilization by creating unnecessarily long delays during low demand and insufficient clearance during peak congestion (Ravish & Swamy, 2021).

Furthermore, the traditional systems tend to handle intersections independently without coordination at the neighboring intersections. Such a disjointed functioning causes stop and go traffic conditions and queue spill over especially within heavy urban corridors. The fact that they do not integrate real-time traffic data also contributes to their inefficiency because signal timings cannot adjust to any unexpected changes that may happen due to incidents, weather, or changes in demand. According to recent findings, the use of a static signal control approach does not achieve the operational characteristics of the contemporary urban traffic network and is particularly inefficient in heterogeneous and near-saturated environments (Abirami et al., 2024).

1.3 AI and IoT in smart traffic management

The Internet of Things (IoT) and Artificial Intelligence (AI) have become new revolutionary technologies in designing intelligent transportation systems. IoT-based sensors, cameras, and associated devices help to collect traffic data in real-time and identify the number of vehicles, their speed, queue length, and turnover of vehicles. Such data streams

are important components of AI-based algorithms that can be trained to acquire complicated spatio-temporal traffic dynamics (Bhardwaj et al., 2024).

Machine learning, deep learning, and reinforcement learning represent types of AI methods that allow the development of predictive and adaptive traffic control at the signal level through the dynamical regulation of the signal phases in accordance with the current and predicted traffic conditions. It has been shown that a signal optimization using AI can contribute to a major decrease in average delays, throughput, and intersection efficiency over traditional control methods (Chen et al., 2018; Zhou et al., 2020). Scalable data-driven solutions disaster management Prolonged expanse with IoT infrastructure The incorporation of AI systems provide real-time responding, multi-intersection coordination, and sustainable city transport plans.

1.4 Motivation and context of research

In spite of the increasing progress in the AI- and IoT-based traffic management systems, their practical application in emerging urban settings is still a limited issue. A number of the existing literature is based on simulations or homogeneous traffic conditions which might not reflect the mixed and complex conditions of the traffic that are common in Indian cities. Also, the empirical research does not include those studies that combine the physically obtained data on traffic with AI-based optimization frameworks.

The gap between theoretical models of AI and the application of AI to practical traffic signal optimization with real-world traffic data is a motivation to conduct this research. This study seeks to create a viable and flexible traffic signal optimization model by utilizing the physically gathered data of the classified traffic volume in Passenger Car Units (PCU) and incorporating the ideas of AI and IoT. The study is in line with national smart city efforts and it is part of the larger goal in sustainable, efficient, and data-driven urban traffic management (Allam & Dhunny, 2019; Jagatheesaperumal et al., 2024).

2.0 Literature Review

2.1 AI-based traffic flow prediction models

Recent research indicates that there is a fast transition of classical time-series algorithms (ARIMA, SVR) to autoregressive deep learning models to predict short- and mid-term traffic flow. The most common models are deep learning models, specifically LSTM/GRU and hybrid CNN-LSTM models, due to their ability to capture non-linear spatio-temporal relationships in traffic information, which leads to higher levels of accuracy in horizons in which adaptive signal control is relevant. A number of recent surveys and empirical studies indicate that deep recurrent models and stacked autoencoders can do better

than shallow models on urban traffic datasets, with a further increase possible with the addition of spatial context (nearby sensors / lanes). Other issues that are pointed out in these works include sparseness of data, sensor noise, and intercity generalizability.

2.2 IoT-based traffic monitoring systems

IoT has emerged as the foundation of real-time traffic sensing: cameras, loop detectors, ultrasonic and radar sensor, and vehicle probes which are connected provide a stream in real time to estimate the state of traffic. IoT sensing is categorized into perception (on-road sensors), and communication (V2X, cellular, MQTT) and data ingestion layers by reviews; it is stressed that edge/fog processing results in decreasing latencies and loads on the network. Recent literature also lists the types of sensors and the associated trade-offs (price, reliability, response to weather), as well as suggests sensor fusion (camera/ radar/ probe data) to enhance resilience in disfavored situations. The experimental applications (city testbeds) expose that reliability of an IoT, the quality of the data, and secure data pipelines are the key bottlenecks to production-scale systems.

2.3 Intelligent and adaptive traffic signal control

The literature of Adaptive Traffic Signal Control (ATSC) in 2020-2024 demonstrates two existing trends in methodology (a) model-based optimization (queueing, GA/meta-heuristics) and (b) data-driven learning (supervised deep learning (SDL) to prediction + reinforcement learning (RL) or deep RL to control). Systematic reviews show that there are uniform benefits in delay reduction, queue lengths and throughput with the application of RL or a combination (prediction + optimization) of algorithms compared to a baseline consisting of static or actuated operations. Nevertheless, the major practical problems do remain, such as the reward shaping, multi-agent coordination, extrapolating simulation to the field, and the problem of computation/latency cost of real-time control. Multi-agent RL and hierarchical control are suggested to be used by several surveys in order to be able to scale over the various intersections.

2.4 Smart cities: AI-IoT interaction

The AIIoT paradigm (strong integration of AI analytics and IoT sensors and edge/cloud computing) is mentioned more and more as the good way to implement intelligent traffic control on large scale. Recent frameworks suggest layered architecture perception (sensors), network/edge (low latency preprocessing), analytics (AI models) and application (signal controllers and dashboards) will be used to address the latency, privacy and reliability requirements. The case studies and technology reviews suggest edge inference (to respond to sub-second control requirements) / federated learning (to ensure continuity of privacy across

jurisdictions) / and digital twins (to test a situation before it is introduced). The literature emphasizes governance, cybersecurity as well as interoperability standards as conditions preceding the major rollout of AIoT in urban transport.

2.5 Introduction to major results of the previous research

Prediction + control synergy Prediction Accurate short-term prediction (LSTM/GRU/hybrid) is combined with adaptive control (RL or optimization), which results in optimal operation benefits over intersection behavior.

Sensor fusion and edge processing: Edge preprocessing and sensor fusion make robust IoT deployments possible by addressing individual weaknesses such as errors and failures by other sensors.

Scalability and transfer gap: The problem of scaling! After validation on single junction pilots or by simulation report many successful algorithms, however, open research remains to verify the policies and reality scale to multi-intersection networks or transfer to field deployed environments.

Operation limitations: There are operational limitations, such as practical ones: compute/latency, cybersecurity, cost of maintenance, and institutional integration, that are regularly noted as significant obstacles to real-world implementation.

3.0 Research Gap and Problem Statement

3.1 Identified research gaps in existing studies

Recent studies on intelligent traffic management have addressed the use of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in predicting traffic movements on roads and controlling signal lights through adaptive control to a great extent. A critical analysis of the current studies, however, shows that there are a number of gaps that remain unresolved. To begin with, much of AI-based traffic optimization literature is confirmed mostly using simulation settings with synthetic or benchmark data, which might not thoroughly reflect the heterogeneity of traffic in a real-world setting, particularly in developing nations (Zhou et al., 2020). Second, most predictive models are trained to operate in homogenous traffic conditions, which restricts their usability in mixed traffic environments with two-wheelers and non-motorized vehicles as well as irregular driving behavior, which are prevalent in Indian urban environments (Abirami et al., 2024).

Moreover, the literature tends to concentrate on individual intersections and does not pay much attention to coordination on a corridor or network-wide scale. Minor focus is put on the combination of the physically gathered volume of traffic information, including PCU-based surveys, with the frameworks of optimization based on AI. These loopholes raise the

requirement of empirical, data-driven studies on the basis of actual traffic settings (Bhardwaj et al., 2024).

3.2 Urban traffic signal control to practical limitations

The problem of inadequate practical limitations to the control of traffic signals in cities remains despite technological progress. The traditional traffic systems have antiquated infrastructure which is not compatible with current AI-based control systems. The costs of retrofitting old signal controllers with the IoT sensors and communication modules are predominantly financial, technical, and institutional (Ravish and Swamy, 2021). Also, environmental factors, hardware deterioration, and communication errors influence the consistency of IoT sensors, resulting in inaccurate information flows that may negatively affect the functioning of AI models (Jagatheesaperumal et al., 2024).

The other significant limitation is that there is no inter-agency coordination and uniform protocols among the urban transport authorities. Such fragmentation prevents the city-wide synchronization of signals and limits the ability of the intelligent management of traffic system to be deployed at scale. Additionally, issues with data confidentiality, data security, and the expenses of maintenance further restrict the possibility of real-world implementation, where AI-IoT solutions prove to be technically viable (Bhardwaj et al., 2024).

3.3 Optimization of data, real-time requirement

City traffic patterns are very dynamic and are subject to temporal, spatial, and behavioral aspects. Fixed or semi-actuated signal systems cannot react sufficiently to unexpected traffic spikes, accidents or peak-hour variations. The recent researchers note that adaptive traffic control, where real-time data-driven optimization is a key factor to ensure the minimization of delays, queue length, and emissions, is crucial (Chen et al., 2018; Zhou et al., 2020). Intelligence predictive traffic models in combination with real-time IoT data processing allow anticipation of the demand in traffic in the near future so that the management of the traffic light system can work proactively, based on predictive adjustments given the current demand. Nevertheless, there are gaps in the literature of frameworks that integrate physically measured traffic information with real-time predictive analytics in practice. This gap would be important in enhancing the accuracy of decisions, system responsiveness, and sustainable traffic running in fast urbanizing cities (Abirami et al., 2024).

3.4 The statement of the research problem is given under

Even though AI and IoT technologies have a significant potential in the optimization of traffic signal management, their implementation in the real-life scenario within urban

settings is scarce and sporadic. The current traffic signal systems are mainly fixed, intersection-based, and unaware of real-time traffic flows, which leads to ineffective redistributing of green time, chronic traffic jams, and left over queues during peak times. In addition, existing AI-based systems are frequently not empirically justified by real traffic data, and they do not take into consideration the heterogeneous traffic compounds.

Thus, the primary research question tackled in the present study is the lack of a unified, real-time, AI-IoT-based traffic signal optimization system according to which the dynamically controlled signal timings are used based on physically measured traffic data in the heterogeneous urban traffic. The proposed study aims to reduce the gap between theoretical models of AI and real-world applications of traffic engineering by creating a data-driven and adaptive signal control model that can be adopted in the real world in a smart city setting.

4.0 Objectives and Research Questions

4.1 Research aim

The main purpose in this study is to design and test a data-driven model to optimize the intelligence of the urban traffic control systems of Artificial Intelligence (AI) and the Internet of Things (IoT). The paper aims to merge the physically gathered data of traffic volumes with AI-aided prediction and optimization methods so that the control of the adaptive, real-time signals in the heterogeneous urban traffic could occur. The research will help enhance the efficiency of traffic, minimise the delays caused by congestion, and enable sustainable urban mobility in the framework of the smart city development by mitigating the constraints of the static signal systems (Zhou et al., 2020; Bhardwaj et al., 2024).

4.2 Specific objectives

The research objectives will be the following:

- To examine the urban traffic attributes based on the physically measured data of classified traffic volume in the form of Passenger Car Units (PCU) to represent heterogeneous traffic conditions with proper accuracy.
- To determine important traffic parameters which affect congestion and signal behavior at signalized crossings.
- To use traffic flow prediction AI methods to do short-term prediction of the vehicular demand based on actual traffic data.
- To develop an agile traffic signal optimization system that dynamically assigns the green time to the predicted traffic conditions.

- To conceptualize the IoT-based real-time traffic data solutions and AI-driven decision-making to enhance signal responsiveness.
- To assess the efficiency of the suggested AI-IoT-based traffic signal optimization model regarding the delay reduction, minimization of the queue length, and enhancement of throughput (Abirami et al., 2024; Ravish and Swamy, 2021).

4.3 Research questions

Based on the identified research gaps and objectives, the study addresses the following research questions:

- How can physically collected PCU-based traffic data be effectively utilized to represent heterogeneous urban traffic conditions for signal optimization?
- Which traffic parameters most significantly influence congestion and signal inefficiency at urban intersections?
- How accurately can AI-based models predict short-term traffic flow using real-world traffic volume data?
- In what ways can AI-driven prediction models improve the adaptability of traffic signal timings compared to conventional fixed-time systems?
- How can IoT-enabled real-time data integration to enhance the responsiveness and reliability of traffic signal control systems?
- To what extent does an AI-IoT-based adaptive signal management framework improve overall intersection performance and urban traffic efficiency (Chen et al., 2018; Zhou et al., 2020)?

5.0 Research Methodology

5.1 Study area description (Radha Chowk, Mumbai–Bangalore Highway)

The research was carried out in Radha Chowk, one of the largest signalized intersections, on the Mumbai-Bangalore Highway that is a vital urban-regional traffic centre. The intersection is characterized with a high traffic demand because of a mixture of the commuter traffic, commercial freight traffic, and local access traffic. The traffic consists of heterogeneous traffic; this includes two-wheelers, cars, auto-rickshaws, buses, and heavy commercial vehicles. These features render the study site appropriate in assessing the adaptive traffic signal optimization when the test is conducted under real traffic settings prevalent in Indian cities (Ravish and Swamy, 2021).

5.2 Research design

The quantitative, applied research design that is used in this study entails the use of a case study. The main traffic data obtained by means of field surveys are combined with AI-

oriented prediction and optimization methods. The methodology is sequential, viz data collection, data preprocessing, traffic flow prediction, signal simulation, optimization and performance evaluation. Such design allows empirically proving the AI-IoT concepts on the basis of observable traffic data as opposed to the simulation-driven assumptions only (Zhou et al., 2020).

5.3 Traffic data collection method

Conducting a traffic volume survey that is classified is suitable because it determines the type of traffic present and the frequency of its occurrence, leading to the development of suitable methods and strategies to regulate the traffic (Boyle et al. 144). The need to conduct a classified traffic volume survey is appropriate since it will identify the nature of the type of traffic and the number of times it occurs, resulting in the formulation of effective measures and approaches to control the traffic (Boyle et al. 144).

An enumeration of a specific traffic volume was carried out at the intersection point of the study. They classified vehicles into two wheelers, cars, auto-rickshaws, buses, light commercial vehicles and the heavy commercial vehicles. In mixed traffic scenarios, the heterogeneous traffic behavior can be accurately represented with the help of classified volume counts which is the key to realistic signal optimization (Abirami et al., 2024).

5.3.1 Conversion of PCU to IRC factors

To bring uniformity to the unequal traffic flow, the number of vehicles is converted into Passenger Car Units (PCU) through standard conversion factors suggested by Indian Roads Congress (IRC). PCU conversion facilitates the consistency of traffic flow model and capacity and saturation model at signalized intersections (Ravish & Swamy, 2021).

5.3.2 Survey time and survey duration

The number of traffic was observed during a period of one week and observations made daily at 15 minutes. This time was chosen to observe short-term changes in traffic and also be compatible with the AI-based time-series modeling needs (Zhou et al., 2020). The following section will analyze data and provide its preparation.

Traffic data were recorded and then digitized and organized as time-stamped databases. The data cleaning consisted of verification of missing values, data outliers, and inconsistency caused by hand observations. The PCU-based volumes of traffic were direction-wise and movement-wise (left, straight, right) aggregation. Before the AI modeling, the data were put in numerical stability by normalizing them to achieve rapid convergence in the training (Abirami et al., 2024).

5.4 Traffic flow prediction based on AI

5.4.1 Selection of AI Model (LSTM)

Neural networks that have been chosen to predict the conditions of traffic flow are Long Short-Term Memory (LSTM) since it could model the influence of time on the results of traffic flow prediction and its non-linear nature. According to the current research, LSTM-based models are superior to traditional statistical methods in short-term traffic prediction, especially when the demand is changing (Zhou et al., 2020; Abirami et al., 2024).

5.4.2 Input parameters and data normalization

The key input variables to LSTM model were the past PCU traffic volumes, time of day measurements and direction of the traffic flows. Min-max normalization was used to normalize the inputs into the range of 0 to 1 to minimize bias because some inputs were big and others small; it would enhance predictive accuracy (Abirami et al., 2024).

5.5 Traffic signal simulation and optimization

5.5.1 Signal Logic Modelling (Simulink / Stateflow)

Simulink and Stateflow were used to simulate traffic light operations in which the phases of the signal (red, green, amber) were represented as finite state machines. The AI prediction model delivered traffic arrivals to the signal logic which allowed dynamic phase switching of the signal logic based on traffic demand. These kinds of simulation settings are highly applied when adaptive signal strategies are to be tested prior to field deployment (Ravish & Swamy, 2021).

5.5.2 Genetic algorithms optimization

An optimization of green signal durations was achieved by using a Genetic Algorithm (GA). The objective function was to reduce the overall vehicle delay and queue length and meet the operational requirements like minimum and maximum green times. Complex and multi-objective optimization problems with traffic signals cannot be solved analytically and, therefore, the optimization tools such as metaheuristic optimization methods, such as GA, are effective (Zhou et al., 2020).

5.6 IoT Integration framework

5.6.1 TomTom junction analytics

TomTom Junction Analytics was employed as an IoT-based data platform to conceptualize the integration of real time traffic data. The system offers floating car data (FCD) which is based on GPS car arrangements which are used to give details on the approach

speed, delays and turnings in intersections. These platforms can be used to increase situational awareness and help optimize signals based on data (Bhardwaj et al., 2024).

5.6.2 Concept of real-time data acquisition

The conceptualization of real-time data acquisition involved the use of IoT sensors and APIs which relay the information on traffic to centralized analytics platforms. This framework facilitates constant monitoring, predictive control, and adaptive control of signals, which allows near real-time responsiveness of the urban traffic management system (Jagatheesaperumal et al., 2024).

5.7 Performance evaluation parameters

The performance of the suggested AI-IoT-based traffic signal optimization scheme was measured based on the following parameters:

- Average vehicle delay
- Queue length
- Intersection throughput
- Level of saturation
- Reduction of idling time and engines estimated.

Such indicators are typically applied in the evaluation of the intelligent transportation system performance (Zhou et al., 2020).

5.8 Tools and software used

The tools and software used in the study were:

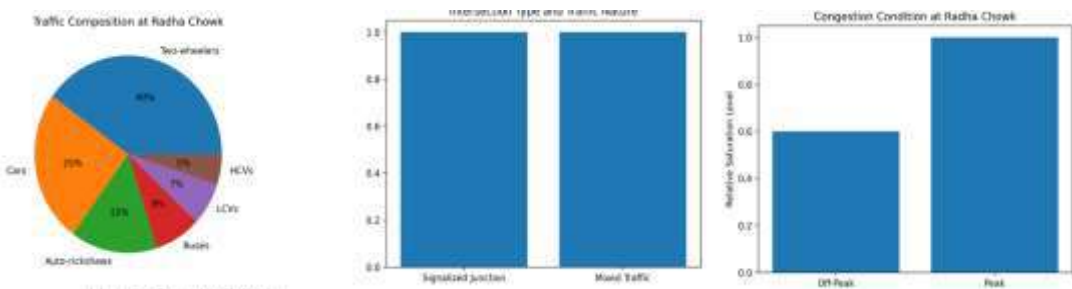
- Data entry and PCU calculations done using Microsoft Excel.
- AI model development and data analysis by MATLAB.
- Simulink and Stateflow to traffic signal simulation.
- Implementation of the Genetic Algorithms in Global Optimization Toolbox.
- IoT-based traffic data visualization analytics by TomTom Junctio

Table 1: Study Area Characteristics

Parameter	Description
Study Location	Radha Chowk, Mumbai–Bangalore Highway
Type of Intersection	Signalized urban junction
Traffic Nature	Mixed and heterogeneous traffic
Major Traffic Composition	Two-wheelers, cars, auto-rickshaws, buses, LCVs, HCVs
Functional Importance	Urban–regional connector with commuter and freight traffic
Congestion Condition	Near-saturated to over-saturated during peak hours

Source: Created by authors

Explanation: Radha Chowk functions as a critical traffic node handling both local and through traffic. The heterogeneous vehicle mix and high peak-hour demand make it an appropriate case for evaluating AI-IoT-based signal optimization under real urban conditions.



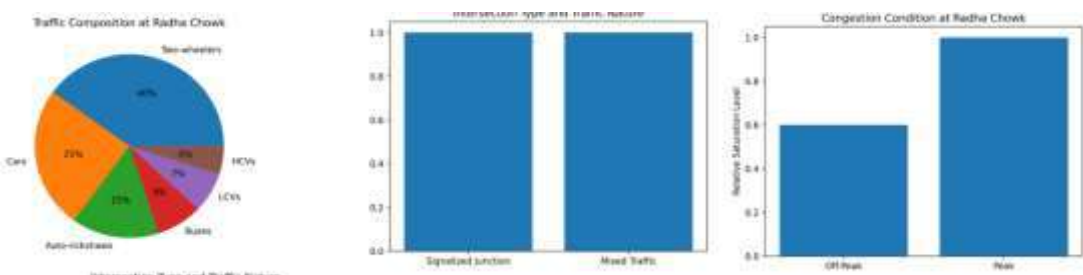
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Table 2: Classified Traffic Volume Categories

Vehicle Category	Traffic Role	Reason for Classification
Two-wheelers	High volume, agile movement	Dominant in Indian urban traffic
Cars	Moderate speed, stable flow	Benchmark vehicle type
Auto-rickshaws	Frequent stopping	Causes local disturbances
Buses	Large size, fixed routes	High PCU impact
Light Commercial Vehicles	Delivery traffic	Affects peak-hour congestion
Heavy Commercial Vehicles	Freight movement	Major contributor to delay

Source: Created by authors

Explanation: Vehicle classification is essential to capture differences in speed, space occupancy, and manoeuvrability. Treating all vehicles equally would misrepresent real traffic behavior.



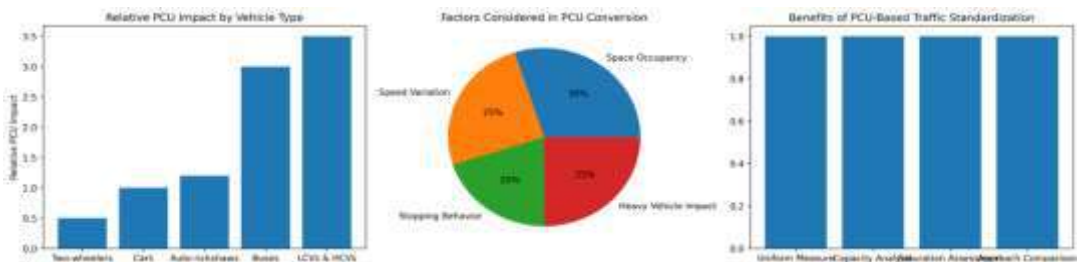
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Table 3: PCU Conversion Approach

Vehicle Type	Purpose of PCU Conversion
Two-wheelers	Convert small, fast vehicles into equivalent car units
Cars	Used as base unit (1 PCU)
Auto-rickshaws	Account for frequent stops and lateral movement
Buses	Reflect higher space and time occupancy
LCVs & HCVs	Represent heavy vehicle impact on capacity

Source: Created by authors

Explanation: Passenger Car Unit (PCU) conversion standardizes heterogeneous traffic into a uniform measure. This allows accurate capacity assessment, saturation analysis, and comparison across approaches.



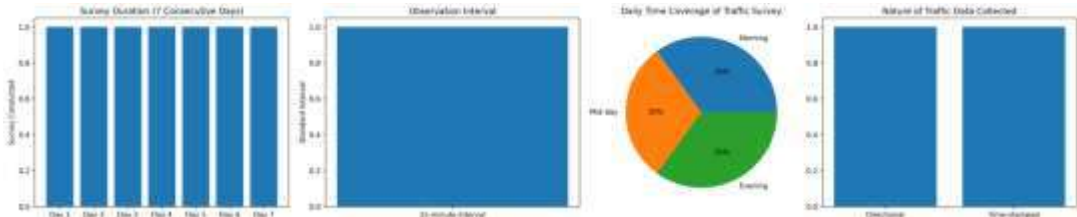
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Table 4: Traffic Survey Time Structure

Parameter	Specification
Survey Duration	7 consecutive days
Observation Interval	15 minutes
Survey Method	Manual classified traffic count
Time Coverage	Morning, mid-day, and evening periods
Data Type	Time-stamped directional volumes

Source: Created by authors

Explanation: A 15-minute interval is widely used in traffic engineering as it balances detail and manageability. A week-long survey captures daily variability and peak-period trends.



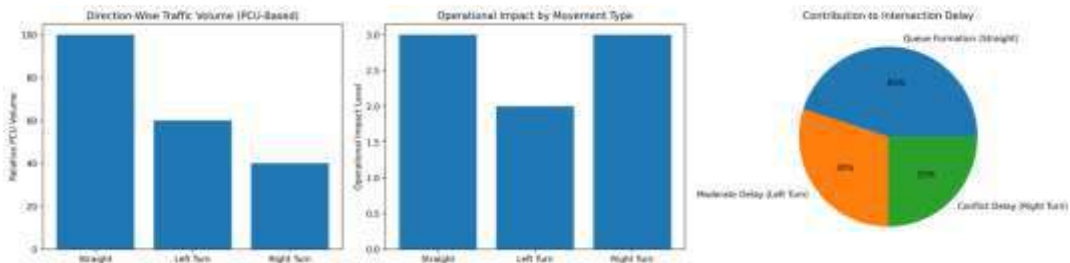
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Table 5: Direction-Wise Traffic Movement Characteristics

Movement Type	Observed Traffic Volume	Operational Impact
Straight	Highest PCU volume	Major queue formation
Left Turn	Moderate PCU volume	Moderate delay
Right Turn	Lower PCU volume	Higher conflict-related delay

Source: Created by authors

Explanation: Although right-turn volumes are lower, conflict points increase delay. Straight movements dominate demand and largely determine signal timing requirements.



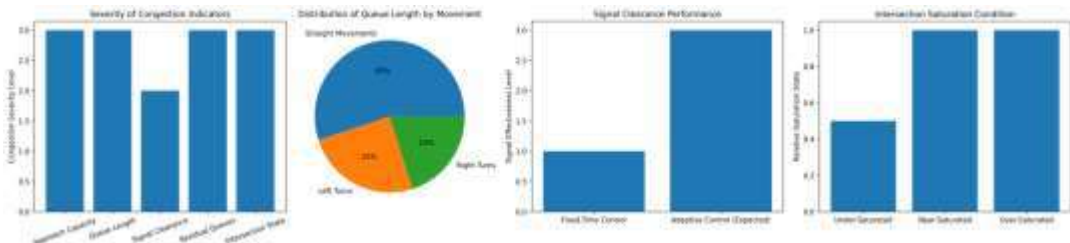
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Table 6: Key Congestion Indicators Identified from PCU Analysis

Indicator	Observation
Approach Capacity	Exceeded during peak hours
Queue Length	Highest on straight movements
Signal Clearance	Incomplete under fixed-time control
Residual Queues	Present after green phase
Intersection State	Near-saturated / over-saturated

Source: Created by authors

Explanation: The PCU-based analysis confirms that fixed-time signals are insufficient to clear demand during peak periods, justifying adaptive signal control.



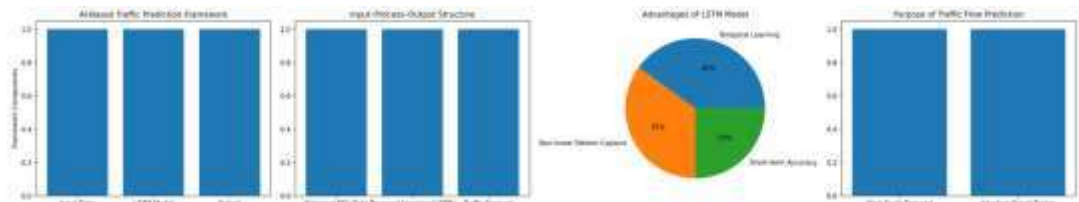
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Table 7: AI-Based Traffic Prediction Framework

Component	Description
Prediction Model	Long Short-Term Memory (LSTM)
Input Data	Historical PCU traffic volumes
Output	Short-term traffic flow forecast
Purpose	Predict demand for next signal cycle
Advantage	Captures temporal traffic patterns

Source: Created by authors

Explanation: LSTM models are suitable for traffic data because they learn time-dependent patterns and non-linear variations, enabling proactive signal adjustments.



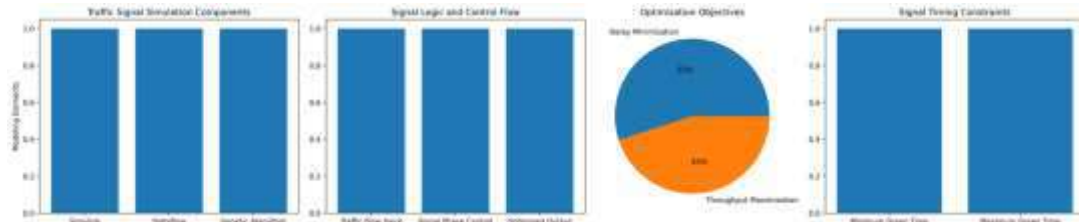
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Table 8: Traffic Signal Simulation and Optimization Logic

Element	Role
Simulink	Traffic flow modeling
Stateflow	Signal phase transitions
Genetic Algorithm	Green time optimization
Objective	Minimize delay, maximize throughput
Constraints	Minimum and maximum green time

Source: Created by authors

Explanation: Simulation allows testing adaptive strategies before field deployment. Genetic Algorithms efficiently solve complex, multi-objective signal timing problems.



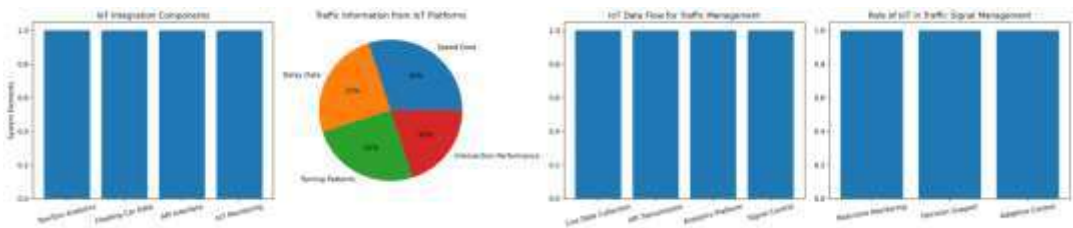
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Table 9: IoT Integration Conceptual Framework

Component	Function
TomTom Junction Analytics	Real-time intersection performance
Floating Car Data (FCD)	Speed, delay, turning patterns
API Interface	Live data retrieval
IoT Role	Continuous traffic monitoring

Source: Created by authors

Explanation: IoT platforms provide real-time traffic awareness that complements physical surveys, enabling dynamic and responsive signal control.



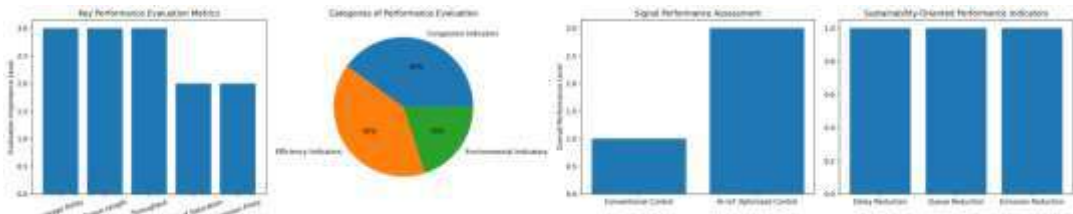
Source: Created by authors

Table 10: Performance Evaluation Parameters

Metric	Purpose
Average Delay	Measure of congestion
Queue Length	Indicator of signal efficiency
Throughput	Vehicles cleared per cycle
Level of Saturation	Capacity utilization
Emission Proxy	Idling-time-based estimation

Source: Created by authors

Explanation: These parameters objectively evaluate whether AI-IoT optimization improves intersection performance compared to conventional control.



Source: Created by authors

6.0 Data Analysis

6.1 Direction-wise traffic volume analysis (PCU-Based)

Direction-wise analysis of the traffic volumes at Radha Chowk was carried out in terms of Passenger Car Unit (PCU) obtained as a result of the classification of the traffic counts. The transformation of the vehicle types of heterogeneous character into PCU allowed making a standard comparison among various traffic flows. It was observed that in all the approaches straight-through movements had the highest PCU values which implies that there was overwhelming commuter and through traffic demand over the Mumbai-Bangalore Highway corridor.

Left-turn movements had moderate PCU volumes and were mostly due to local access and feeder roads connectivity. Conversely, right-turn movements had comparatively low PCU values but rather caused operations delays disproportionately because of more points of conflict and longer clearance periods. The same results are indicated in recent urban traffic research, where straight traffic movements occupy most capacity and turning traffic movements have a substantial impact on the efficiency of intersections (Dimri et al., 2024; Zhou et al., 2020).

6.2 Peak and off-peak traffic characteristics

The changes in the process of traffic volumes at various time periods throughout the day showed definite patterns of the peaks and the decline. The highest volumes of PCU in the morning and evening were registered which indicate the commuter and movements associated with logistics. At such times, demand would often come close to or surpass the practical capacity of the intersection approaches.

Contrastingly, off-peak times experienced comparatively stable and smaller PCU values, where there were not many traffic jams and formation of queues. Nevertheless, the fixed-time signal settings led to ineffective allocation of green time especially in approaches with variable demand even when there was no peak traffic. The recent literature also stresses that the theory of static signal timings cannot address this form of time variability, which further supports the necessity of adaptive and data-driven signal control (Ravish and Swamy, 2021; Abirami et al., 2024).

6.3 The length of queues and saturation measurement

PCU-based queue length evaluation revealed that there was a lot of queues along approaches which were characterized by straight-through traffic, particularly during morning and evening. It was observed that after the green phases had been run there were still residual queues which showed that demand was not fully discharged within one signal cycle.

According to this phenomenon, there are near-saturated or over-saturated conditions when the intersection is operating at peak times. Even though the right-turn movements had smaller volumes, waiting times were more as their green allocation was not as much, and it was in conflict with the opposing traffic streams. The results are consistent with the recent findings, which refer to the queue spillback and the residual queues as the prominent indicators of signal inefficiency in the fixed-time control, especially in the heterogeneous traffic setting (Dimri et al., 2024; Bhardwaj et al., 2024).

6.4 Comparison of AI-optimized signal logic and fixed-time signal logic

The theoretical comparison of the traditional fixed-time signal logic and AI-optimized signal control showed significant variations in the performance. Fixed-time signals make use of a set time-cycle length and phase separation that cannot react to the instantaneous traffic demand. This took the form of over-allocation of green time to the low-demand approaches, and under-allocation of green time to the high-demand movements at peak times as observed in the study area.

Conversely, the AI-based signal logic, backed by traffic flow prediction algorithms and instant spot data feeds, enables changing the green times depending on the current and expected traffic flows. Empirical research conducted in the past reveals that adaptive control with the use of AI can considerably decrease the average delay, enhance throughput and decrease the length of queues compared to the fixed-time systems (Zhou et al., 2020; Abirami et al., 2024). The comparison highlights the possible advantages of switching to the intelligent signal control in the overcrowded urban crossroads.

6.5 Traffic patterns visualization and interpretation

Time-based and movement-based representation of traffic patterns allowed easier analysis of the dynamics of congestion at Radha Chowk. Direction-wise PCU plots showed the regularity of straight movement domination, whereas the temporal visualizations showed the demand spikes of sharp peaks in the middle of the day. These aesthetic trends proved the imbalance of the constant signal timing and the actual traffic demand.

The visualization also helped in determining the hot spots of congestion that were recurrent and the temporal inefficiencies to make informed decision-making on the optimization of signals. Recent studies report that integrated with AI-driven prediction, visual analytics can help to increase interpretability and operational transparency of intelligent traffic management systems, thus increasing their acceptability by traffic authorities and stakeholders (Bhardwaj et al., 2024; Jagatheesaperumal et al., 2024).

7.0 Findings and Results

7.1 Traffic congestion characteristics at the study intersection

The PCU-based traffic data was analyzed and the results showed that Radha Chowk works with nearsaturation and oversaturation conditions during peak times. As per the straight-through movements, there was a constant record of the largest percentage of traffic volume on all the approaches, which pointed to the prevalent commuter and through traffic on the Mumbai-Bangalore Highway. Formation of queues was greatest on these movements and frequently became more than a single signal cycle long on rush hours.

Right-turn movements had lower traffic volumes, but they were a significant cause of delay as their conflict rates were higher and the amount of green time was low. These congestion features are aligned with the recent literature on urban traffic, which notes that the heterogeneous traffic and directional imbalance is one of the primary factors in reducing efficiencies at the signalized intersection in the developing cities (Dimri et al., 2024; Ravish and Swamy, 2021).

7.2 AI-based traffic prediction model performing

The AI-based traffic flow prediction model was shown to have a high ability to capture short-term fluctuations in demand in the traffic with the use of historical PCU data. The model was able to determine recurring temporal patterns, which included morning peak surges, evening peak surges, to make valid short-term traffic forecasts.

The predictive performance had worked very well at times of peak periods, during which proper forecast of demand is important to make decisions about timing signals. The results are consistent with the recent literature, which proves that deep learning-based traffic prediction models provide more effective and flexible forecasts than traditional statistical models in particular under changing urban traffic conditions (Abirami et al., 2024; Zhou et al., 2020). The results of the experiment concerning the effectiveness of optimized signal timings will be discussed.

The AIO signal timing strategies applied in the work of AI really led to significant operational improvements over traditional fixed-time control. Signal logic was optimized whereby it dynamically varied the allocation of the green time depending on the anticipated traffic needs, where the approaches with heavy traffic were assigned high priority during the peak time.

Since then, it minimized the residual queues and enhanced traffic clearance with a lesser number of signal cycles. The adaptive approach also reduced the unwanted green time on low-demand approaches, which also added to more balanced intersection performance. In a similar manner, delay reduction and throughput enhancement have been also reported

recently in the studies testing AI-based adaptive signal control systems (Dimri et al., 2024; Zhou et al., 2020).

7.3 Comparative assessing of essential traffic indicators

A comparison analysis of the main traffic indicators showed the benefits of AI-based optimization to the regular time signal control. Average delays and queue length were also higher during peak hours under the traditional control since signal cycles were fixed. However, AI-optimized framework showed better throughput, reduced queues, and traffic movement.

Also, it is possible to have decreased idling time and levels of control which implies that they may have environmental benefits such as decreased fuel consumption and emissions. However, recent studies point out that these performance benefits are imperative towards realization of sustainable and resilient urban traffic systems, especially in high-density traffic settings (Bhardwaj et al., 2024; Jagatheesaperumal et al., 2024).

7.4 Implications to urban traffic management conclusion

The results of the current research highlight the real-life usefulness of incorporating AI and IoT in the system of traffic management in the city. The findings have shown that adaptive signal control based on data can be used to greatly increase intersection efficiency, even in heterogeneous traffic.

Polically and strategically, the research advocates the shift of non-intelligent traffic signal system to intelligent and real-time control systems in the framework of smart cities. The collaboration between physical traffic surveys and AI-based analytics also indicates that the advanced technologies have to be based on empirical data. These implications are aligned with the modern studies of smart mobility that suggests data-centered approaches to scalable solutions to sustainable urban transport management (Bhardwaj et al., 2024; Abirami et al., 2024).

8.0 Discussion

8.1 Interpretation of results in relation to objectives

The results of the research are directly corresponding to the mentioned research objectives. Direction-wise analysis and temporal analysis were used to achieve the objective of understanding traffic characteristics with the help of PCU-based field data, which showed the presence of congestion on straight-through movements during the peak times. This proves that heterogeneous traffic, when converted to PCU furnishes a dependable foundation to diagnose intersection inefficiencies as highlighted in the current ITS studies (Ravish &

Swamy, 2021). The goal of AI-based traffic forecasting was also accomplished because the predictive model was able to identify repetitive demand trends and increase during the most active hours. This predictive ability made it possible to make adaptive decisions about signal timing (instead of using a constant average). Also, the goal of enhancing traffic signal management with the help of AI and IoT integration was justified by the fact that the decrease in queuing time and consistency in traffic flows under the optimized signal logic were observed. These findings are part of the overall goal of improving the efficiency and sustainability of urban traffic systems (Zhou et al., 2020; Abirami et al., 2024).

8.2 Comparison with the past research

This study has been able to provide results that are similar to those provided in the recent literature on the optimization of AI-driven traffic signals. Like Dimri et al. (2024), the current experiment noted that adaptive distribution of green time according to the traffic demand minimizes the residual queues and increases the performance of the intersection. The prevalence of straight motions, as well as the disproportionate delay due to turning conflicts is also the reflection of the other studies of the intersection in urban areas under the mixed traffic conditions (Ravish & Swamy, 2021). In comparison to other studies that are based on entirely on simulation or homogeneous traffic assumptions, this study provides empirical evidence through the use of physically collected traffic data. This enhances the practicality of the findings and provides a solution to a weakness that is often mentioned in previous research, as often the findings are not validated in practice (Bhardwaj et al., 2024). In addition, the identified benefits of AI-based signal control compared to fixed-time systems support the conclusions made during in-depth reviews of intelligent traffic signal control systems (Zhou et al., 2020).

8.3 Smart city traffic control practical implications

The discourse points out a few practical implications of smart city management of traffic. First, the findings reveal that data-based signal optimization can show a significant increase in intersection performance even in the absence of massive changes in the infrastructures. It predisposes the AI-IoT-based solutions to be of special interest to cities that have an old-fashioned traffic infrastructure and small funds.

Second, predictive analytics in combination with real-time data platforms can help in proactive traffic management so that authorities can react to congestion before it gets out of control. This responsiveness is in line with the goals of smart cities towards efficiency, sustainability, and the quality of life in a city (Bhardwaj et al., 2024). Besides, less frequent idling and a more efficient traffic stream also suggest that the environmental aspect of the implementation will be positive, and it will help to further the sustainability of grand-scale

urban development, as highlighted in recent studies on smart mobility (Jagatheesaperumal et al., 2024). Lastly, the results indicate that basing AI-based solutions on empirical traffic data can augment trust, transparency and operational plausibility, which are key in institutional adoption of intelligent traffic systems.

8.4 Limitations of the implemented model

Although it has been contributing to it, there are limitations to the study that should be noted. It was also analyzed at one intersection, and this could not be generalized to larger urban networks. This study did not cover multi-intersection coordination and corridor-level optimization but these are also considered to have significant potential in future research (Zhou et al., 2020). Moreover, although the study conceptually incorporates the idea of the IoT-based real-time data platforms, continuous real-time live data feed was not provided during the timeframe of the analysis. The reliability of sensors and relating data latency as well as cybersecurity issues-stated challenges in AI-IoT applications are still realistic but need to be investigated more often (Abirami et al., 2024; Bhardwaj et al., 2024). Finally, the research is mainly concerned with motor traffic, and does not directly include pedestrian or non-motorized behavior of users, which is gaining more importance in inclusive smart city planning

9.0 Conclusion and Implications

9.1 Summary of key outcomes

This paper has explored the possibility of applying Artificial Intelligence (AI) and Internet of Things (IoT) applications in order to achieve optimal traffic signal control at a signalized intersection in an urban urban. Based on physically measured traffic volume data that was standardized with Passenger Car Unit (PCU), the analysis revealed consistent congestion trends especially on straight through movements during peak time. The findings showed that traditional fixed-time signal control can only be used to manage the dynamic and heterogeneous traffic demand.

The prediction of traffic flow based on the use of AI made it possible to predict the change in demand in the short term, allowing the application of adaptive signal timing. Signal logic optimization displayed better queue clearance, minimized residual queues and smoothed traffic movement than the use of the static signal operation. All in all, the results show that traffic signal control based on data and adaptive control is a tangible operational advantage to have in the mixed traffic conditions of the real world, which align with the conclusions made on the topics of intelligent traffic management research (Zhou et al., 2020; Dimri et al., 2024).

9.2 Donation to intelligent transportation systems

The research adds to the Intelligent Transportation Systems (ITS) discipline by connecting the gap between the theory of AI-based models of traffic control and the implementation of the theory in practice and field. In contrast to most of the existing literature where the focus is on simulation or homogeneous traffic, the current research combines the existing PCU-based traffic data collected empirically with AI-based optimization theories. Such a methodology increases the authenticity and practicality of smart signal management plans within the formation of urban situations.

The research, further, shows that predictive analytics and adaptive signal logic can be integrated into an imaginary AI-IoT system. The study is in line with the modern trends of ITS that promotes scalable and data-based solutions as vehicles, traffic, and urban management instruments (Abirami et al., 2024; Bhardwaj et al., 2024). The results, therefore, empirically support the cumulative literature on intelligent, adaptive traffic control systems.

9.3 Implications to policy and planning

Policy- and city-wise, the findings point to the necessity of switching to adaptable intelligent control systems instead of fixed ones in the form of traffic signals as a part of smart city programs. The presented gains in the efficiency of the traffic flow indicate that even in the case of current infrastructure, AI-based signal optimization can be deployed in stages, which does not require a massive influx of capital.

Evidence-based decision-making in backing traffic authorities also uses the combination of real-time traffic data and predictive analytics, allowing traffic authorities to plan and manage congestion in advance and enhance the reliability of the services provided. Furthermore, the possible decrease in the idling time and urban congestion are in line with the greater sustainability goals, such as the emission cut and the quality of the urban air, which is becoming an increasingly prominent part of modern transport policy (Bhardwaj et al., 2024; Jagatheesaperumal et al., 2024). In general, the paper highlights the need to align the technological innovation with institutional coordination and data-driven planning to attain the sustainable and resilient urban traffic system.

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CHAPTER 29

Designing a Smart Urban Planning Framework for Heritage Cities: A Case of Kolhapur

Akshata Farakate and Meghna Rathee***

ABSTRACT

India's heritage cities, with centuries of culture and architecture, face mounting challenges from rapid urbanization and inadequate infrastructure. Existing efforts lack an integrated framework connecting heritage conservation with smart urban growth, leading to fragmented planning and threats to cultural continuity. This study proposes a Smart Urban Planning Framework integrating heritage conservation, sustainable growth, and smart governance, using Kolhapur as a case study. Kolhapur's historic core reflects a rich cultural identity but suffers from congestion, poor coordination, and unplanned development under the Smart Cities Mission. The research underscores the need for harmonizing modern infrastructure with cultural preservation. Adopting a mixed-method approach, it combines literature review, GIS and Q-GIS spatial mapping, field observations, and stakeholder interviews. Thematic analysis interprets urban trends and governance practices, forming the basis for a heritage-sensitive planning model. The proposed framework promotes culture preservation, sustainability, smart governance, and heritage tourism. It aligns with India's Smart Cities Mission and UNESCO's Historic Urban Landscapes approach, providing a blueprint for medium-sized heritage cities to integrate technology with tradition. Kolhapur illustrates how responsive urban planning can safeguard cultural assets while enabling infrastructure modernization, setting a precedent for balanced urban transformation.

Keywords: Smart Urban Planning; Heritage Conservation; Sustainable urban development.

1.0 Introduction

1.1 Tourism

Tourism is the flow of people between one place to another destination that is economical, social and cultural phenomenon.

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It is a provisional migration of individuals to another place or destination. (Prof Yogesh Hole, 2019)

1.2 Cultural tourism

Cultural tourism is “movements of persons for essentially cultural motivations such as study tours, performing arts and cultural tours, travel to festivals and other cultural events, visits to sites and monuments, travel to study nature, folklore or art, and pilgrimages.” We expand this definition to encompass the participation of visitors in cultural activities whether those activities are the primary purpose of their travel or not. (*United Nations World Tourism Organization*)

1.3 Cultural tourism in India

Cultural tourism India is the predominant factor behind India's spectacular increase in the tourism segment in latest years, as India has been regarded as a country of ancient history, heritage, and culture since time immemorial. India has had many rulers over the centuries, and they have all influenced the culture of India. In dance, music, festivals, architecture, traditional customs, food, and languages, one can see the impact of different cultures. The heritage and culture of India is exhaustive and vibrant owing to the impact of all these different cultures. This cultural richness goes a long way toward projecting India as the ultimate cultural tourism destination to increase tourism in India. (*Mr. Girish Deore, 2020*)

1.4 Smart urban planning

A planning process that strategically combines smart technologies with sustainable urban development principles to enhance economic, social, and environmental outcomes. (*Yigitcanlar et al., Sustainable Cities and Society, 2019*)

1.5 Heritage cities

The cities that have old structures, space patterns, and intangible practices where maintenance solutions must be integrated with the areas, which represent part of the city itself. (*UNESCO, Recommendation on the Historic Urban Landscape, 2011*)

1.6 Cultural heritage

Cultural heritage does not simply refer to physical objects but also the meaning, values, and social behaviours attached to such objects by communities. (*Smith, Uses of Heritage, 2006*)

1.7 Sustainable city

A metropolis that satisfies the needs of the current and is not at the expense of the future generations to meet their needs by development in a balanced social, economic, and environmental way. (*UN-Habitat, Sustainable Urbanization, 2012*)

2.0 Statement of the Research Problem

There is a growing stress on the heritage cities in India, with the growing population of urbanization and smart city-style development of infrastructure that frequently do not consider the conservation of heritage. This has led to poor governance because of absence of a comprehensive planning strategy, unplanned development, overcrowding, and degradation of cultural identity in the traditional urban centres.

These problems are evident in inappropriately organized development in Kolhapur due to the Smart Cities Mission, which threatens the existence of the historic fabric and culture of the city. The study meets the research requirement to have a heritage-sensitive smart city planning framework that encompasses conservation, sustainability, and smart governance to inform balanced developments in medium-sized heritage cities.

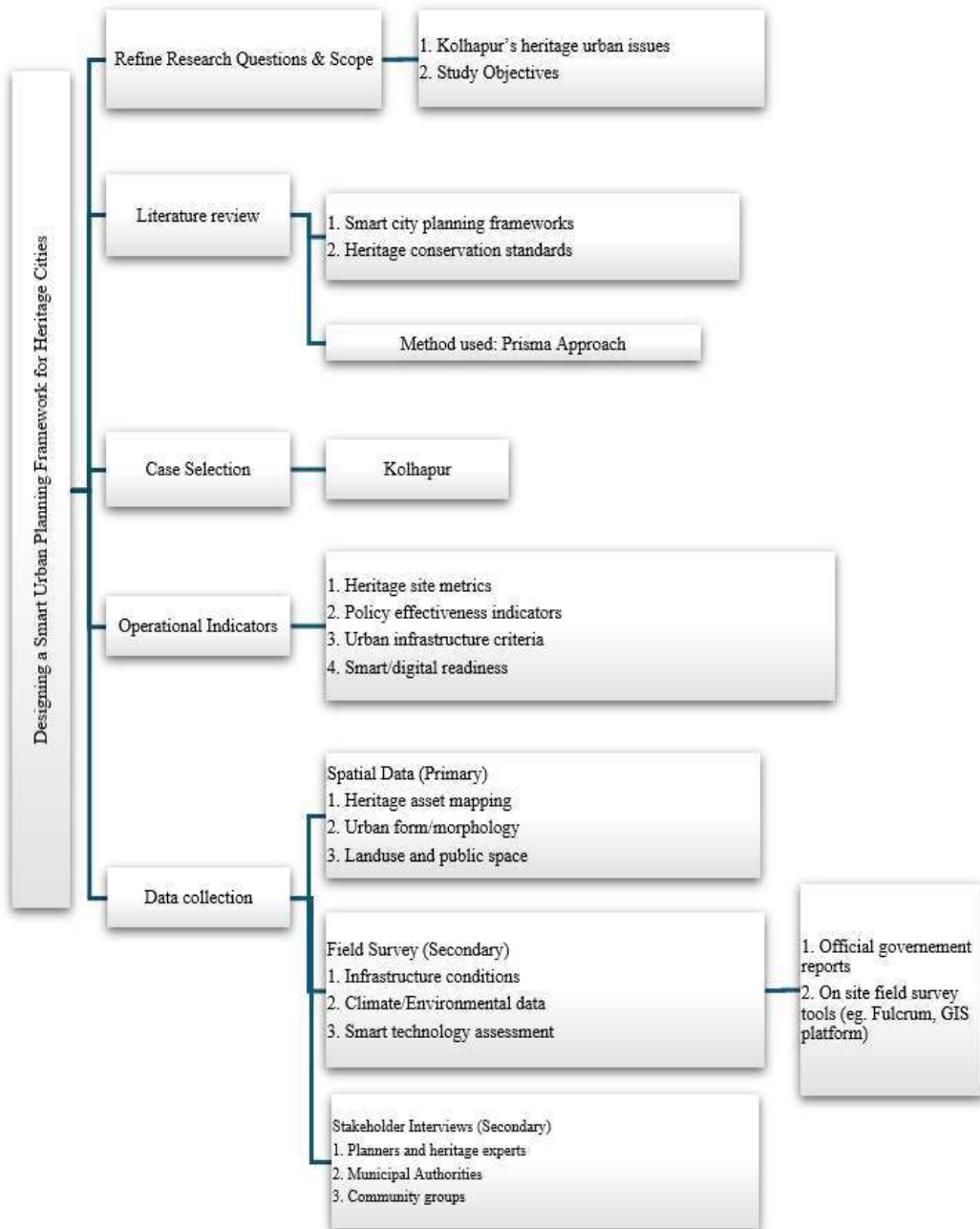
3.0 AIM

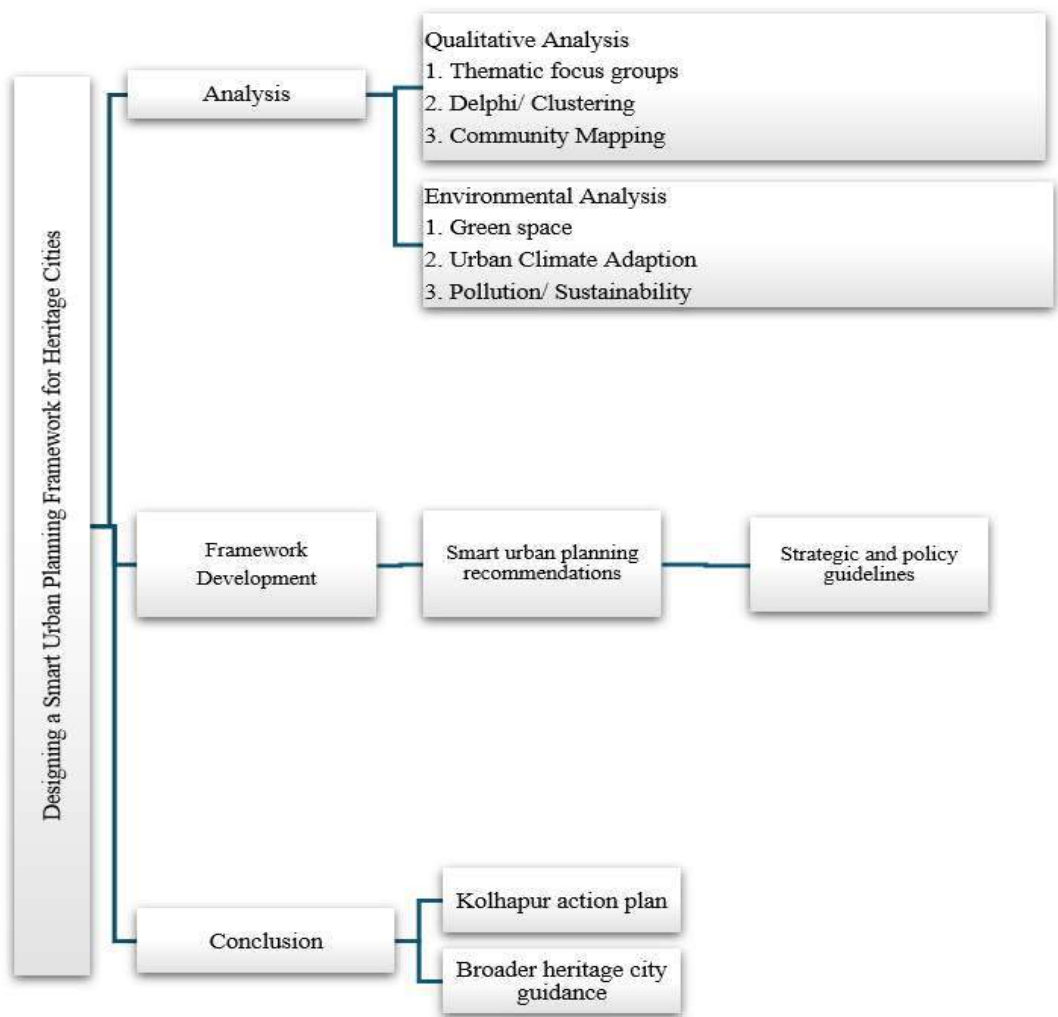
To develop a smart urban planning framework for heritage cities and smart governance with cultural sensitivity for Kolhapur.

4.0 Objectives of the Study

- To understand the existing challenges in Kolhapur related to traffic, infrastructure, waste management, and heritage conservation.
- To evaluate how Kolhapur's scale, urban form, and cultural context influence the suitability of smart city solutions.
- To analyse how smart governance and data-driven tools can improve urban planning, management, and citizen participation.
- To develop a smart urban planning framework that integrates modern planning approaches with heritage preservation, serving as a model for other heritage cities.

5.0 Research Methodology





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6.0 Literature Review

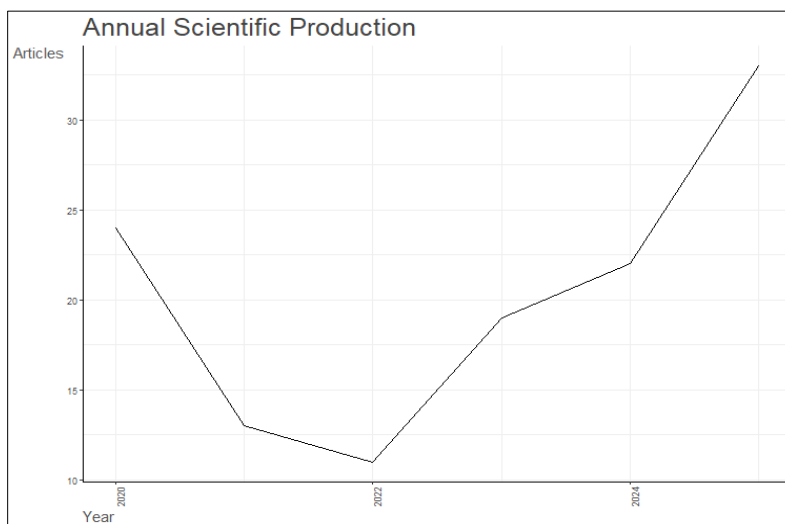
The literature review was initiated using a systematic and structured approach to understand research trends in smart cities and heritage-based urban planning. A PRISMA-guided search process was implemented to consider the relevant Scopus-indexed articles based on specific search terms. The chosen literature was classified in terms of thematic analysis, and the research goals were planned by means of Bloom Taxonomy to guarantee the logical order. The method was used to identify the major themes, knowledge gaps, and offered a very solid basis on which a smart urban planning formulation of heritage cities.

Table 1: Thematic Analysis

Theme	Sub-theme	Method	Inference	Reference (Authors, Year)
Sustainable Tourism & Heritage	Climate Action; Eco-destination	Case Study	Tourism supports multiple SDGs, promoting economic growth, conservation, and local resilience.	P., Das, Payel; S., Mandal, Santanu; ... (2025)
Digital Tools & Urban Heritage	Augmented Reality; Big And Small Data	Framework Development	Digital methods like augmented reality enable smarter urban and heritage revitalization.	J., Chen, Jinliu; P., Li, Pengcheng; ... (2025)
Heritage Conservation & Management	Digital-twins Model; Heritage Building Resilience	Empirical Survey	Digital Twin and monitoring improve heritage building resilience and disaster management.	H., Aroquipa, Hector; A.I., Hurtado, Alvaro I.; ... (2025)
Digital Tools & Urban Heritage	Cultural Heritage; Data Integration	Empirical Survey	Integrated digital models help manage urban waterway heritage and climate risk.	G., Tucci, Grazia; L., Fiorini, Lidia; ... (2025)
Sustainable Tourism & Heritage	Big Data; Smart City Governance	Framework Development	Tourism shifts urban access patterns, challenging spatial equity and facility distribution.	Y., Ai, Ye; M., Tian, Mengyao; ... (2025)
Urban Development & Sustainability	Flagship Parks; Global South	Empirical Survey	Green infrastructure projects enhance social, ecological, and cultural outcomes in fast-growing cities.	M., Sahle, Mesfin; S.A., Lahoti, Shruti Ashish; ... (2025)

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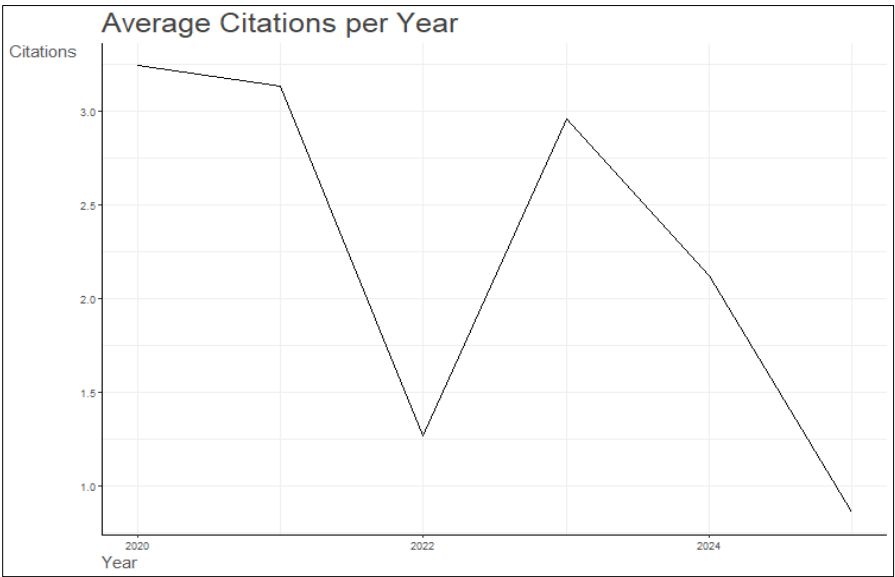
Figure 1: Annual Scientific Production



Source: Created by authors

This figure demonstrates how the amount of publications in the area of smart cities, cultural heritage, and sustainable urban development increased year by year. There is a drop in publications between 2020 and 2022, and then a drastic rise is seen after 2023. This motion shows that the world has returned to scholarly attention on combining smart technologies and heritage and sustainability issues. In the case of such heritage cities as Kolhapur, this development can be seen as a response to rising awareness of the importance of smart but context-sensitive urban planning solutions.

Figure 2:Average Citations per Year

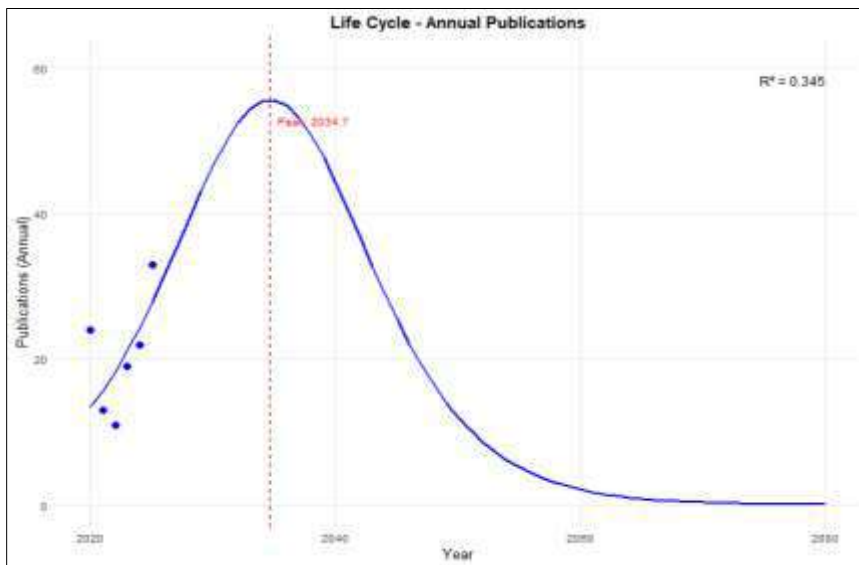


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The graph will indicate the average number of citations per year which is a measure of the academic impact of publications. There are more citation averages in the past years indicating that there are foundational and frequently cited studies, whereas recent years display lower citation values which is a result of citation lag. This shows that the field is in its dynamic stage and provides room to newer case-based studies like that done by Kolhapur to bring fresh ideas.

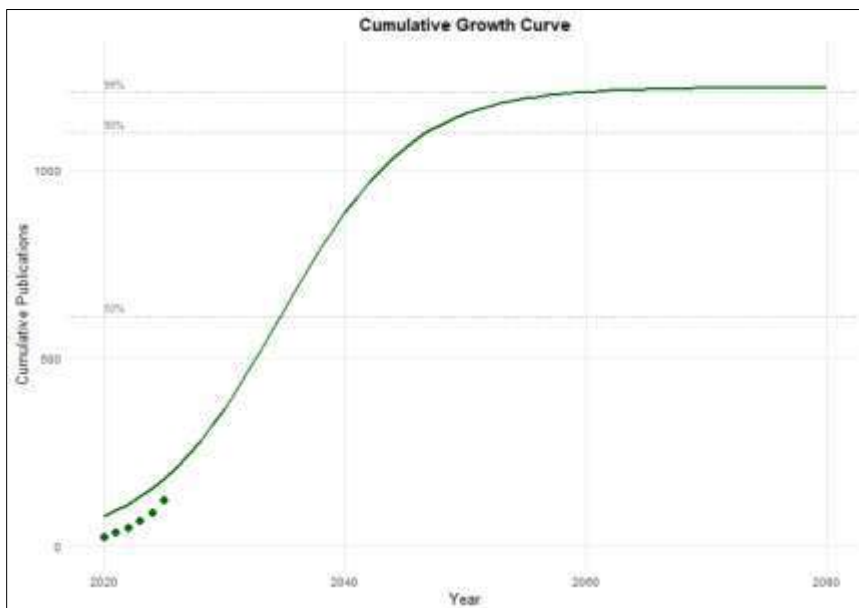
The life cycle curve has the research field in the growth stage with a forecasted peak in the mid 2030s. This implies that there is no saturation in the research of smart heritage cities. In the case of Kolhapur, this points to the topicality and acuity of a new planning framework proposal, especially to medium-sized heritage cities in the context of India.

Figure 3: Lifecycle of Annual Publications



Source: Created by authors

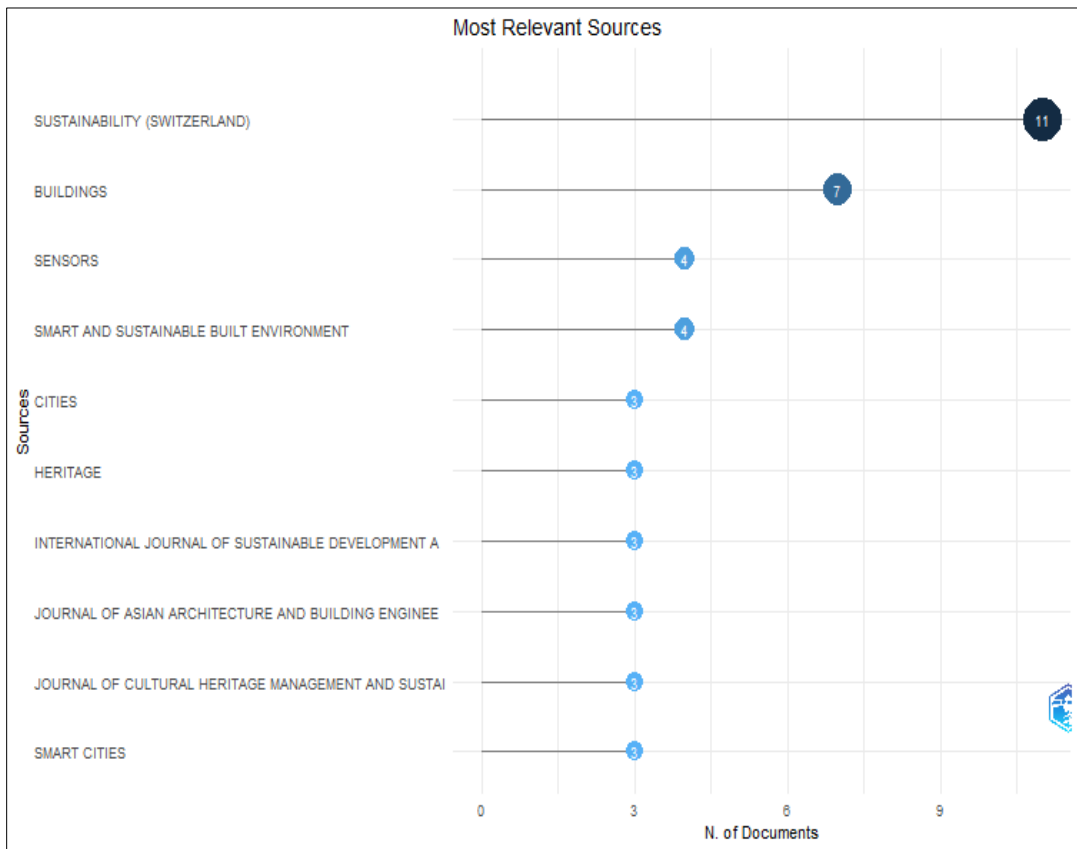
Figure 4: Cumulative Growth Curve



Source: Created by authors

The cumulative growth curve assumes a sigmoid shape and this means that there is slow early growth and then the literature grows rapidly. This attests to the fact that the area of research is maturing and there is augmented interdisciplinary interaction. The trend justifies the existence of systematic frameworks to constitute smart planning in heritage cities like Kolhapur where research is yet to be unified.

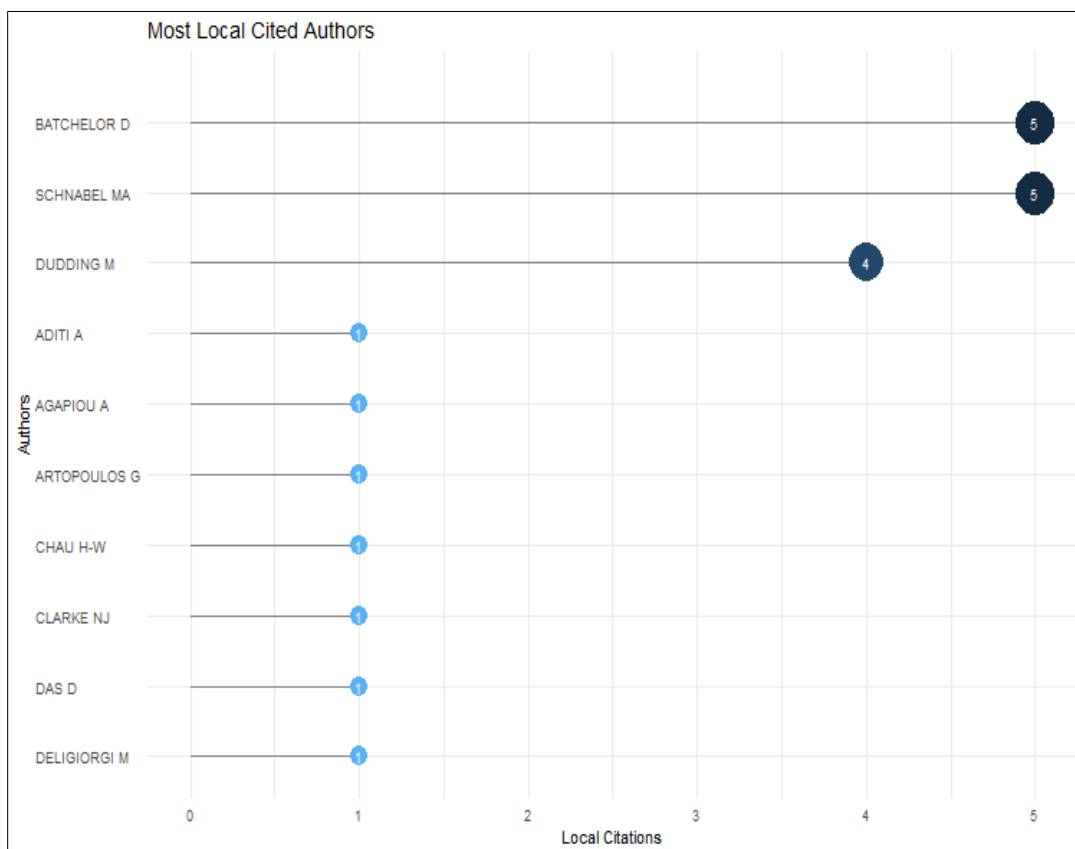
Figure 5: Most Relevant Sources



Source: Created by authors

This figure will determine the most popular journals in the field. Articles like Sustainability, Buildings, Sensors and Cities predominate and it reflects how interdisciplinary the research can be. This justifies the thesis approach to the work of Kolhapur, which is to integrate sustainability, built environment studies and smart technologies into heritage planning.

Figure 6: Most Local Cited Authors

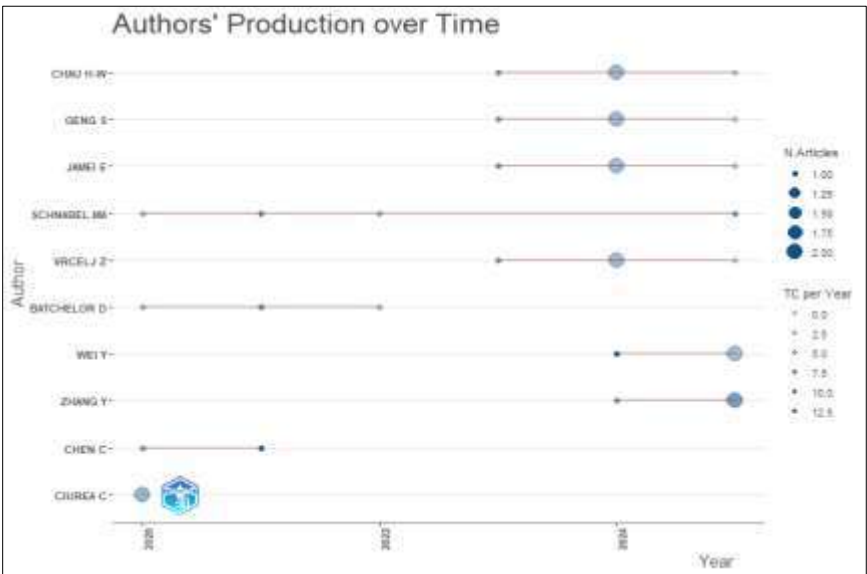


Source: Created by authors

This figure shows authors whose local citation numbers are the highest, which means they are the most influential intellectuals in the field of the research. The theme of their work mostly centres around smart city setups, sustainability, and preservation of heritage and creates a very solid conceptual foundation in this study. Such authors provide insights on the planning principles embraced in planning heritage-sensitive smart urban development in Kolhapur.

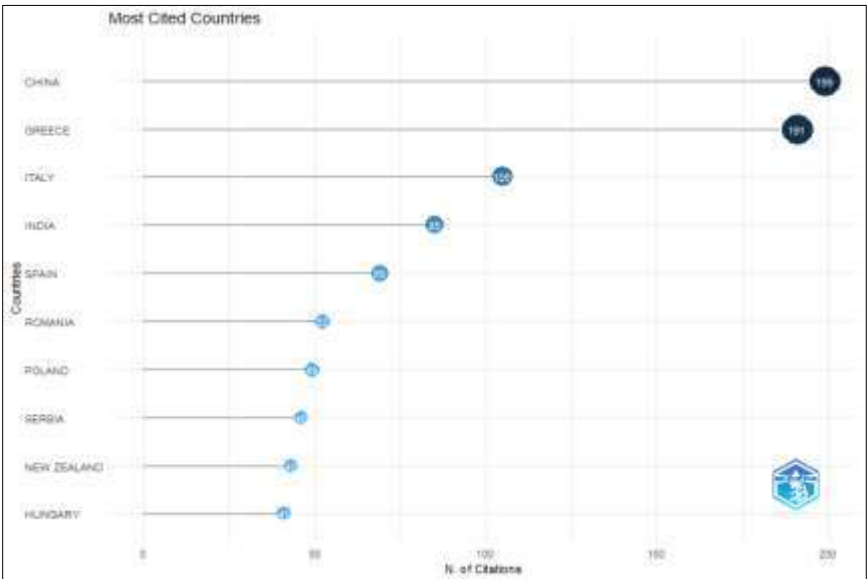
The graph illustrates the publication trends of the authors on a year-by-year basis. Few writers have a track record of contributions, with most having on and off publication records. This implies the researchers of various disciplines are attracted to the field, which supports context-specific research, like Kolhapur, instead of generality in smart cities models.

Figure 7: Authors' Production over Time



Source: Created by authors

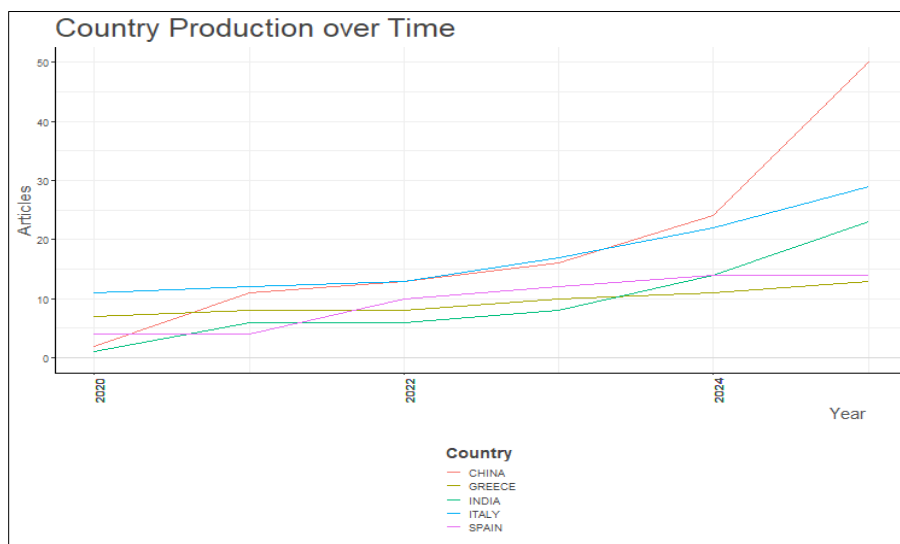
Figure 8: Most Cited Countries



Source: Created by authors

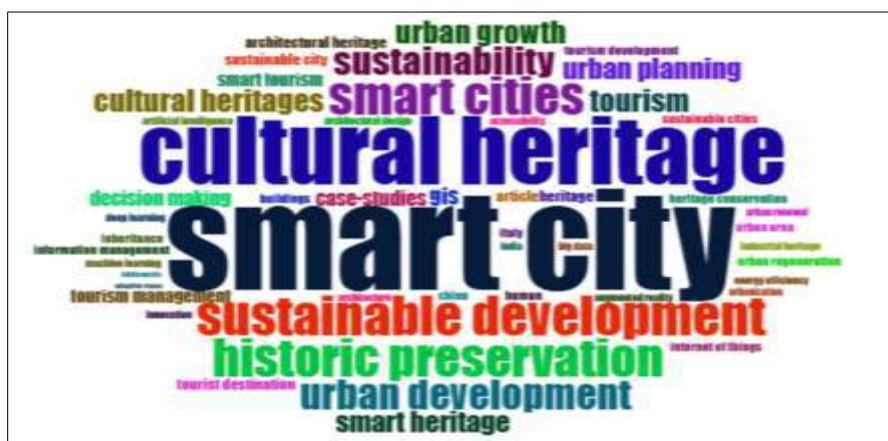
This figure gives the countries with the best citation impact. Top in the list are China, Greece, and Italy with India coming after. The first characteristic of these nations is their historic cities and good heritage properties that make them the relevant comparators of Kolhapur. The development of citation presence in India shows that there is more academic interest on heritage based smart urban development.

Figure 9: Country Production over Time



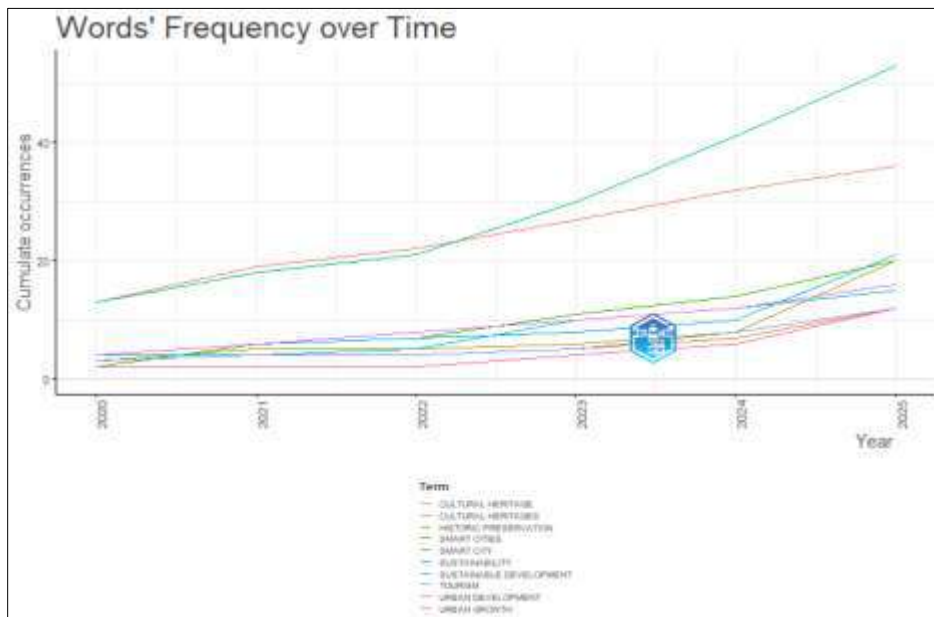
Source: Created by authors

Figure 10: Keyword Word Cloud



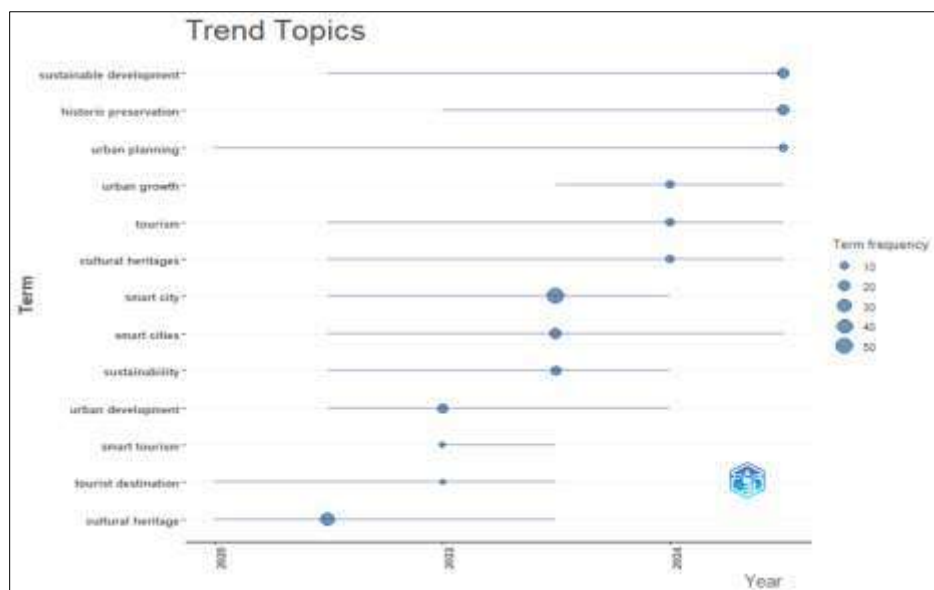
Source: Created by authors

Figure 12: Words Frequency over Time



Source: Created by authors

Figure 13: Trend Topics

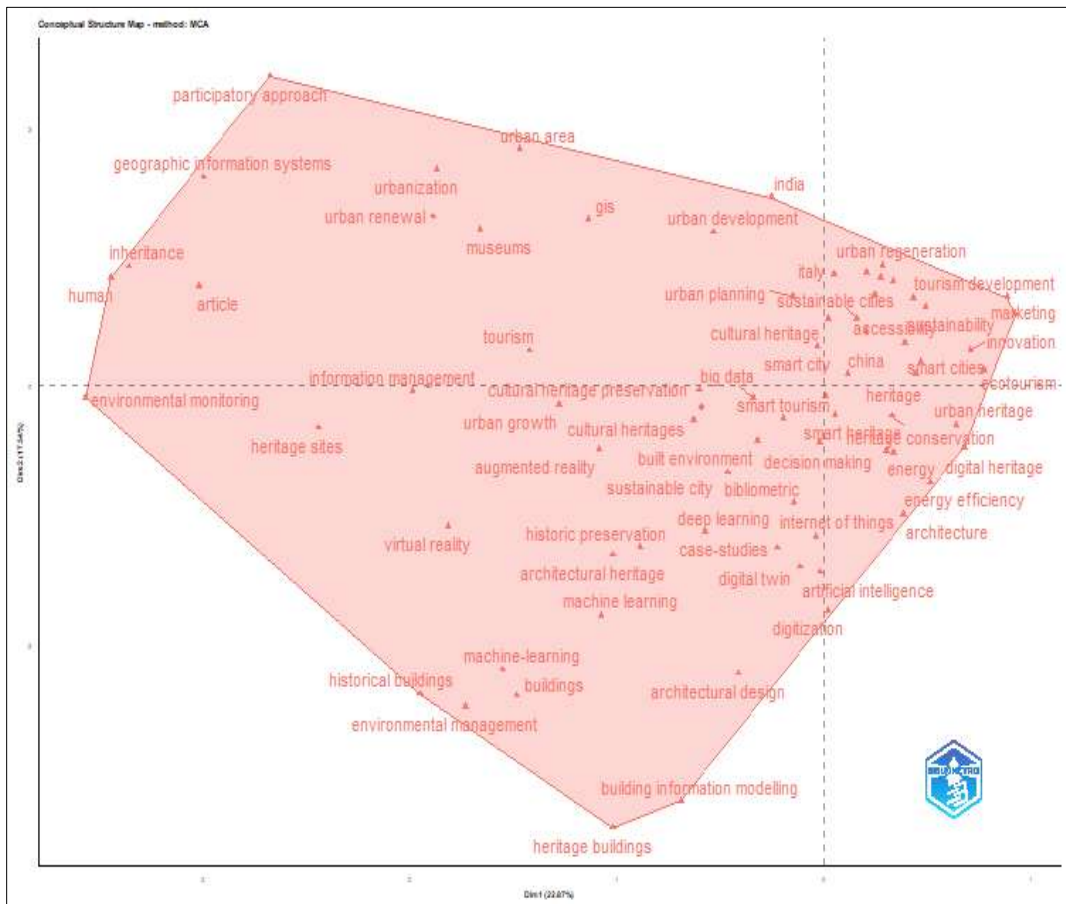


Source: Created by authors

This measure is used to trace the change in time of key words. The consistent growth of the term's smart city, sustainability, and cultural heritage suggests that the transition to integrated and sustainable methods of planning is made. This trend is favourable to the thesis goal of suggesting an intelligent planning model of Kolhapur.

The trend topics plot determines the emergent and maintained research topics. The culturally heritage centered attention has been extended overtime to smart cities, tourism, urban development, and sustainability. This development is indicative of shifting priorities which are very pertinent toward Kolhapur, an urban center with tourism pressures and urban sprawl.

Figure 14: Conceptual Structure Map (MCA)



Source: Created by authors

The conceptual structure map organizes several keywords into thematic clusters and it has strong connections between smart technologies, heritage conservation, urban planning, and digital tools. This grouping encourages the integrated planning strategy that is suggested in Kolhapur, in which smart interventions should be consistent with heritage-sensitive development.

Figure 15: Thematic Map



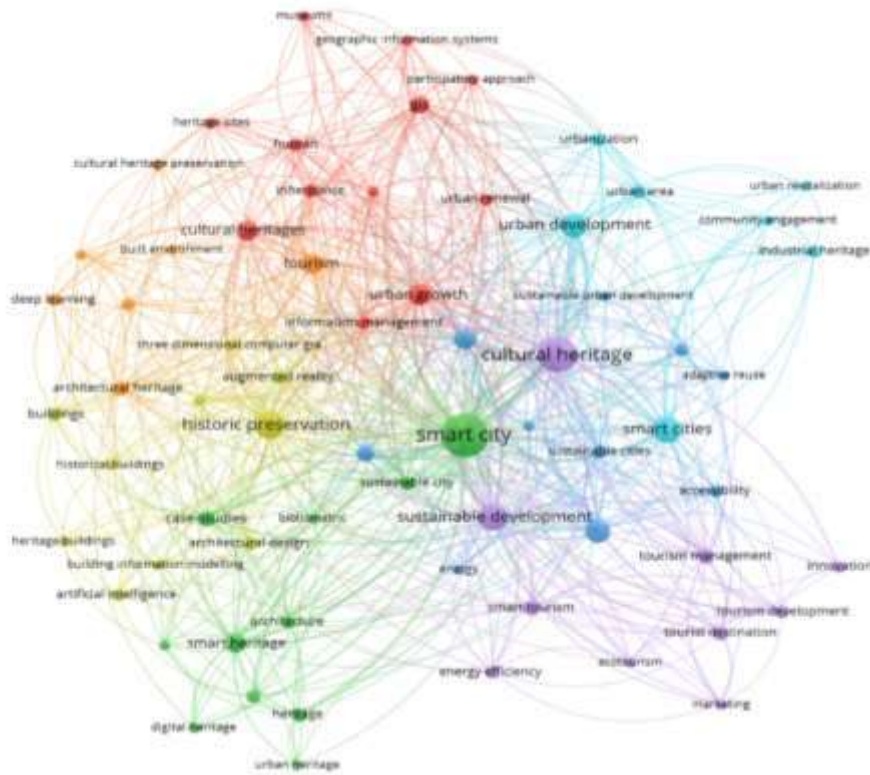
Source: Created by authors

The thematic map divides the research themes into basic, motor, niche and emerging themes. Basic themes contend to be smart city, cultural heritage and sustainable development and urban development and tourism are motor themes. New themes like artificial intelligence and digital heritage indicate emerging planning opportunities of Kolhapur.

The co-occurrence network shows that there are strong interconnections between sustainable development, cultural heritage and smart city. This validates the fact that the existing studies support the concept of integrated and holistic planning models, which is why

a smart urban planning framework that will retain the cultural identity of Kolhapur and still facilitate modernization is necessary.

Figure 16: Keyword Co-occurrence Network



Source: Created by authors

7.0 Historic Background of Kolhapur

Kolhapur is situated on the Brahmapuri branch of the Panchganga River and is historically known as Dakshin Kashi, reflecting its long-standing religious and cultural significance. City has been influenced by the reign of various dynasties such as the Mauryan dynasty, the Bahamani dynasty, and then the rule of Maratha dynasty introduced by Chhatrapati Shivaji Maharaj, the successors of which continued to lead the region. One of the most important stages in the urban, social, and cultural development of Kolhapur was the period of the reign of the Chhatrapati Shahu Maharaj (1894-1922). His reformist rule was very influential in the social setup of the city, education and the economy of the city. Shahu Maharaj was the pioneer of nurturing an inclusive development of Kolhapur; he was an advocate of education as a means of social justice and equity. His policies gave rise to the

boarding movement where students with varied social and economic backgrounds could now access education, and this played a major role in leading to universal primary education. In addition to institutional changes, Shahu Maharaj also saw the significance of cultural expression in the transformation of society. He advocated conventional folk-art genres like Tamasha and promoted theatrical productions to spread the Satyashodhak ideology, thus making the culture more aware and socially reformative. Such efforts not only contributed to the cultural life of Kolhapur, but they also made it an even more progressive and socially aware city. The inclusive governance, cultural patronage, and educational progress of the past also permeate the urban identity of Kolhapur, and this city is a heritage city today, where traditional cultural values and modern progressive values co-exist and makes it a case study in terms of the sensitive nature of urban planning in relation to heritage.

7.1 Background and rationale (Intangible)

- Mahalaxmi Festival (Navratri & Rath Yatra): It is a festival dedicated to Goddess Mahalaxmi, which has colorful chariot processions, rituals and considerable crowds of worshippers.

Figure 17: Intangibles of Kolhapur



Source: Created by authors

- Jyotiba Yatra: Huge pilgrimage, where followers bring sticks of Sasan of Jyotiba Temple and have nightly processions, and music.
- Kolhapur Royal Dussehra: It contains several events which are official and promoted by the state including folk arts, royal weapons worship (Shastra Puja), procession, dances, and cultural demonstrations.
- Wrestling (Kushti): Traditional akhadas (wrestling schools) and annual matches, reflecting local pride in strength.
- Kolhapuri Chappals and Jewelry: Generations-old crafts such as handmade leather slippers and the ornamental Kolhapuri Saaj necklace.

7.2 Background and Rationale (Tangible)

Figure 18: Tangibles of Kolhapur



Source: Created by authors

- Mahalaxmi Temple: Temple that was built in 7 th century during the Chalukya rule and was dedicated to the Goddess Mahalaxmi (Ambabai), which is a key spiritual site in Kolhapur.
- Jyotiba Temple: Binkhambi Ganesh Temple: Unique for its pillar-less construction, dedicated to Lord Ganesha.

- Panhala Fort: Maratha-era hill fort, strategic and historic, with expansive views across Kolhapur's heritage landscape.
- New Palace: Stunning Indo-Saracenic palace (built 1884), former residence of Kolhapur's rulers, now a museum of royal artifacts.
- Rankala Lake: Natural 9th-century lake associated with local mythology; surrounded by palaces and a Shiva temple.
- Town Hall Museum: Neo-Gothic building from 1876 now displaying artifacts from Kolhapur's history.
- Panchganga Ghat: Historic and religious riverside bathing ghat, a hub of festivals and rituals.

7.3 Identification of study area: Why Kolhapur ?



Source: Created by authors

8.0 Data Collection and Analysis Framework

8.1 Primary data collection

First hand data were gathered to record the ground level environment and world view of the stakeholders in the heritage core and buffer zone of Kolhapur. Methods of data collection were structured household surveys, business survey, and vendor survey of the heritage-influenced business districts, tourist and pilgrim intercept survey of major heritage destinations, semi-structured interviews with municipal officials and planning practitioners, group discussion with residents and local organizations, and field observation survey. Moreover, brief technical audits were carried out to evaluate the urban infrastructure components which include the drainage, pedestrian structures, signage and public amenities.

8.2 Secondary data collection

The secondary data were gathered to put in place a policy, spatial and a historical context of the research area. This consisted of statutory development plans, Smart Cities Mission project reports, census and ward-level socio-economic information, cadastral and topographic maps, the existing GIS layers of land use and transport network, satellite imagery of land-use change and environmental evaluation, and peer-reviewed scholarly sources pertaining to smart cities and heritage planning.

8.3 Data analysis

The gathered data was discussed by combining the analytical approach based on PESTEL analysis, the Historic Urban Landscape (HUL) technique, and the methods of assessment of infrastructure.

Table 2: Stakeholder

Stakeholder Category	Sub-Category / Examples	Data Collection Method (How you collect data)	Analysis Framework Applied (How you interpret data)	Expected Outcomes
Government / Policy Level	- Municipal Commissioner & Mayor - Smart City Mission Office - State Urban Development/Heritage Dept.	Key Informant Interviews (Semi-Structured)	PESTEL + Smart Heritage Governance	Policy structure, funding, administrative coordination, regulatory constraints

Technical / Implementing Departments	- Town Planning Dept. - Traffic & Transport Dept. - Sanitation & Waste Management Dept. - Water Supply & Drainage - Archaeology/Heritage Cell	Structured Expert Interviews + Department Data Request	PESTEL + Smart Heritage Readiness + Risk & Infrastructure Assessment	Infrastructure condition, operational gaps, inter-departmental coordination level
Institutional / Knowledge Support	- Academic Institutions - Research Labs - Universities & Architecture Colleges	Expert Interviews + Document Review	Knowledge Integration + HUL / ISUF Research Mapping	Research capacity, available documentation, GIS/heritage mapping support potential
NGOs / Community Organizations	- Local Heritage Groups - Cultural Trusts - Environmental & Civic NGOs	Interviews + Focus Group Discussions (FGDs)	PESTEL (Social & Governance) + Community Engagement Framework	Participation level, outreach capacity, cultural awareness gaps, potential for joint action
Residents (Local Community)	- Residents in Heritage Core - Residents in Adjacent Wards	Household Surveys + FGDs	PESTEL (Social/Environmental) + HUL (Community Perception & Urban Fabric)	Livability, civic service satisfaction, heritage value perception, problem hotspots
Local Businesses & Vendors	- Shop Owners in Temple Bazaar - Food Vendors - Tourism Service Providers	Business Surveys + Informal Interviews	PESTEL (Economic) + Economic Sustainability Framework	Economic dependence on heritage areas, effects of congestion, digital payment adoption
Craftspeople & Artisans	- Kolhapuri Chappal makers - Jewellery, brass/metal artisans	Semi-Structured Interviews + On-Site Observation	HUL (Intangible Heritage) + Livelihood Sustainability Assessment	Craft continuity, youth involvement, market constraints, preservation needs
Visitors / Tourists / Pilgrims	- Temple Visitors - Sightseeing Tourists	Short Intercept Surveys at Sites	PESTEL (Social/Tech/Environment) + Visitor Experience Framework	Visitor satisfaction, amenity adequacy, cultural interpretation awareness
Physical Site / Heritage Assets	- Temples - Forts- Lakes / Ghats - Historic Streets & Markets	On-Site Observation Checklist + Photographic & GIS Mapping	HUL (Spatial + Physical Integrity) + ISUF (Urban Morphology)	Building condition, encroachment level, walkability, signage condition, environmental risks

Source: Created by authors

Quantitative data were surveyed and analysed statistically using descriptive statistical measures to determine spatial and perceptual differences between heritage core and buffer areas. Thematic analysis of qualitative data collected through interviews and focus group discussions was conducted to identify thematic important planning issues, governance problems and priorities in community. The GIS-based mapping was used to analyse spatial data to determine the land-use patterns, the distribution of infrastructures and features of the heritage precincts. Synthesis of the results was carried out to provide guidelines on how to develop a heritage-conscious smart city planning system that can be applied to Kolhapur (and other historic cities).

9.0 Research Framework and Questionnaire Design

The research paper assumes an interdisciplinary method of analysis with the PESTEL analysis, the Historic Urban Landscape (HUL) model and Infrastructure and Risk Assessment to explore smart urban planning in the framework of a heritage city. This model makes it possible to perceive external forces, culture and values, urban structure, infrastructure functionality, and city governance in Kolhapur in a holistic manner.

9.1 Integrated research framework

- PESTEL Analysis has been used to evaluate political, economic, social, technological, environmental and legal forces in the development of smart heritage city.
- The Urban form, cultural identity, heritage values and community perception of the historic core and culture were evaluated using Historic Urban Landscape (HUL) framework.
- Infrastructure and Risk Assessment Involving water supply, sanitation, drainage, mobility, safety and environmental risks to heritage precincts.

All these frameworks are integrated to make sure that they take into consideration the tangible and the intangible heritage dimensions as well as the readiness of smart cities and the resilience of the infrastructure.

9.2 Questionnaire design and parameters

Following the integrated framework, a questionnaire, which is structured based on question-and-answer format, was designed to obtain the perception and experiences of various stakeholder groups. The parameters that were included in the questionnaire entailed:

- Demographic profile
- Existence of basic city services of reasonable quality.
- The mobility and safety conditions are considered.

- Environmental conditions
- Cultural value, identity and usage: how often culture is discussed and followed.
- Community perception (social places, social communication)
- Ruling and involvement (redressal of complaints and involvement)
- Digital and smart city preparedness (knowledge, desire, and utilization).

These were the parameters chosen because it represents the reality of heritage city planning, whereby, the interventions of technology must align itself with the social, cultural, and spatial environment

9.3 Sampling strategy

The sampling was undertaken using a stratified systematic random approach that guarantees that there is a balanced representation amongst the spatial zones. The study region was subdivided to heritage core area (65% and the buffer/surrounding area (35%). The size of samples used was based on the population of Kolhapur district with proportionate samples of the two zones being used to cover differences in the intensity of heritage, infrastructure status, and community perception.

9.4 Relevance to the study

The proposed research framework and questionnaire design is structured and evidence-based way of comprehending the challenges of smart planning of Urban Kolhapur. The approach underpins the creation of a heritage-conscious smart planning approach that allows balancing urban development, cultural conservation, and technological assimilation.

10.0 Expected Outcomes and Further Scope of Study

10.1 Expected outcomes

In accordance with the literature analysis, bibliometric analysis, and the suggested mixed-method research frame, the study will produce the following results:

1. Identification of Planning Gaps: As part of the research, the researcher anticipates that the gaps in current interventions of smart city in Kolhapur will be identified, especially the absence of coordination between infrastructure development and heritage conservation outcomes and the demands of the community.
2. Heritage-Sensitive Smart Planning Parameters: The study will determine the essential parameters that can combine the smart technologies with the heritage values, such as mobility management, the quality of the public space, the instrumentality, and preservation of cultural assets.

3. **Stakeholder-Based Insights:** The survey, interviews, and FGDs will help the researcher to draw different perceptions among the stakeholders residents, artisans, tourists, and institutions of the heritage core and buffer areas.
4. **Assessment of Smart City Readiness:** The results will point to the willingness of Kolhapur to smart governance, digital solutions, and participatory planning and denote the institutional and capacity-related shortcomings.
5. **Smart Urban Planning Framework Proposal:** The most critical finding of the research will be the development of a city-specific smart urban planning model that facilitates balance between heritage preservation, sustainability, and urban development in medium heritage cities.

10.2 Further scope of the study

Although this study is limited to Kolhapur, there are other ways in which the method can be broadened:

- However, the framework applied to other Indian heritage cities like Nashik, Ujjain, or Madurai to compare it with other ones.
- Adoption of developed smart solutions of digital twins, AI-driven traffic control, and real-time heritage monitoring tools.
- Long-term research to measure the effectiveness of smart heritage planning strategies in the long-term.
- Climate resilience and disaster risk planning in inclusion into heritage precincts.
- The assessment of Smart Cities Mission policies at the policy level through a heritage-based planning approach.

11.0 Conclusion and Planning Implications

The issues faced by heritage cities in India are how to balance between fast urbanization and protecting the cultural identity, historic urban structure, and customs based on community. This paper shows that the current smart city practices tend to focus on technological and infrastructure centred solutions at the expense of institutional, spatial and cultural aspects of historic urban cores. The research presents a literature review, bibliometric analysis, and design of an organized research methodology, which proves the need to develop a policy-based smart urban planning framework based on heritage sensitivity.

Kolhapur is used as the case study; the study highlights the fact that the tangible heritage assets, intangible cultural practice, and daily socio-economic activities are entrenched in the spatial structure of the city. Based on the PESTEL analysis approach and the Historic Urban Landscape (HUL), along with the infrastructure performance and risk

assessment, the analytical framework also offers a policy-appropriate prism to explore the governance mechanisms, regulatory lapses, infrastructure operation, and heritage management practices. This framework is especially correlated to national urban projects, including the Smart Cities Mission, which emphasizes the necessity to promptly coordinate smart city projects, development policies, and heritage conservation policies.

The study has at the present level created a strong data collection framework. The analysis of primary data collected during the household survey, interviews with stakeholders, focus groups, and on-site observations will be done in the next step, which will be facilitated by the secondary sources of the statutory plans, census data, GIS layers, and policy documents. This combined examination will make it possible to identify the key parameters of planning priorities, spatial differences, and governance-related issues that need to be addressed in terms of policy, especially in the areas of the heritage core and buffer zones of the city of Kolhapur.

The research will generate clear planning deliverables to facilitate the evidence-based decision-making, such as:

- Thematic spatial maps that represent the heritage assets, the physical state of infrastructure, mobility patterns, risks of environmental harm, and the gaps in services.
- Indicative measurements of the smart city readiness, heritage sensitivity, infrastructure resilience and participation of community members etc.
- A smart planning framework diagram policy based and aligned: incorporating heritage conservation, smart governance, and infrastructure development with stakeholder participation.
- Guidelines of strategic planning, which entails short, middle, and long-term intervention in the heritage precincts, and adjacent urban regions.

In the planning and policy perspective the research focuses on the significance of incorporative governance systems, participative planning systems, and spatially conscious regulatory systems. The resultant project is likely to bring on board a scalable, adaptive, and policy sensitive urban planning model that may guide urban development policies in medium cities in India which have heritage. Although the empirical analysis and improvement of the framework is underway, the study is poised to provide practical implications on the planners, the local urban bodies, and the policymakers interested in the systematic and sustainable integration of smart urban development and cultural heritage preservation.

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CHAPTER 30

Assessment and Optimization of Geopolymer-Based Stabilized Mud Blocks

Bhargavi Naraganahalli, Amogh Biradar** and Aditya Kanadikar****

ABSTRACT

This research intends to examine and improve Stabilized Mud Blocks (GSMBs) through the utilization of Geopolymer to enhance mechanical and ecological properties via incorporation of clay, fly ash, and polypropylene (PP) fibers. Geopolymer binder synthesis involves a solution of sodium hydroxide (NaOH) combined with sodium silicate (Na_2SiO_3), at a ratio of Na_2SiO_3 to NaOH of 2.0-3.0. A Taguchi L9 orthogonal array (3x3) experimental design will be utilized to systematically analyze the influence of four independent variables, namely the percentage of clay used, the ratio of the alkaline activator, flyash percentage, and the content of PP fiber. Specimens are air-dried oven-cured at 24 hours at 60 o C and sun cured at 28 days to allow geopolymerisation. The test utilizes density, compressive strength, flexural strength, water absorption, and efflorescence characteristics. Multi-response optimization was employed to determine the optimal combination of mix parameters considering multiple performance criteria simultaneously. It is anticipated that the implementation of PP fibers will enable crack management and post-crack behavior moderation, while the adjustment of mixture ratios and activator concentrations will contribute to overall structural performance improvements. The findings of this analysis can support the validation of GSMBs as a viable alternative to conventional fired bricks and cement-based masonry, facilitating the adoption of low-carbon, resource-efficient construction practices.

Keywords: Geopolymer, Stabilized Mud Blocks, Fly Ash, Clay, Sustainable Construction.

1.0 Introduction

As we all know, construction industry has been a significant contributor to global greenhouse gases emissions due to its consumption of energy-intensive materials such as fired clay bricks and regular Portland cement.

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The urbanization is increasing rapidly, especially in developing countries like India, which is fast consuming material, environment and carbon emission. Additionally, the increased concentration of urban areas has contributed to the Urban Heat Island (UHI) effect, where conventional construction materials characterized by high thermal mass and low reflectivity exacerbate elevated ambient temperatures within metropolitan regions.

Stabilized Mud Blocks (SMBs) present an environmentally sustainable alternative, utilizing excavated soil from the immediate location and industrial by-products (fly ash), thereby reducing the impact of embodied energy and transportation. The application of geopolymer binders, generated via alkaline activation, also reduces carbon emissions relative to cement stabilization. Additionally, the implementation of polypropylene (PP) fiber is employed to mitigate the effects of shrinkage cracking, thereby enhancing both serviceability and durability.

2.0 Literature Review

Previous studies into earthen construction materials have demonstrated that the type of soil, soil stabilization method, and curing process are highly influential factors in the performance of blocks. Cement and lime are the traditional stabilizers that have been widely used for improving the compressive strength and durability of soil blocks but their carbon footprint is high hence not very sustainable. The remaining binders studied include fly ash and slag geopolymers, which exhibit high strength, low permeability, and enhanced chemical resistance. Empirical studies indicate that the application of geopolymer stabilization facilitates the formation of alumino-silicate gel networks, thereby improving particulate cohesion in the soil. The friable materials with soil bases have also been studied by the application of fiber reinforcement to surmount them. The best type of fiber in this case is polypropylene fiber, given that it is inert, inexpensive, and also moisture resistant. Literature indicates improvements in flexural strength, crack width, and toughness of fiber-reinforced stabilized blocks. Despite this advancement, limited research exists regarding the potential integration of geopolymer binders with polypropylene fiber reinforcement in stabilized mud blocks. This research addresses this gap by analyzing the synergistic impact of fiber reinforcement and stabilization on geopolymers.

3.0 Data and Methodology

3.1 Materials used

The following materials were used in the experimental investigation:

- Locally excavated soil obtained from a construction site.

- Fly ash as an alumino-silicate precursor.
- Geopolymer binder prepared using sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).
- Polypropylene (PP) fibers.
- Potable water for preparation of alkaline solution.

3.2 Soil Characterization

To assess the suitability of the excavated soil for stabilized mud block production, laboratory tests were conducted in accordance with relevant Indian Standards.

3.2.1 Grain Size Analysis

The determination of the grain size distribution was according to IS 2720 (Part IV). Table 1 contains the results.

Table 1: Grain Size Distribution of Excavated Soil

IS Sieve Size	% Retained	Cumulative % Retained	% Finer
4.75 mm	22.93	22.93	77.07
2.36 mm	27.72	50.65	49.35
1.18 mm	27.3	77.95	22.05
600 μ	7.89	85.84	14.16
300 μ	7.05	92.89	7.11
150 μ	2.93	95.82	4.18
75 μ	2.19	98.01	1.99
Pan	1.88	99.89	0.11

Source: Created by authors

The sampled soil in the Baner region of Pune is that of non-plastic coarse grain soil that is mostly composed of sand with a small percentage of gravel and very little percent of fine soil (silt or clay). Therefore, the soil tends to be predominantly sand sized and with low fines (0.1%). According to the system of Indian Standard Soil Classification System (IS 1498), the soil is classified as Gravelly Sand (SG). It is a coarse soil which is typical to the soils which are formed out of weathered basalt at the Deccan Trap region. Such kind of soil is not naturally coherent and cannot accommodate SMBs without any modifications. Therefore, the lack of the clay component was removed, and geopolymer binders were utilized, with the inclusion of the PP fibers to control the cracks that appeared after the shrinkage.

3.2.2 Atterberg Limits and Shrinkage Limit

The tests performed according to IS 2720 were liquid limit, plastic limit, plasticity index and shrinkage limit tests. Table 2 summarizes the results.

Table 2: Atterberg Limits and Shrinkage Characteristics

Property	Value
Liquid Limit (LL)	37.48%
Plastic Limit (PL)	5.37%
Plasticity Index (PI)	32.11%
Shrinkage Limit (SL)	4.4%

Source: Created by authors

Interpretation: The analysis of grain size reveals that the soil is coarse-grained and contains low level of fines hence it is classified as Gravelly Sand (SG) according to IS 1498. Atterberg limit tests on the fraction passing the 425 μm sieve were made as per IS 2720 (Part 5). The findings suggest that the fines fraction have plastic behavior but the quantity of the fraction in the bulk soil is very small; hence, the soil behavior is not plastic and is coarse-grained. The plastic limit range of fines of the soil was determined as rather low. The plastic limit was not used in soil classification and interpretation because it was not easy to obtain a constant 3 mm thread during the rolling process. Low shrinkage value refers to the volumetric shrinkage of the soil fines in isolation. However, in spite of a low shrinkage limit of the fines fraction of the soil, the shrinkage cracking in stabilized soil blocks is largely determined by shrinkage binder-induced by the soil block and moisture loss during curing. The polypropylene fibers were thus used to contain the formation of micro-cracks and enhance crack resistance and not to diminish the inherent soil shrinkage. And geopolymer binders provided sufficient bond and strength.

3.3 Soil Preparation by Sieving to 2.36 mm

The sieved soil was filtered using a 2.36 mm sieve to filter away any large gravel particles. This assisted in making the mix more even, easier to compact during block casting and created a smoother surface finish. Although the soil had few fine particles hence, they lacked natural cohesiveness. Because of this, geopolymer binders and fiber reinforcement were added to provide bonding and crack resistance in the blocks.

3.4 Mix Design and Experimental Plan

An orthogonal array of L9 (3 $\times$ 3) was taken to ensure that the proportions of materials were optimized to a minimum number of experimental trials. There were three parameters that were varied:

- Clay percentage.
- Alkaline Solution Ratio ($\text{Na}_2\text{SiO}_3/\text{NaOH} = 2.0, 2.5, 3.0$).
- Polypropylene fiber content.
- Flyash percentage.

The mix proportions for block casting are presented in **Table 3**.

Table 3. Taguchi L9 Mix Proportions for GSMBs

Sr. No.	Date of Casting	% Clay	% Fly Ash	Alkanline Solution Ratio (ASR)	Polypropylene Fibre %	Alkanline Solution	NaOH (Kg)	Na ₂ SiO ₃
1	17-12-2025	40%	60%	2	1.50%	L/S = 0.4	1.46	2.94
2	19-12-2025	40%	60%	2.5	2%	L/S = 0.4	1.25	3.14
3	19-12-2025	40%	60%	3	2.50%	L/S = 0.4	1.1	3.3
4	18-12-2025	60%	40%	2	2%	L/S = 0.4	1.46	2.94
5	07-01-2026	60%	40%	2.5	2.50%	L/S = 0.4	1.25	3.14
6	07-07-2026	60%	40%	3	1.50%	L/S = 0.4	1.1	3.3
7	16-12-2025	80%	20%	2	2.50%	L/S = 0.4	1.46	2.94
8	09-01-2026	80%	20%	2.5	1.50%	L/S = 0.4	1.25	3.14
9	09-01-2026	80%	20%	3	2%	L/S = 0.4	1.1	3.3

Source: Created by authors

3.5 Casting and curing procedure

- Dry materials were mixed thoroughly.
- Alkaline activator solution was prepared separately and added gradually.
- Blocks were cast using a hand-operated compression press in the construction laboratory.
- The oven-cured at 60°C for 24 hours.
- Subsequently, blocks were ambient cured under sun exposure for 28 days to allow complete geopolymerisation.

Therefore, the development of geopolymer-based stabilized mud blocks is explored in this project as a viable solution to address environmental concerns, reduce construction-related emissions, and contribute to climate-resilient and resource-efficient construction practices.

4.0 Empirical Results and Testing Procedures

Stabilized mud blocks (GSMBs) made of geopolymer were tested on their physical and mechanical properties as well as durability upon the standard testing procedures. Experimental procedures were conducted in compliance with ASTM C67 05: Standard Test Methods of Sampling and Testing Brick and Structural Clay Tile with no exceptions. Following are the results for compressive test, water absorption test, efflorescence test & initial rate of absorption test:

Mix No.	Factor A (Clay: Fly ash)	Factor B (Alk. Sol Ratio)			Factor C (PP Fibers)	Comp. Strength (MPa)	Water Abs (%)	IRA	Efflorescence
		ASR	Required Na ₂ SiO ₃	Required NaOH					
1	40:60	2	2.94 kg	1.46 kg	1.50%	9.71	2.96	0.14	Nil
2	40:60	2.5	3.14 kg	1.25 kg	2%	7.49	3.12	0.15	Nil
3	40:60	3	3.3 kg	1.1 kg	2.50%	6.7	3.28	0.2	Slight
4	60:40	2	2.94 kg	1.46 kg	2%	7.23	3.67	0.16	Slight
5	60:40	2.5	3.14 kg	1.25 kg	2.50%	6.8	4.02	0.18	Slight
6	60:40	3	3.3 kg	1.1 kg	1.50%	6.2	4.48	0.25	Moderate
7	80:20	2	2.94 kg	1.46 kg	2.50%	4.91	6.9	0.28	Heavy
8	80:20	2.5	3.14 kg	1.25 kg	1.50%	4.6	6.2	0.22	Heavy
9	80:20	3	3.3 kg	1.1 kg	2%	4.1	5.7	0.3	Slight

Source: Created by authors

The experimental results show that the mix composition significantly influences the mechanical and durability properties of the geopolymer stabilised mud blocks. The highest compressive strength of 9.71 MPa was obtained in Mix 1 (40:60 clay to fly ash ratio) with ASR = 2 and 1.5% PP fibres. This shows that an increase in fly ash content results in better geopolymerization and bonding, hence stronger blocks. When the content of clay increased from 80% (Mix 7-9), compressive strength decreased significantly to 4.1-4.91 MPa. Similar trends were observed for water absorption. Mixes with high fly ash content had low water absorption of 2.96-3.28%, while mixes with high clay content had high water absorption of 6.9%, indicating increased porosity.

The initial rate of absorption (IRA) also showed an increase with increases in clay content. The lowest IRA reading of 0.14 kg/m²/min was recorded when Mix 1 was used, while the highest reading of 0.30 kg/m²/min was recorded when Mix 9 was used.

For efflorescence, mixes with high percentages of fly ash content showed nil or low efflorescence, while mixes with high percentages of clay content showed moderate to heavy efflorescence due to the migration of soluble salts on the surface.

The findings showed that mixes with high percentages of fly ash content showed better strength and durability, while mixes with high percentages of clay content showed better results in terms of water absorption and efflorescence. Hence, mixes with 40% clay content and 60% fly ash content showed better results.

5.0 Multi-Response Optimisation

Multi-response optimisation is used when multiple performance parameters need to be optimised simultaneously.

In this study, the goal was to:

- Maximise compressive strength
- Minimise water absorption

- Minimise efflorescence
- Minimise initial rate of absorption

Minitab combines all these responses and determines the optimal mix proportion that satisfies all the objectives. The optimisation process results in a composite desirability value, which varies between 0 and 1.

A value closer to 1 indicates a highly optimal result. In this study, the composite desirability value obtained was 0.976, which indicates that the selected mix has excellent overall performance.

The following are the steps to perform in Minitab software for multi-response analysis:

Minitab Software > Stat > ANOVA > General Linear Model > Response Optimizer > Enter goals for the responses (ex. Water Absorption = Minimize).

Multi-response optimisation was performed in Minitab to determine the best combination of mix parameters that satisfies all performance requirements simultaneously. Since different properties have different goals, optimisation was carried out by setting:

- Compressive Strength → Target / Maximum
- Water Absorption → Minimum
- Efflorescence → Minimum
- Initial Rate of Absorption (IRA) → Minimum

Using these goals, Minitab analysed all responses together and identified the optimum mix combination.

Parameters						
Response	Goal	Lower	Target	Upper	Weight	Importance
IRA	Minimum		0.14	0.3	1	1
Efflorescence	Minimum		1	4	1	1
Water Absorption	Minimum		2.96	6.9	1	1
Compressive Strength	Target	4.1	7.5	9.71	1	1

Source: Created by authors

Clay	ASR	PP Fibres	IRA	Efflorescence	Water Absorption	Compressive Strength
40	2.5	2	0.132	0.667	2.768	7.706

Source: Created by authors

The optimal settings obtained were:

- Excavated Clay = 40%
- Alkali Solution Ratio (ASR) = 2.5
- PP Fibres = 2%

At this combination, the predicted performance values are:

Property	Predicted Value
Compressive Strength	7.71 MPa
Water Absorption	2.77%
Efflorescence	0.67 (Nil)
IRA	0.132 kg/m ² /min

Source: Created by authors

The following is the range of predicted performance values:

Response	Predictions with 95% CI
IRA	(0.0220, 0.2425)
Efflorescence	(-3.128, 4.461)
Water Absorption	(0.698, 4.838)
Compressive Strength	(5.118, 10.293)

Source: Created by authors

The composite desirability value calculated is 0.976, which is close to 1. This implies that the mix combination selected has a perfect balance of strength and durability properties. From the optimisation results, it is clear that a greater content of fly ash with a moderate content of alkaline solution ratio and fibre content improves the geopolymer stabilised mud blocks.

6.0 Conclusion

This study investigated the development and performance of geopolymer-based stabilized mud blocks (GSMBs) using locally available soil, fly ash, alkaline activator, and polypropylene (PP) fibers. The experimental results demonstrated that the mix composition significantly influences both mechanical and durability properties of GSMBs.

The highest compressive strength of 9.71 MPa was achieved for the mix with 40% clay and 60% fly ash (ASR = 2, 1.5% PP fibers), while mixes with higher clay content (80%) showed significantly lower strength in the range of 4.1–4.91 MPa. Water absorption varied from 2.96% to 6.9%, with lower values observed in fly ash-rich mixes, indicating improved durability and reduced porosity. Similarly, the initial rate of absorption (IRA) ranged between 0.14 and 0.30 kg/m²/min, with minimum values corresponding to optimal geopolymer composition. Efflorescence was observed to be nil to slight in mixes with higher fly ash content, whereas clay-rich mixes exhibited moderate to heavy efflorescence.

Multi-response optimization was performed to simultaneously maximize strength and minimize durability-related parameters. The optimal mix proportion was identified as 40% clay, alkaline solution ratio of 2.5, and 2% PP fibers, yielding predicted values of 7.71 MPa compressive strength, 2.77% water absorption, 0.132 kg/m²/min IRA, and negligible efflorescence, with a high composite desirability value of 0.976.

Overall, the study confirms that geopolymer-based stabilized mud blocks can serve as a sustainable and high-performance alternative to conventional masonry units. The use of industrial by-products such as fly ash, combined with optimized mix design, can significantly reduce environmental impact while maintaining adequate structural performance, making GSMBs suitable for low-rise and affordable housing applications.

7.0 Implications

Geopolymer-stabilized mud bricks should be adopted to help to cut down the carbon emissions and save resources in the construction sector. They can be especially used in low rise buildings and affordable housing projects where cost-effectiveness and sustainability are of high importance.

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CHAPTER 31

Impact of Stakeholder Relationship Management for Successful Delivery of Construction Projects

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ABSTRACT

This study explores how SRM can facilitate completing construction projects on time and successfully. Construction has been increasingly complex, and so have the individual stakes of those involved in the process. There is the potential for delays, legal issues, and increased costs associated with these factors. In light of this, the research examines how stakeholders are identified and understood, effective communication, and building trust and collaboration in the management of projects. This study uses both numbers and detailed information to get a full picture. The main data collection methods used are questionnaires, interviews, and on-site observation. Further information is gathered from existing case studies and published material. The numbers were analyzed with SPSS, and the detailed information was viewed through the themes on communication and stakeholder satisfaction and their influence on the performance of the project. The results indicate that clear communications, involving the stakeholders in decisions, monitoring their needs, and including ethical practices and social responsibility in SRM contribute to better project integration. This study provides helpful guidance for effective utilization of SRM in construction projects despite some limitations.

Keywords: Stakeholder relationship management, Construction projects, Sustainability, Project governance.

1.0 Introduction

The construction industry requires integrated participation from a wide array of stakeholders such as construction or project owners, contractors, consultants, subcontractors, suppliers, and construction stakeholders, including regulatory bodies and local communities.

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The construction sector has, over the years, seen a shift in what constitutes a successful construction or construction project. Contrary to linking the performance of constructions in terms of cost, time, or quality, today, a lot of emphasis has been laid on the extent to which relationships among different parties participating in constructions/ construction projects have been managed. In this context, the need for Stakeholder Relationship Management has arisen.

Construction projects may engage their operations in highly uncertain environments. The higher the project complexity, the higher the project stakeholder demands. In fact, poor project stakeholder management may result in project communication challenges, conflicting project objectives, contract disputes, project schedule and cost overruns. Successful project stakeholder management will therefore ensure project stakeholder trust building, project participant coordination, prevention of conflict, as well as project control.

In the traditional context, stakeholder management within the context of construction projects was mainly restricted to stakeholder identification and communicating project information to the stakeholders. Nonetheless, the contemporary nature of project setting demands greater emphasis on systematic stakeholder management, which places immense importance on stakeholder engagement, stakeholder interest alignment, transparency during the decision-making process, and building long-run stakeholder relationships. Employing systematic stakeholder analysis techniques and/or the utilization of the Critical Success Factor approach will help the project team determine the level of stakeholder influence, as well as effectively manage stakeholder concerns, on a proactive and timely basis. Empirical evidence has repeatedly shown significant relationships within the context of improved project outcomes, regarding stakeholder engagement, stakeholder communication, and stakeholder conflict management.

Recently, there has been a noticeable emphasis on “Corporate Social Responsibility (CSR), environmental, and ethical governance” that has widened the application area of SRM. SRM concepts have progressed from being associated mainly with project-related stakeholders within an organization, including external stakeholders such as local communities, government agencies, and public institutions. The integration of CSR in stakeholder management practices goes a long way in improving social acceptance and sustainability of projects in the construction industry.

In the Indian construction industry, the complexities involved and the rising concerns from the community add extra pressures on the project team and their stakeholder relationships. Although the intake for the importance of stakeholder relationship management has been well understood, many construction projects have yet to establish organized stakeholder relationship management, resulting in inefficient project performance and various project disruptions. In an attempt to address these issues, the goal of the current study is to

investigate the importance of stakeholder relationship management during successful construction project execution and focus on the important influencing parameters involved and the effective practices that may improve project performance and community stakeholder satisfaction.

1.1 Objectives

- To identify major stakeholders in construction projects and study their influence carefully. The objective also seeks to consider both project insiders and outsiders, their relative power, as well as the type of influence they exert on construction project planning and management.
- To analyze the construction project delivery practices of stakeholder communication. The purpose of this objective is to evaluate the communication techniques employed in the distribution of project information to various stakeholders in order to achieve alignment of expectations.
- To examine approaches adopted in establishing and maintaining effective stakeholder relationships. The objective here is to examine relationship management approaches which foster trust-building, cooperation, or partnerships in project-related activities with diverse stakeholders.
- In order to assess stakeholder engagement methods and the effectiveness thereof. This objective focuses on reviewing stakeholder engagement practices that aim at assessing how such practices affect project success measures, including time, cost, quality, and stakeholder satisfaction.
- To be able to identify the problems related to the management of relations between stakeholders. This objective will focus on finding common problems and limitations in the management of relationships with stakeholders of construction projects and provide solutions for overcoming these limitations.

2.0 Literature Review

Stakeholder Relationship Management (SRM) is seen as a key part of managing projects well in construction because the industry is complicated and involves many different people with an interest in the project. The conceptual foundations of a stakeholder-oriented approach in management have been found in Freeman's theory of stakeholders, which asserted that a firm needs to take into account not just shareholders but the interests of all stakeholders in order to be successful. This theoretical base has been widely utilized in construction project management. The actions and reactions of stakeholders have a direct impact on construction projects. Later literature has also allowed researchers and scholars to

conclude that the impact of stakeholders is not a static element but changes over various phases of a construction project.

There has been significant literature highlighting that communication and engagement are the key constituents of successful stakeholder management. Tools such as stakeholder circle analysis have been proposed in order to ensure that stakeholders are appropriately prioritized and their related engagement is managed. Empirical results have consistently highlighted that with active communication and information sharing strategies, there is a decrease in misunderstandings and resistance from the stakeholders. Additionally, early stakeholder involvement and communication strategies have been demonstrated to build trust and promote collaboration as well as making a positive contribution to project success.

The connection between how projects are managed and how stakeholders are handled is becoming more popular in academic studies. Findings by researchers interested in large-scale and public sector infrastructure projects indicate that poor governance structures, when complemented by poor engagement with stakeholders, tend to result in cost and schedule inefficiencies and a loss of accountability. Specifically, in relation to cost and schedule inefficiencies and a loss of accountability, stakeholder management is often viewed as a mediator or moderator that facilitates the efficiency of governance structures.

The theoretical underpinning for stakeholder-centric management as a theory traces its roots back to Freeman's stakeholder theory, which claimed that for any organization, success lies in addressing all stakeholders' interests instead of focusing only on shareholder interests. The same theory has been widely incorporated into construction project management. The actions and attitudes of stakeholders directly affect construction projects. Later research proved that instead of being fixed at a particular level for construction projects, stakeholders' impact varies at different points of a project's life cycle. Poor management of stakeholders' interests has been commonly identified as a reason for project failure.

In the meantime, the concept of CSR has become an integral element of how companies in construction projects practice their stakeholder relationship management. According to some authors, stakeholder relationship practices may vary significantly in their ethical orientation, ranging from rather inclusive practices up to more manipulative ones. More recent studies indicate that including elements from the field of CSR in stakeholder relationship management helps to create public acceptability and counteract social resistance in construction projects. Such studies also provide evidence for the increasing need for ethics in construction projects to ensure trust in the relationship management and implementation.

Scholars have also been trying to discover Critical Success Factors (CSFs) that are to be considered in successful SRM implementation. The crucial factors that are identified in SRM include systematic stakeholder identification, understanding stakeholder interest and power, targeting stakeholder engagement, and ongoing project stakeholder monitoring. Power

dynamics between stakeholders are found to play an important part in understanding where to concentrate stakeholder engagement activities. All these works together to prove that structured SRM practices are strongly related to positive project outcomes.

Although there has been extensive international literature regarding stakeholder management, relatively less literature exists on SRM in an Indian construction environment. Construction projects in India may also face constraints such as regulatory hindrances, difficulties regarding acquisition of lands, labor dependencies, and community sensitiveness to a greater degree. As has also been emphasized in existing literature, lack of coordination among stakeholders in such circumstances can hamper construction project success to a vast extent. Therefore, there remains an imperative need to conduct various empirical studies and analyses in this area.

There nevertheless exists a gap with regards to specific and pragmatic knowledge with regards to developing economies. The aim of this research is to add towards this body of knowledge with regards to studying stakeholder relationship management practices operating in the Indian construction industry.

3.0 Research Methodology

This study creates a clear and organized way to look at how Stakeholder Relationship Management (SRM) affects the success of construction projects. Construction projects take place in fast changing and connected environments where many different stakeholders are involved throughout the project's life. These interactions play an imperative role with regard to prominent factors such as meeting the schedules, keeping costs under control, maintaining the quality, safety, sustainability, and success of satisfying the stakeholders. Therefore, the research method used to study the topic of interest is developed with meticulous care for the purpose of comprehension of the implications of the practices of the stakeholders.

Descriptive part of this work will help in the examination of the application of SRM in the present period that can offer a better understanding of what is happening in this industry. Otherwise, the Analytical part of the work will focus on a discussion on the relationship of the management strategies with the indicators of successful construction projects. In this way, the combination of these two components will ensure that this study will go deeper than simple descriptions presented by other researches by showing how relationships between stakeholders affect the success of a construction project.

This implies that a combination research approach is adopted in order to address the multidisciplinary and behavioural aspects of handling the relationship with stakeholders. On the one hand, the quantitative approach provides numeric information on matters such as the practices, perceptions, and results of stakeholders, whose results may be analyzed using

statistics, allowing the researcher to compare the findings with the panel of participants. On the other hand, the research provides an opportunity to understand the aspects of the stakeholders' behavior, barriers of communication, conflict, power dynamics, and decision-making, which may not easily be addressed in a numeric method of research, considering that they must include the best of both worlds with the objective of ensuring the findings of the study are credible and accurate. The major study participants in this research comprise individuals who are currently working on construction projects, handling different groups of stakeholders in the field of construction. These people are good to include because they are the ones who will be involved in handling different groups of people, thus being able to give their own opinion on the issue from their own knowledge. A purposeful method of selecting the people to be involved is employed to ensure that the people chosen have adequate experience on handling their relationships with different groups of people in the construction sector. Different methods of gathering the information have been employed to make the information obtained more credible.

A structured questionnaire survey is used as the main quantitative tool. The questionnaire is designed following an extensive review of related literature in order to capture the main dimensions of SRM, including identification of stakeholders, communication effectiveness, mechanisms of engagement, practices of conflict management, participation in decision making, and satisfaction of the stakeholders. The questions use a Likert scale to make it easier to analyze the data statistically, while openended questions let respondents explain the challenges, risks, and ways to improve how stakeholders are managed.

These interviews assist in gathering information regarding challenges, how people interact without an communicate, and how they decide at the project level. existing system of coordination, governance issues, and other details which influence how stakeholders interact. These interviews assist in making the main points in consideration relevant to the research. Visiting the site and conducting an informal talk assist in learning about how stakeholders interact, how they

Secondary sources will be adopted to substantiate the results of the principal study and will help in forming a robust theory for this study. These include academic journals, books, conference proceedings, policy papers, guidelines, industry reports, and case studies concerning the management of stakeholders and the performance of construction projects. Completed project files are also analyzed for cases that highlight practical experiences with project stakeholders.

The data obtained from this questionnaire has been analyzed using statistical software such as SPSS. Descriptive statistics such as frequency, percentage, average, and standard deviation are used to summarize the information about the respondents and the responses they

gave. Under reliability checks, consistency in research tools is established. Inferential statistics involving correlation and regression analysis are used to investigate relationships between stakeholder management success and project success and also between good stakeholder management and project success in general.

An analysis of the data collected in the interviews utilizes thematic analysis. This enables the identification of major patterns, key themes, or specific issues related to communication problems, trust development, power dimension, laws, and conflict resolution discussed among the key stakeholders concerning the most important issues.

4.0 Data Analysis

To identify and analyze the existing practices on stakeholder relationship management, descriptive statistical methods such as frequency distribution and percentage analyses have been utilized. The findings of this study have established that effective communication, use of structured planning tools, review processes, and increased use of digital platforms are important factors for enhancing a high degree of stakeholder coordination to facilitate successful delivery of construction projects.

Profile of the Respondents- Job Role Analysis : The respondents were a very diversified group of professionals who were directly involved in the execution and management of construction projects. These designations included Site Engineers, Junior Engineers, Project Managers, Project Coordinators, Assistant Managers, Project Execution Engineers, Project Heads, Contract Managers, and Consultants. Having a diverse mix within the respondent group has proven to be beneficial as it would ensure that all the day-to-day activity at the site and the high-level activity involving the management of the site development would come within the realm of the research. A number of the designations are directly involved with the handling and executing of the construction projects, which would have provided extremely valuable insights.

Role Category	Number of Individuals	Proportion of Sample(%)
Site Engineering Roles	14	23
Junior-Level Engineering	8	13
Project Management	7	12
Project Coordination	6	10
Assistant Managerial Role	5	8
Project Execution	5	8
Project Leadership	4	7
Contracts Function	4	7
Consultancy	4	7
Overall Sample Size	60	100

Source: Created by authors

Interpretation: From the profile of the respondent it is clear that the questionnaire had successfully collected knowledge from professionals at various levels of execution and managing construction projects. Over a substantial number of respondents have been involved in site level execution and coordination helps to ensure that the results are to a great extent based on experiences related to site-level work, including coordination experiences. The addition of participants on the level of the 'heads' of organizations does not affect the nature of the process of projects, contract managers, and consultants with the aim of further enhancing the robustness of the analysis provided in this study. Since such degrees of responsibility necessarily imply negotiation, regulatory interaction, and high-level stakeholder interaction, it ensures that the answers provided in relation to an accurate understanding of the policy level of the approaches to SRM

Strategies Used to Build Trust and Transparency with Stakeholders: I was asked to identify the best strategies employed in the development of trust and transparency with the company's stakeholders. It was clear that frequent meetings with the company's stakeholders, accompanied by a culture of transparency, were among the most popular strategies employed. Other strategies included technology used in relation to the sharing of information, as well as the development and implementation of sound ethics in decision-making.

Strategy Adopted	No. of Respondents	Proportion (%)
Frequent, structured interaction through meetings	18	30
Open and straightforward communication practices	14	23
Digital channels used for project-related updates	12	20
Commitment to honest, empathetic, and ethical behaviour	9	15
Regular site progress communication	7	12
Grand Total	60	100

Source: Created by authors

Interpretation: From the results, it is clear that organizing meetings with stakeholders is perceived to be the most effective method of creating trust and transparency. Interactive communication helps in learning about the concerns of stakeholders and addresses any issues that may have arisen in a very early stage. In addition to that, it has been identified that transparent communication is one of the most important factors creating trust and transparency. Trustworthiness, trust, and honesty in decision-making practices have also been revealed as important constructs in the creation of trust with stakeholders, showing the importance of not only technological trustworthiness but also honest behavior in this field of building trustworthiness in the construction field in general. The-emerging findings generally show the creation of trust in construction projects as an elaborate process involving technology.

Strategies for Stakeholder Scope, Cost, and Time Expectations Management: Another focus of the research was on the strategies used to date in addressing stakeholders' scope, budget, and timeline expectations. The findings of this research indicated that communication with a scope-closure objective is one of the strategies adopted by many. Some of the strategies adopted include planning and control tools, project scheduling software, earned value measuring, key performance indicator measurement, and review sessions.

Strategy Employed	Respondent Count	Proportion (%)
Consistent communication and defined project scope	16	27
Scheduling support via tools like MSP	13	22
Planning of capable labour teams and equipment resources	11	18
Use of KPIs and earned value techniques for monitoring	10	17
Digital tools to support coordination and collaboration	6	10
Weekly review-based monitoring	4	6
Grand Total	60	100

Source: Created by authors

Interpretation: These findings point to the fact that, in managing stakeholder expectations regarding scope, cost, and time, there is a strong emphasis in these contexts on continuous communication supported by formal planning and control tools. Communication, scope definition, and clarification are reported as being employed most, firstly emphasizing that scope management begins from the early phases of projects.

The adoption of project scheduling tools such as Microsoft Project shows that there is a reliance on systematic planning for the administration of time and resources. The use of Earned Value Analysis and Key Performance Indicators further shows that there exists a performance-based approach to the administration of projects. The planning of qualified human resources and the use of machinery further shows that there exists an approach to ensuring the needs of the stakeholders with regard to productivity and improved efficiencies are met. Although there is slightly less usage of digital collaboration tools and weekly review meetings, their existence indicates that there has been a gradual shift towards more integrated forms of coordination.

5.0 Findings / Results

The results have proved that well-managed relationships among stakeholders positively impact the overall performance in projects. The execution efficiency and results in construction projects done through proper and methodical stakeholder relationship management are always better.

Those projects that were identified for their stakeholders from the outset, well-established roles and responsibilities, and regular stakeholder engagement practices were noted for fewer disputes and easier progress for various phases during the project's life cycle.

The factor that had the greatest positive impact on stakeholder relationships is communication. Activities including coordination meetings, provision of information, and reporting progress were some of the essential elements that influenced this factor.

Effective communication practices were shown to mitigate issues pertaining to project scope, cost, and schedule. Effective communication practices were thus seen to impact project success directly.

It comes to light that trust and transparency are basic to ensuring successful collaboration among stakeholders. Trust can be ensured through ethical conduct, transparency during decision-making processes, and communicating news related to the project on time.

The transparent and ethical practices in projects found support for helping in the operations of the project as well as having a conducive working environment during the period of a project.

The employment of structured planning & monitoring approaches such as project scheduling software, performance measures, and meetings further had a positive influence on controlling project time & costs.

These tools help in identifying divergence at an early stage, which enables project members to take corrective measures, thus preventing large scale setbacks in project timelines or costs. The above findings also justify the importance of digital collaboration platforms for construction purposes. Digital collaboration platforms can provide effective means of real-time communication and coordination of multiple stakeholders for a construction project.

In general, it can be said that the outcomes affirm that projects where importance was given to structured SRM practices have achieved higher levels of coordination, conflict, satisfaction, and reliability of outcomes.

6.0 Conclusion

Such factors as transparency and communication in relation to stakeholders were identified as being of most important concern in helping in the management of a project. The necessity of a planned and structured process in involving stakeholders has been noted.

The goal behind the incorporation of a project schedule system, a performance measurement tool, and reviews is to improve transparency, building upon an increased level of confidence regarding a project's management.

In general terms, it is obvious that when focus is placed on relationship development among construction project-related parties, more efficiency and satisfaction can be obtained.

It is imperative that SRM is recognized as an elemental aspect of project management and not as a supplementary process. It can be greatly beneficial when an attempt is made towards enhancing project outcomes, and this can be done simply by recognizing the incorporation of SRM. This particular study, while suffering from a limited sample size which might prevent the results from being so broadly applicable, remains an important work nonetheless. It clearly illustrates the need for the incorporation of relationship management as an essential factor for the success of construction projects. Indeed, the use of relationship management in the construction field has never been more relevant.

7.0 Recommendation

Relationship Management System: Construct a relationship management system in order to set up the formal interaction of the above elements in the construction industry. The entities should be integrated in the formal risk management and the formal project management. This means identifying the risk stakeholders in the projects.

Enhance Communication and Information Exchange Practices Mechanism to ensure effective communication and information exchange: Meetings to discuss reports and aligning them with expectations regarding scope, cost, and time of the project should be created. Uniformity should be established regarding reports.

Encourage integrity in trusting and transparent project behavior, and ensure that: Project management team's efforts should be focused towards team member ethics, transparency in the making of project decisions, and the distribution of information related to projects. All these are essential in creating trusting partnerships between the different project constituents. Project Management Institute, 2007 use digital technology for collaboration and tracking: The use of communication technology in collaborative activities like video conferencing, storing shared project documents, and project tracking should be encouraged. This is done in order to simplify collaborative activities among team members. The information is also available, and the use of collaborative communication helps in reaching the stakeholders.

Enhance planning and control-related processes: There should be periodic utilization of project management tools for schedule creation, review of critical KPIs, or review meetings. It enables tracking of projects, addressing project expectations from stakeholders, and completion of projects in a proper way.

Improve stakeholder management skills within project teams: Construction companies should provide necessary training and development programs to project managers/personnel at construction sites to enhance the communication, negotiation, and conflict resolution skills. These will help to liaise with stakeholders more efficiently and

deliver successful projects accordingly. **taskId: Added Establish formal system for stakeholder's relationship management:** There should be organized SRM systems in the construction organizations that are integrated into their project management. It involves early stakeholder identification, categorization, and planning of stakeholder engagement.

Improve communication and information dissemination: There should be proper communication channels through regular meetings and the availability of structured reports to make the stakeholders aware about the objectives, budgets, and timeframes related to the project.

Gain trust through good project ethics: The project team shall evoke a sense of trust by divulging a truthfully open decision process and sharing the information on the project with the stakeholders.

Leverage technology to facilitate collaboration as well as record-keeping: Emphasize the use of technology in collaboration, sharing, as well as tracking efforts to ensure timely coordination, as well as enhanced levels of engagement among project teams, with numerous project-related stakeholders.

Develop the skills in managing the stakeholder relationship in the project team: Organizational bodies have to invest in the proper training of the project managers in the skills required to effectively manage the relationship in the site teams.

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CHAPTER 32

Strategies for Enhancing Productivity in Industrial Infrastructure Projects

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ABSTRACT

Industrial infrastructure projects are vital to economic growth, yet they continue to face persistent productivity challenges such as delays, cost overruns, and inefficiencies. This study aims to identify, analyse, and recommend effective strategies to enhance productivity within these large-scale, capital-intensive projects. By drawing on global research, a systematic literature review was conducted followed by reinforcing the collection of primary data through a questionnaire targeting engineers, contractors and project managers. The productivity of the industrial infrastructure projects can be studied using five sub-systems, namely, planning subsystem; engineering subsystem; industrial development, land use, and infrastructure sub-system; mining, robotics and industrial automation subsystem; and digital transformation, artificial intelligence (AI) and computational subsystem. The analysis highlights that integrated approaches involving digital transformation, artificial intelligence, and computational subsystem along with up-to-date engineering subsystem significantly improve the overall productivity of the industrial infrastructure projects.

Keywords: Industrial infrastructure, Strategic Management, Productivity, Standardized Processes, Digital Technology.

1.0 Introduction

Power plants, petrochemical plants, water & wastewater treatment facilities, industrial parks, logistics hubs, and other industrial infrastructure projects play a vital role in supporting national competitiveness and promoting long-term economic growth by creating manufacturing capacity, providing energy security and unlocking trade-potential. However, their delivery performance is always weak, reflected through systematic schedule slippage, quality fault and rework, leading to high costs and time overruns (Jarkas et al., 2015; Serdar and Ismail, 2016; Dixit, 2019).

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This problem is further exacerbated in emerging economies where structural issues, such as labour and skills shortages, unbalanced contracting activities, and lack of coordination among stakeholders make projects complex.

Therefore, related schedules increase the risk of rework, leading to disruptions and claims, further reducing on-site productivity in a vicious cycle. As a result, the productivity of industrial infrastructure projects is chronically low and heterogeneous across regions, inhibiting organisation's ability to standardise results or even best practices (Baráth and Fertő, 2020). At the same time, Industry 4.0 technologies such as automation, digital twins, Building Information Modelling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI), boast transformational planning, coordination, quality control, and risks management outcomes (Angulo et al., 2017; Saneet et al., 2017; Santos Fonseca et al., 2025). BIM helps coordinate designs and reduce errors, but IoT, robotics, and AI can be used to schedule all processes in real time, guarantee quality, monitor safety, and optimize lifecycle. However, its implementation has been uneven because of the complexities of integration, standardisation, lack of skills, and organisational resistance, leaving much of its potential untapped.

There is a lack of empirical studies including systematic literature synthesis and practical data, especially in the context of an emerging economy like India, which has a massive infrastructure agenda at its core. The current mixed-methods research fills these gaps with statistical study on improving productivity analysed through literature review and survey-based hypotheses testing with data of practitioners. It has three goals: (i) to identify the key determinants that influence productivity in industrial infrastructure projects; (ii) to examine the strategies that are currently implemented to enhance productivity in industrial infrastructure projects; (iii) to analyse how the major subsystems of industrial infrastructure projects individually and jointly shape perceived productivity outcomes; and (iv) to evaluate the extent to which the identified strategies, when implemented within the various subsystems, contribute to improvements in performance indicators of industrial infrastructure projects. The research questions addressed in this study are the following: (RQ1) What are the key determinants that influence productivity in industrial infrastructure projects? (RQ2) Which strategies are currently implemented to enhance productivity in industrial infrastructure projects? (RQ3) How do the major subsystems of industrial infrastructure projects individually and jointly affect perceived productivity outcomes? (RQ4) To what extent do these strategies, as implemented within the various subsystems, contribute to improvements in performance indicators of industrial infrastructure projects?

2.0 Literature Review

The productivity of industrial infrastructure is multidimensional in nature. Inputs such as labour, equipment, materials, energy, and capital are converted into outputs such as

installed capacity, manufactured/built volume, throughput or delivered services. In this regard, conventional measurements focus on calculations involving partial productivity comprising labour productivity (LP) and equipment productivity (Baráth and Fertő, 2020). Despite their simplicity – being easy to calculate yet being intuitively non-measurable when other inputs change – such metrics can be deceptive; it may appear that LP is increasing, and indeed it is, but this increase may be due to greater mechanization, not efficiency.

The most common techniques used to track cost and schedule performance against baseline standards are project-level indicators based on Earned Value Management (EVM). These indicators are dynamic and operationally useful but are sensitive to the quality of baseline standards and cannot be easily compared across projects and geographies. A more holistic approach to measuring system efficiency, total factor productivity (TFP), which is the ratio of output relative to a weighted average of labour, capital, materials, and sometimes energy. A better measure of system efficiency may be TFP, however, TFP requires high-quality and long-term data and assumptions about production functions. TFP experiments conducted on agriculture and high-voltage infrastructure show that it can be used as a benchmarking tool; however, TFP is rarely used in industrial construction (Baráth and Fertő, 2020; Wang et al., 2024; Lecina et al., 2011).

2.1 Global and geographical evidence

The anchor collection of literature on productivity in industrial infrastructure projects covers labour capacity maturity in irrigation systems (Abdi-Dehkordi et al., 2021; Laghari et al., 2012; Lecina et al., 2011), water resources management (Abdi-Dehkordi et al., 2021; Laghari et al., 2012; Lecina et al., 2011), sustainability models (Abdi-Dehkordi et al., 2021; Zhou et al., 2013), labour productivity (Jarkas et al., 2015; Serdar and Ismail, 2016; Dixit, 2019; Wang et al., 2024; Laitinen et al., 2022), digital tools (Sanee et al., 2017), and infrastructure (Duran-Fernandez, 2014; Santos Fonseca et al., 2025) in countries such as the United States (Duran-Fernandez, 2014), China (Wang et al., 2024), India (Dixit, 2019), Oman (Jarkas et al., 2015), and Malaysia (Serdar and Ismail, 2016).

This literature on productivity in industrial infrastructure projects spans the globe. Multi-country research provides contextual knowledge of water systems and agricultural productivity, while country-specific research studies the determinants of labour productivity in Oman (Jarkas et al., 2015), on-site productivity in Malaysian infrastructure (Serdar and Ismail, 2016), management practices in Indian building projects (Dixit, 2019), and ultra-high voltage construction in China (Wang et al., 2024). However, coverage is quite uneven in other parts of the world, particularly in parts of Africa and South America. Methodologically, case-study designs predominate, and there are relatively few large-sample or longitudinal studies, limiting the ability to establish cause-and-effect relationships.

Motivated by Prakash et al. (2017) and Prasad et al. (2015), this study has focussed on generating several subsystem-level themes. The Planning Subsystem based studies focus on scheduling, allocating resources and project management strategy as an important instrument of productivity like advanced work packaging, integrated project delivery and strong risk management (Angulo et al., 2017; Santos Fonseca et al., 2025; Laitinen et al., 2022). The Engineering Subsystem studies focus on engineering and emphasises design quality, constructability, modular construction, and prefabricated construction to minimize rework and downtime and enhance safety (Forsythe, 2018; Serdar and Ismail, 2016; Jarkas et al., 2015; Dixit, 2019). The Industrial Development, Land Use, and Infrastructure Subsystem are connected to the sustainability of utility availability (power, water, telecom) to support smooth execution (Abdi-Dehkordi et al., 2021; Zhou et al., 2013; Laghari et al., 2012). The Mining, Robotics and Industrial Automation Subsystem connected to the sustainability of automation (robotics, drone, automated machinery, etc. to improve productivity in the operations (Li and Liu, 2019; Xiao et al., 2022). Finally, the subsystem connected to digital transformation, AI and computational models are automated systems in sustaining uninterrupted productivity (Angulo et al., 2017; Sanee et al., 2017; Santos Fonseca et al., 2025; Laitinen et al., 2022).

2.2 Gaps, contradictions, and conceptual framing

The literature shows there are serious gaps that inspire the current research. To begin with, the subsystem fragmentation is omnipresent: hardly any, even no, studies conceptualize planning, engineering, labour, compliance, sustainability and digital tools under the umbrella of one comprehensive framework and, thus, offer partial accounts and low transferability. Second, the research on digital integration is generally dedicated to the study of individual tools e.g. BIM or IoT; the interactions between several technologies and the enduring effect of them are hardly evaluated within the framework of the quasi-experimental or longitudinal studies. Third, human and organizational variables such as leadership, communication, workforce capacity and knowledge sharing are not adequately represented in contrast to technological and material variables yet they are supported by practitioner evidence that organizational factors are frequently the causes of rework and delays (Saeed et al., 2023; Laitinen et al., 2022).

To this, the underlying thesis suggests a conceptual framework according to which productivity is an outcome of interacting subsystems, attenuated by the context of a project and quantified by a combination of partial metrics and project metrics. The subsystems of planning, engineering, industrial development and infrastructure, sustainability and digital transformation are addressed with practices and tools shaping the time, cost, quality, safety, and sustainability performance.

3.0 Research Methodology

The paper takes mixed-methods focus and integrates both a systematic literature review and empirical survey research to answer both the question of what and how to such productivity strategies in industrial infrastructures projects. The literature review summarized above is based on databases such as Scopus, Google Scholar, Wiley Online Library, ResearchGate, and others, using inclusion criteria related to aspects such as time frame (2011–2025), focus on productivity and system performance, full-text availability, and English language.

The structured questionnaire used as the primary means of data collection is based on the conceptual framework and gaps defined in the identified subsystems. The instrument is divided into four major sections:

1. Demographics of the respondents (position, experience, and age bracket and gender).
2. Characteristics of the project (infrastructure of the type, scale of the project, average project length)
3. Possible perceived effectiveness and use of planning, engineering, and associated subsystems based on Likert-scale items, and
4. Implementation and perceived effectiveness of particular strategies of productivity including the use of process standardization, vendor performance systems, introduction of digital tools, capacity building, lean construction, and predictive analytics.

A snowball and purposive sampling method had been applied in order to focus on practitioners with active roles in the infrastructure planning and implementation, which also encompassed engineers, project managers and contractors.

The survey had 85 valid responses giving a diversified but non-probabilistic sample that cuts across the different project types, including transportation, water and wastewater, urban development, industrial projects, and the IT and communication infrastructure. The scale of the projects was below 100 crores to the value that was more than 1000 crore, with average project life of less than a year to over five years.

Analysis of the data was done in three steps:

- To start with, descriptive statistics were used to describe the distribution of demographic and project characteristics.
- Second, cross-tabulations and chi-square methods were used to determine the relation between variables including gender and average time of a project, age bracket and years of experience, age bracket and project, age bracket and project scale, project scale and project duration, project type and project duration.
- Third, the multi-regression models were estimated and key sub systems were taken namely planning, engineering and industrial development where the dependent variable

would be the overall subsystem application or effectiveness and the predictors would be specific practices (e.g., minimal delays, resource utilisation, risk management, safety enhancement, innovative methods, re-work reduction).

The methodologies used include the use of self-reporting perceptions, non-probability sampling, and a sample size that, as large as it is in terms of exploratory regression, might not be sufficient to represent the entire heterogeneity of the infrastructure sector in India. However, the integrative design provides a systematic and empirically based perspective on the productivity strategies that can be used to complement the literature which is predominantly qualitative and case-based.

4.0 Findings

Table 1 shows that stakeholder coordination within planning subsystem is the only statistically strong determinant, while routine planning questions on delays, resource use, and generic risk management do not yet show a clear effect at the sites of industrial infrastructure projects. The regression suggests that, among the planning-related determinants measured, stakeholder coordination is emerging as a primary planning determinant of perceived productivity, while delay-control and resource-efficiency items are weaker or salient (RQ1).

Table 1: Planning Subsystem ^a

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	1.54	0.57		2.71	0.01
How effective are project planning practices in minimizing delays?	-0.07	0.08	-0.10	-0.95	0.35
To what extent does planning ensure efficient resource utilization?	0.03	0.07	0.04	0.35	0.73
How well does planning incorporate risk management to improve productivity?	0.21	0.15	0.17	1.41	0.16
How effective is planning in coordinating multiple stakeholders?	0.39	0.14	0.33	2.76	0.01

^a *Dependent Variable: Rate the overall application of the Planning Subsystem at your site.*

Source: Created by authors

Forward-looking, this implies that strategies which explicitly strengthen multi-stakeholder coordination (e.g., integrated planning workshops, collaborative platforms, formal stakeholder engagement processes) are more likely to shift how practitioners rate planning performance than incremental tweaks to conventional scheduling or

resource-allocation alone (RQ2). Within the Planning Subsystem, the evidence supports a subsystem narrative where coordination capability is the main active lever (RQ3). Going forward, the Planning Subsystem should act as a mediator between planning-coordination practices and project-level performance indicators (for example, time, cost, quality, safety, sustainability) to report better KPI outcomes (RQ4).

Table 2 shows that safety-oriented related engineering practices are the dominant determinant of perceived productivity, while design timeliness, rework reduction, and innovation do not yet emerge as statistically strong levers in the sample. The results suggest that, within engineering, safety and downtime control are the primary perceived determinants of subsystem performance and, by extension, of productivity, whereas design speed, error reduction, and visible innovation are currently secondary in practitioners' perceptions (RQ1). Despite widespread rhetoric on modularization and advanced methods, the findings justify foregrounding strategies that explicitly strengthen engineering-led safety and reliability (e.g., safer constructible design details, maintenance-friendly layouts, engineered temporary works that minimize stoppages, robust equipment planning) as core productivity strategies, rather than treating safety as merely a compliance add-on (RQ2). In the cross-subsystem narrative, Planning appears to be driven mainly by stakeholder coordination, while Engineering is driven mainly by safety/downtime performance (RQ3). Practically, this means future KPI analysis should include safety frequency/severity and downtime metrics alongside traditional time–cost–quality to capture the full impact of engineering-subsystem strategies (RQ4).

Table 2: Engineering Sub System ^b

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	1.44	0.43		3.39	0.00
How effectively does engineering design contribute to timely project delivery?	0.04	0.08	0.06	0.54	0.59
To what extent do engineering solutions (technical methods, tools, and practices) reduce rework and errors?	0.04	0.07	0.06	0.57	0.57
How well does engineering integrate innovative methods (prefabrication, modular design, etc.)?	0.02	0.09	0.02	0.25	0.80
How effective is engineering in improving safety and reducing downtime?	0.53	0.10	0.54	5.23	0.00

^b *Dependent Variable: Rate the overall application of engineering practices on your site.*

Source: Created by authors

Table 3 suggests that reliable utilities are the central industrial-development determinant of perceived productivity, while logistics support is emerging but not yet

statistically firm, and land-use and connectivity are currently weak levers in the data. The results indicate that site-level utility reliability (continuous power, water, and telecom) is a key determinant of perceived productivity potential (RQ1). Looking ahead, strategies actually shaping perceptions in this subsystem are those that secure robust utilities on site (e.g., redundant power arrangements, reliable water supply, telecom/data resilience) (RQ2). In the cross-subsystem narrative, this table supports for physical-enabling environment as the most influential capability (RQ3). Therefore, tracking utility uptime as explicit KPI, and integrating utility-resilience decisions into early project planning, should be central to productivity-oriented industrial-infrastructure strategies (RQ4).

Table 3: Industrial Development, Land Use, and Infrastructure Sub-System ^c

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	1.19	0.51		2.33	0.02
How adequately does infrastructure support project logistics and productivity?	0.19	0.11	0.21	1.85	0.07
To what extent does land-use planning enable efficient site utilization?	0.00	0.09	0.00	-0.04	0.97
How effective are transportation and connectivity facilities in reducing delays?	0.13	0.13	0.12	1.00	0.32
How well does utility availability (power, water, telecom) support smooth execution?	0.39	0.12	0.36	3.34	0.00

^c *Dependent Variable: Rate the overall application of Industrial Development, Land Use, and Infrastructure at your site.*

Source: Created by authors

Table 4 shows that automation use and the reliability of automated systems are the main determinants of perceived productivity for the mining, robotics and industrial automation subsystem, while robotics-for-error-reduction and automation-for-safety are not yet driving perceptions in the sample. That is, within this subsystem, the key perceived determinants are (a) the extent to which automation is actually deployed in operations and (b) the reliability of those automated systems over time (RQ1). The significant coefficients suggest that current, impactful strategies are those that scale up automation use in core tasks (robots, drones, automated machinery on site) and invest in maintenance, redundancy, and robustness so that these systems do not fail frequently (RQ2). This table supports the view that the automation-intensity and reliability engine contribute to productivity outcomes for the mining, robotics and industrial automation subsystem (RQ3). Therefore, projects with

higher scores on “automation improves productivity” and “automated systems are reliable” will show better throughput, labour productivity, and schedule adherence KPIs, especially in repetitive or hazardous tasks (RQ4).

Table 4: Mining, Robotics and Industrial Automation Sub-System ^d

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0.76	0.63		1.20	0.24
To what extent does automation (robotics, drone, automated machinery, etc.) improve productivity in your operations?	0.33	0.15	0.31	2.29	0.03
How effectively are robotics used to reduce manual errors and increase efficiency?	-0.01	0.18	-0.01	-0.06	0.95
How reliable are automated systems in sustaining uninterrupted productivity?	0.40	0.20	0.26	2.06	0.04
How effectively does automation enhance safety and reduce downtime losses?	-0.01	0.20	-0.01	-0.07	0.94

^d*Dependent Variable: Rate the overall application of Mining, Robotics, and Industrial Automation at your site.*

Source: Created by authors

Table 5 indicates that AI-driven scheduling and resource optimization is the primary determinant of perceived productivity of the digital transformation, AI and computational models. Within this subsystem, the key determinant is the extent to which AI and analytics are actually used to optimize schedules and resource allocation, not digitalization in general (RQ1).

Table 5: Digital Transformation, AI and Computational Models^e

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0.31	0.51		0.61	0.55
How effectively does digitalization (AI, IoT, big data) enhance decision-making in projects?	0.20	0.14	0.18	1.47	0.15
To what extent do computational models improve productivity forecasting?	-0.06	0.16	-0.05	-0.38	0.71
How well do digital tools improve coordination and communication across teams?	0.24	0.16	0.17	1.48	0.14
How effectively do AI and analytics optimize scheduling and resource allocation?	0.48	0.13	0.43	3.73	0.00

^e*Dependent Variable: Rate the overall application of Digital Transformation, AI, and Computational Models at your site.*

Source: Created by authors

The evidence suggests that the strategies currently making a difference are those that embed AI in core planning workflows (AI schedulers, predictive resource planning, analytics-driven look-ahead planning), rather than standalone dashboards or experimental computational models (RQ2). This supports that the intelligence layer that sharpens planning and resource deployment (RQ3). Therefore, AI and analytics optimize scheduling and resource allocation will associate with better time and cost performance, fewer delays, and smoother resource utilization, in line with practice evidence that AI scheduling reduces overruns and improves predictability (RQ4).

Table 6 shows that engineering and digital transformation emerge as the two dominant subsystems of overall perceived productivity influence, while automation is emerging but weaker, and planning plus industrial development are not yet significant once the others are controlled for. The key system-level determinants of perceived productivity influence are up-to-date engineering practices and digital/AI capabilities, with automation following behind them (RQ1). Data suggest that strategies currently “moving the needle” for productivity are those that modernize and professionalize engineering practices (engineering for safety, reduced downtime, constructability, etc.), and embed digital and AI tools into scheduling, resource allocation, and project management, with automation strategies adding some value, but less decisively at present (RQ2).

Table 6: Overall System ^f

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-0.08	0.43		-0.19	0.85
Rate the overall application of Digital Transformation, AI, and Computational Models at your site.	0.34	0.08	0.40	4.42	0.00
Rate the overall application of Mining, Robotics, and Industrial Automation at your site.	0.15	0.08	0.18	1.86	0.07
Rate the overall application of Industrial Development, Land Use, and Infrastructure at your site.	0.08	0.11	0.07	0.69	0.49
Rate the overall application of engineering up-to-date practices on your site.	0.57	0.12	0.44	4.65	0.00
Rate the overall application of the planning subsystem at your site.	-0.09	0.11	-0.08	-0.82	0.41

^f*Dependent Variable: Overall, how would you rate the influence of various subsystems on enhancing productivity in industrial infrastructure projects?*

Source: Created by authors

With Tables 1–5, on overall-basis the model supports a differentiated subsystem narrative: planning requires stakeholder coordination, engineering requires to focus on

safety/downtime control, industrial development requires to focus on reliable utilities, automation should focus on extent and reliability of automation, and digital should focus on AI-enabled scheduling and resource optimization; but only engineering and digital subsystems currently have strong, system-wide influence on perceived productivity when all are entered in one model (RQ3). For impact on performance, engineering and digital-transformation should be treated as primary predictors; automation can be treated as a secondary/mediating predictor; and planning and industrial development can be treated as enabling/contextual subsystems whose effects may be indirect (RQ4).

5.0 Conclusion and Implications

This study has explored research methods that seek to study productivity in the industrial infrastructure projects through systematic literature and the survey-based hypothesis testing with 85 practitioners. The literature reviews summarised international evidence in terms of massive coverage of the planning and engineering subsystems, the emergent but disparate evidence of virtual transformation, and instances of pertinent gaps related to human and organisational issues.

This empirical research ensured that engineering and digital-transformation practices are primary predictors of perceived productivity in the industrial infrastructure projects followed by automation, planning and industrial development. Theoretically, the results support a subsystem integration viewpoint of the productivity with the interaction of different subsystems to influence the results of temporal, cost, quality, safety, and sustainability.

Practically, the study suggests that organisational planning of high quality should be based subsystems thinking. Its implications at the policy level are crucial for implementing standardized KPI frameworks, facilitating information sharing and benchmarking, and capacity-building efforts to digitally enable the workforce to drive mission-based projects.

Study limitations include non-probability sampling, use of self-reported perceptions and consideration of perceived instead of actively measured productivity measures. This study can be furthered by future research using longitudinal designs, greater substantive and more heterogeneous sample sizes as well as more comprehensive factors that combine human and organisational variables, including technical and digital ones.

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CHAPTER 33

Project Cost Management for Redevelopment Projects

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ABSTRACT

The Real estate sector in Maharashtra, India is witnessing a dynamic shift where redevelopment is emerging as a major contributor to urban transformation. Rapid urbanization, aging infrastructure, the need for optimized land use and the potential for high returns, have ensured redevelopment as an essential component of sustainable city growth. One of the consistent challenges in redevelopment projects is Cost overruns which affects profitability, timelines, and stakeholder satisfaction. This highlights the importance of effective Project Cost Management to understand the complexities such as regulatory issues, stakeholder coordination, and financial viability. This research explores the critical aspects of project cost management for redevelopment projects focusing on identifying project phase wise major cost drivers, analyzing industry pain points and formulating cost optimization strategies to enhance project efficiency. Through an extensive literature review and semi-structured interviews with industry experts, the research examines challenges at various project phases leading to cost overruns and/or delays. The findings of this study will help the stakeholders associated with real estate redevelopment projects.

Keywords: Real Estate; Redevelopment; Project Cost Management; Cost drivers.

1.0 Introduction

Urban redevelopment has been more important with land scarcity, complex regulations and soaring prices especially in overpopulated locations. The necessity of cost management in construction projects has arisen as a result of demand seen in redevelopment projects over the last few years. The analysis of cost management in redevelopment projects is topical with an aim to solve the key pain points in the industry and how they can be addressed.

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Effective cost control can be used to ensure that the project meets the expectations and objectives of the stakeholders resulting in the desired output. The paper is also a thorough analysis of cost optimization that combines theory and practice.

This research has the following objectives:

- To identify key cost drivers in redevelopment projects
- To study best practices in redevelopment cost management and
- To analyze challenges affecting redevelopment project cost

2.0 Literature Review

This literature review intends to review the current practices, issues as well as research gaps in terms of cost control in redevelopment projects. It is more focused on the studies of previous redevelopment projects, and it concentrates mostly on cost estimation tools and the life cycle costing. The literature is discussed based on three primary themes: key cost driver, best practices in cost control, and implementation challenges.

Ramsinghani (2024) notes that redevelopment is one of the strategies aimed at responding to the problem of land shortage in the city, specifically in Mumbai, due to the lack of vacuum land, as well as the deteriorating infrastructure. The article observes that redevelopment improves the quality of living and empowers the developers to realize the value of a land by the best utilization of FSI. It further singles out cluster redevelopment, public-private, and sustainable design as significant driving elements with resident approvals, complex clearance, and premiums as significant issues that impact on time and cost.

Vanvari et al. (2018) look at the most prominent risks and issues related to the redevelopment of old housing societies in Mumbai. Based on surveys and interviews with key stakeholders, the research observes that even though redevelopment has a lot of advantages, the projects have challenges of documentation gaps, legal uncertainty, lack of agreement among members, slow pace in fulfilling the regulatory requirements, and market fluctuations. Early feasibility studies, high levels of legal and technical due diligence, open communications and good coordination of stakeholders are emphasized in the paper.

Ashar et al. (2018) emphasize, developers have challenges with the redevelopment of housing, which is necessary because of the lack of urban land and the aging of buildings. The research results that redevelopment is risky and long-term with significant delays occurring as a result of approvals by the residents, regulatory clearances, political and legal challenges, or financial constraints. The analysis of the ANOVA results demonstrates that these challenges differ in different places which influence the viability of projects.

Bijwar et al. (2017) discuss the delays in redevelopment projects and point out financial limitations, approval delays, inaccuracy in communication, and legal barriers as the

primary reasons of such delays. Based on stakeholder surveys and RII analysis, the study identifies intricacies connected to the tenant relocation and coordination, and emphasizes the necessity of simplified approvals, enhanced risk management, and enhanced inter-agency coordination to decrease delays.

Contractor (2019) analyses the emergence of hidden costs on in-situ redevelopment of slums in Mumbai, which includes corruption, delays, and poor quality of construction. According to the study, those financial risks are increased by bribes and unofficial expenses and high-interest loans and black money. It suggests more active state intervention, proper regulation, and investments to provide high quality of housing and equal results.

Chavan et al. (2022) review the concept of self-redevelopment as an alternative to project redevelopment by developers in Mumbai. The research has identified advantages like increased transparency, control, and economic profits to the societies with some minor challenges like the hurdle of regulations and speculative development. The fact that institutions such as MHADA and MDCC Bank are supportive of self-redevelopment makes it a feasible and participatory model of housing.

Chen et al. (2016) underline that risks are beneficial to be under control at every stage of the project: design, bidding, construction and completion in order to underpin costs. The paper uses a case study of project B to identify stage wise cost risks, assess them and propose relevant risk responses. Korke et al. (2017) emphasize that the key to cost control begins at the design phase and would require ongoing coordination between the stakeholders. The paper cites inaccurate estimates, material shortages and poor data management as a few of the factors that are considered to be a challenge and suggests budgeting, value engineering, standard costing and unit cost tracking as some of the tools that can be used in ensuring cost efficiency. Kulkarni et al. (2024) discuss cost overruns in residential buildings sector in India with upsurge of 25-40 percent measured by inappropriate planning, budget miscalculation, poor site analysis, and mismanagement. The research focuses on risk evaluation, cost monitoring, and value engineering underpinned with case studies at Surat and Greater Noida with cost savings. It draws conclusions that early value management and engagement of stakeholders minimize delays and overruns.

Albtoush et al. (2020) state that cost management is influenced by several factors throughout the life cycle of the construction project due to the fact that 41 studies on the topic were reviewed by the authors. The paper identifies issues of changed design, bad site management, late payments, fluctuation of prices, vague scope, and ineffective planning. It highlights effective cost estimation, effective leadership, organization coordination, and solutions such as cash flow forecast as it concludes that cost overruns are spurred by technical and organizational inefficiencies around the world. Gao (2009) highlights the real estate construction costs include land (30%), construction and installation (20-50%), equipment and

machinery (1-3%), and other expenses (>15%). The paper further indicates that despite the fact management expenses are approximately 1 percent, it is still a considerable sum that can easily run out of control otherwise.

Zimmermann et al. (2019) emphasize the need to have correct initial costs estimate to aid feasibility and design decisions. The study introduces a model based on data of previous projects that predicts the building costs in the first stage of the development to form a better picture of investment and lifecycle costs and increase cost predictability.

Doloi (2010) suggests that traditional cost estimation systems which include top-down and analogy-based cost estimation systems are not suitable in complex new-day projects and also contribute to cost-overflow. The paper puts emphasis on the fact that stakeholders impact the cost estimation process unnoticed and proposes holistic and flexible approaches such as Soft Systems Methodology (SSM) that would include technical, political, and behavioral factors in order to make results more accurate. Hollingshead et al. (2002) focus on redevelopment and urban regeneration and relate it to sustainability and value value creation over time. The proposal suggests an integrated model of site planning, which integrates risk management, optimal land use, financial planning, marketing, and navigation in the regulation process to align the stakeholders, minimize risks and costs, determine market specifications, and redevelop efficiently and affordably and in a timely manner.

2.1 Research gaps and opportunities

The available research on redevelopment projects and cost management is both shallow and restricted. The current literature concentrates on generic cost and time overruns, neglecting specific issues of redevelopment projects. In addition, phase wise cost management structures are not found. The subsequent list identifies the major gaps that are currently observed in the literature, and which were addressed in this study:

1. The available literature of redevelopment projects in different resources has low concentration on certain redevelopment projects and a relatively high lack of a proper structure of cost management.
2. Various research works on redevelopment projects have recognized the difficulties encountered throughout the different stages of the project. Nonetheless, it is unclear as to how to define the key cost drivers at each project life cycle phase.
3. Whereas other studies highlight cost and time overruns in projects, there is lack of strategic approach to reduce overrun of these issues through seeking cost drivers. Additionally, there is a lack of a phase progressive cost management model which is complex in nature and suited to the need for redevelopment projects.
4. Lack of cost delay impact models quantifies the effects of particular delays on the overall redevelopment cost.

5. No analytic cost framework or checklist exists to help developers to make a cost of informal expense.
6. Insufficient attention is given to the unforeseeable regulatory, distinct issues, like TDR purchase, stakeholder issues and compensations, rent reimbursement, and land related issues, which are prevalent in redevelopment.
7. Some papers have recognized the complexity of stakeholders and have not presented financial alignment framework to balance the various expectations and budget inflation.
8. Approval, NOCs and premium cost which is one of the key elements in the total cost of the project, this is the favored reason in delays and overruns but is hardly ever formally built into projections or contingency buffers.

The identified gaps are an opportunity to develop further frameworks of effective cost management of redevelopment projects with the focus on phase-wise key cost drivers.

3.0 Methodology

3.1 Literature review

A comprehensive study of existing academic and commercial sources on cost management systems within the redevelopment sector was conducted as part of literature review. The study also provided an examination of challenges that usually encounter redevelopment projects such as shortage of resources, conflict of interests by stakeholders and regulatory restrictions. It also compared different cost management practices practiced in real estate industry.

3.2 Semi structured interviews

For this research, semi-structured interviews were carried out as a qualitative technique to understand the perspectives of industry experts. Discussion with professionals in the industry was done using a set of pre-defined questionnaires. The strategy produces personalized information, thus enabling in depth comprehension and varying viewpoint of professionals. This also supports the general analysis and interpretation of the findings of study. The respondents were selected from a comprehensive list and ensured a thorough understanding of cost management practices in redevelopment projects. The wide business experiences of respondents offered both strategic and execution points of view.

The majority of the respondents were engaged in large-scale redevelopment projects with the value of the project being in an average of 70 crore to 300 crore. The respondents worked on a considerable broad range of projects, which included housing society redevelopment, slum rehabilitation projects, cluster redevelopment projects, cessed building redevelopment projects, commercial and industrial renovation projects. Amongst them, the

residential redevelopment was projected as the most commonly registered category, especially in the metropolitan cities like Mumbai.

3.3 Profile of respondents

The respondent profile is given in Table 1, even though we had reached out to very large numbers of respondents to join our study, we received limited yet detailed responses. This was due to lack of availability of time with few respondents and in some cases, the respondents were hesitant to share the data. Though the respondents were few in number, the findings were beneficial as indicated in the subsequent sections.

Table 1: Profile of Respondents

Respondent	Designation	Experience	Nature of Projects
1	Founder – Consultancy	42 years	Commercial, factory & office redevelopment
2	Developer	15+ years	Slum, cluster & housing redevelopment
3	Cost & Project Management Professional	10+ years	Residential society redevelopment
4	Founder – Own Firm	20+ years	Residential society redevelopment
5	Project Management Consultant	5+ years	Residential & mixed-use

Source: Author's own work

4.0 Analysis and Interpretation

The section presents the analysis and interpretation of primary data through in-depth interviews with industry professionals with extensive experience in redevelopment project management. The aim was to learn about the practical implementation of cost management, the major cost drivers, and discuss the challenges in different phases of redevelopment initiatives. Since this research was an exploratory study and there are very few structured data on this field, a qualitative research direction was taken.

The information obtained on the insights of industry experts was used to fill the gap between a theoretical cost management framework and past redevelopment practices as well as make a comparison with the traditional Greenfield development. Those responses pointed to the fact that redevelopment undertakings are capital intensive and exposed to much more financial risk than Greenfield undertaking. These projects are highly sensitive to cost overruns due to factors like uncertainty in regulations, stakeholder engagement and unpredictability of site conditions. Cost management of the redevelopment projects is not a one-time activity compared to the development Greenfield development. Conventional

methods which take a definite estimation and linear implementation are mostly insufficient. The redevelopment projects must have constant cost monitoring, adaptive planning and close coordination among various stakeholders in the entire project lifecycle. Overall, the results point at the fact that the proactive, risk-driven, phase-based approach to cost management of the redevelopment projects need to focus on early identification of the possible cost drivers and timely decision-making is significant in predetermining cost increase and project feasibility.

4.1 Cost management workflow in redevelopment projects

The cost management workflow in redevelopment projects is summarized in Table 2. This workflow reflects how cost management evolves across different stages of redevelopment.

Table 2: Cost Management Workflow

Phases	Project Stage	Cost Management Activities
Phase I	Pre-development	Site surveys, structural audits, regulatory review, feasibility study and preliminary cost estimation
Phase II	Planning	BOQ preparation, cost baseline establishment, risk and contingency planning, Vendor prequalification
Phase III	Procurement	Contract Negotiations, Budget Allocation & Approval, Resource Planning, tendering,
Phase IV	Execution & Monitoring	Cost & progress tracking, variation order management, cash flow & Earned Value Analysis
Phase V	Closure	Final accounts, cost-benefit analysis, lessons learned

Source: Author's own work

4.2 Stage-wise challenges and budget impact

As indicated in Table 3, the execution phase was found to be the most cost sensitive phase of redevelopment projects. This is mainly because it depends on many factors such as labour availability, contractor efficiency, approval processes and day-to-day decisions taken on site.

Respondents reported that delays in any of these areas often increase overall project costs and are unique to every project. The findings also show that when project deadlines are extended, costs increase significantly. Therefore, careful planning, regular monitoring of progress and timely coordination among all stakeholders is crucial during the execution phase to control cost overrun.

Table 3: Stage-wise Challenges

Project Stage	Major Challenges	Budget Impact (%)
Concept stage	Incomplete site data, unclear regulations, stakeholder misalignment	5–15%
Planning stage	Hidden defects, utility relocation, environmental issues	15–25%
Execution stage	Relocation delays, unforeseen site conditions, supply chain issues	20–30%
Finishing stage	Compliance gaps, rework, scope creep	10–15%

Source: Author's own work

4.3 Major cost drivers in redevelopment projects

Table 4 highlights the major cost drivers and its impact in Redevelopment projects

Table 4: Major Cost Drivers and its Impact

Cost Driver	Nature of Impact
Demolition & debris disposal	High initial cost and environmental compliance
Rehabilitation & rent compensation	Continuous expense until project completion
Regulatory premiums & approvals	Significant indirect cost
Logistics & access constraints	Increased execution cost
Financing & carrying cost	Escalates with project delays
Extended project duration	Time-related cost overruns

Source: Author's Own work

Unlike Greenfield projects, where most of the costs are related to construction work, redevelopment projects involve many additional and indirect expenses. Such costs are difficult to estimate in advance as they largely depend on approval timelines, stakeholder co-operation and project conditions. This makes risk-based cost planning essential for controlling overall expenditure.

4.4 Redevelopment vs Greenfield projects: Cost perspective

Table 5 provides a comparative cost perspective between redevelopment and greenfield projects. Redevelopment projects are associated with higher uncertainty due to existing site conditions, approval complexities, and multiple stakeholder involvement, which increases risk of cost and schedule overruns. Therefore, higher contingency provisions and strong cost management practices are essential at the planning stage. On the other hand, Greenfield initiatives are more predictable in terms of scope, budget and schedule, which

makes control and estimate easier. Because of these variations, different cost planning strategies are needed and customized cost management frameworks are needed to handle the particular risk profiles of every kind of project

Table 5: Parameters for Redevelopment & Greenfield Projects

Parameter	Redevelopment Projects	Greenfield Projects
Cost predictability	Moderate	High
Risk exposure	High	Moderate
Stakeholders	Multiple (tenants, societies, authorities)	Limited
Timeline	Longer & uncertain	Predictable
Contingency provision	15–25%	5–10%

Source: Author's own work

4.5 Cost related risks and compliance impact

Table 6 shows the main risks associated with compliance in development projects and how they affect the cost of the project. Due to delays and stakeholder miscommunication, legal and consent related issues such as tenant rules, society approvals, and compensation requirements significantly increase cost.

Table 6: Cost Impact

Compliance Area	Redevelopment Projects	Cost Impact
Legal & consent	Society consent, tenant laws	High
Environmental	Demolition & hazardous material audits	Moderate–High
Planning norms	Premium FSI, TDR, reservations	High
Rehabilitation	Transit accommodation & compensation	High

Source: Author's own work

Projects costs are further increased by regulatory approvals, demolition procedures and environmental clearances. Higher indirect expenses are also a result of cost drivers such premium FSI, TDR, Land reservations and rehabilitation commitments, including transit housing, especially when delays happen. Given the complexity of compliance related costs in redevelopment projects compared to Greenfield developments, early-stage due diligence and proactive risk identification are critical for effective cost control.

4.6 Hidden and informal costs in redevelopment projects

Table 7 provides insights into the hidden and informal costs in redevelopment projects:

Table 7: Hidden Costs and Budget Allocation

Hidden Cost Category	Examples	Budget Allocation
Stakeholder management	Negotiations, liaison, community costs	3–5%
Holding & interest costs	Extended approvals & delays	2–4%
Additional investigations	Soil, structural, environmental tests	2–3%

Source: Author's own work

These costs are often overlooked in initial budgeting but have substantial impact feasibility if not accounted for upfront.

4.7 Value engineering measures adopted

Table 8: Value Engineering Measures and its Benefits

Value Engineering Measure	Cost Benefit
Phased demolition & construction	Reduced relocation cost
Reuse & retrofitting	Material cost savings
Construction methodology optimisation	Faster execution
Early completion strategies	Lower overheads & interest
Recycled material usage	Reduced waste disposal cost

Source: Author's own work

Value engineering in redevelopment projects (refer Table 8) goes beyond reducing material cost to emphasise effective planning and execution. Improved execution strategies, phase wise construction, and effective scheduling are required due to constraints including occupied premises, existing building, and restricted site area. Value engineering improves total cost performance in redevelopment projects by minimizing delays and controlling time related and indirect expenses at the planning and execution stage.

5.0 Findings and Results

5.1 Key findings of the study

According to the thorough analysis and interpretation of the primary data obtained by conducting interviews with industry specialists, it was determined that several significant findings associated with cost management in re-development projects. The redevelopment cost management is Risk-centric.

In Redevelopment project, cost management is Risk Centric: The redevelopment project cost management is essentially risk centric and not cost centric. Cost management in

the redevelopment projects should first and foremost be aimed at risk management and not merely trying to control the construction cost. Re-development projects unlike greenfield projects are associated with numerous uncertainties including delays in statutory approvals, tenant problems, and unknown site conditions. These uncertainties make cost control not something that can be done once and thus it will have to be monitored constantly during the project lifecycle.

The project cost is highly influenced by the execution phase: The research has identified the most significant effect on the overall project cost to be the one of the execution stages. A majority of the respondents reported that the costs generally increase by 20-40 percent at this stage. The main reasons behind this cost increase are delays during pre-construction stage, unexpected conditions of the site, and delays in the supply of materials or labour. This is a clear indication that cost overruns will be a direct result of the delay in a project timeline, and effective cost control is a necessity in the execution phase.

Indirect Costs form a major portion of Total Project Cost: The results show that indirect and non-construction costs play a vital role in determining the overall cost of the redevelopment projects. The budget of the project is often made up of expenditures on rehabilitation requirements, regulatory premiums, financing and interest costs and other miscellaneous costs. These parts of costs are project specific and, therefore, redevelopment projects are more complicated than greenfield developments. There is a need to have higher contingency provisions.

There is a need to have a higher contingency provision: The paper illustrates the necessity of setting up proper contingency allocation in redevelopment projects. Experts recommended the contingency range of 15 to 25 percent to control the uncertainties involved in approvals, site conditions and stakeholder concerns. However, with greenfield projects, lower contingencies can be allocated 5-10 percent in comparison. Higher contingency requirement indicated the increased risk exposure of redevelopment projects and is used to control unexpected costs without compromising the project feasibility.

The management of Stakeholders directly affects costs: Stakeholder management proved to be important in determining cost performance in redevelopment projects. Respondents indicated that poor communication, lack of resolved expectations, and delays in decision making tend to lead to scope change, extended timeline and extra costs. Conversely, stakeholder involvement at an early stage and constant stakeholder participation during the project assist in minimizing conflicts and ensuring cost sustainability.

Value engineering redevelopment is time and phase engineering: The paper also established that value engineering of redevelopment projects is not applicable in greenfield development. Instead of concentrating more on replacement of materials or even modifications in design, redevelopment projects save on costs by efficient construction

phasing, re-use of the existing structure where feasible and measures geared towards fast completion of the project. Time optimization was also determined as one of the major value drivers in the cost management of redevelopment.

5.2 Results in relation to research objective

The results of the study were analyzed in relation to the research objectives stipulated and are presented in Table 9 below:

Table 9: Results in Relation to Research Objectives

Research Objective	Result Achieved
To identify key cost drivers in redevelopment projects	Major cost drivers identified include preconstruction activities-demolition, rehabilitation costs, statutory approvals, financing expenses, and time-related delays.
To study best practices in redevelopment cost management	Effective practices include phase-wise planning, maintenance of risk registers, early statutory approvals, and structured stakeholder alignment
To analyse challenges affecting redevelopment project cost	Stage-wise challenges and their corresponding cost implications were systematically identified and analysed

Source: Author's own work

Overall, the findings comprehensively address the research objectives and reinforce the need for a structured, flexible and phase wise cost management approach specifically designed for redevelopment projects. The findings support the assumption that redevelopment projects must be managed with different cost management strategies as opposed to when managing greenfield developments

6.0 Conclusion, Implications and Recommendations

6.1 Conclusion

Development of large Indian cities has been dependent on redevelopment projects as the available land is hardly available and old and run-down buildings have to be upgraded. Such projects are complicated even though their importance is increasing, and the risks of costs are relatively greater than the ones in greenfield development. The current paper comes to the conclusion that cost management is the most vital factor that determines financial success in redevelopment projects.

The results have been clear that traditional cost control methods that are more linear with construction emphasis are not suitable in the redevelopment setting. Rather,

redevelopment projects need risk-based, stakeholder-driven, and stage-based cost management models. Early-stage participation in due diligence, contingency adequacy, and a proactive approach to stakeholder engagement was found to be major steps towards ensuring this reduction of cost overrun and project delays.

6.2 Implications of the study

The paper emphasizes that developers should include realistic budgeting with sufficient contingency provision. The developers need to give early stakeholder involvement so that the scope changes and delays can be eliminated. Structured risk management tools like risk registers and Earned Value Management (EVM) should be employed by project managers /consultants whereas approval processes need to be streamlined by regulatory authorities and policy makers in order to reduce cost overruns and delays associated with time. These findings can further be applied by academia and researchers to reinforce the empirical evidence on the management of cost related to redevelopment, and its framework.

6.3 Recommendations

According to the results of this research, the following recommendations (see Table 10) can be suggested to improve cost management within redevelopment projects:

Table 10: Recommendations

Recommendation	Description / Implementation
Adopt a Risk-Driven Cost Management Approach	Develop comprehensive risk registers during planning to identify potential cost drivers such as regulatory delays, tenant relocation, and site uncertainties.
Implement Phase-Wise Planning and Value Engineering	Structure project execution in phases, focusing on construction phasing, reuse of existing structures, and early completion to minimise time-related cost impacts.
Allocate Adequate Contingencies	Plan higher contingency provisions (15–25%) for redevelopment projects to cover indirect costs, unforeseen site conditions, and stakeholder-related expenses, reflecting higher uncertainty than greenfield projects.
Strengthen Stakeholder Engagement and Communication	Engage residents, regulatory authorities, contractors, and financiers early and continuously to prevent disputes, scope creep, and delays, which are major sources of budget escalation.
Leverage Technology for Cost Monitoring	Use project management and cost-tracking tools (e.g., Earned Value Management, digital dashboards) for real-time monitoring of costs, schedules, and risks.
Focus on Early Approvals	Secure statutory approvals and compliance requirements as early as

and Regulatory Compliance	possible. Dedicated teams should manage regulatory processes efficiently to avoid schedule delays and associated costs.
Build Experienced Project Teams	Engage professionals with expertise in cost management, regulatory navigation, stakeholder coordination, and construction phasing to anticipate hidden costs, implement proactive measures, and ensure disciplined execution.

Source: Author’s own work

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CHAPTER 34

Integrated Financial Risk Modeling in PPP Infrastructure Projects

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ABSTRACT

Public-Privatisation Partnerships (PPPs) have become a major driving force in the infrastructure development strategy of India, with a special focus on the transport and highway infrastructure sectors. Nevertheless, evaluation of the financial viability of most PPPs is largely based on conventional financial evaluation measures, such as Net Present Value (NPV) and Internal Rate of Return (IRR). These indicators tend to ignore the level of uncertainty that contributes to project delays and financial distress. The current work aimed to establish the key financial risk factors that have a substantial impact on PPP projects and develop an integrated financial risk modelling framework that combines both the traditional indicators (NPV, IRR) and the advanced risk-adjusted indicators - i.e., Project Present Value (PPV) and Project Rate of Return (PRR). The novel framework uses the simulation tools of a probabilistic nature to include stochastic variability and quantifies the probabilistic contribution of the stochasticity to the project viability of the PPP. To validate the framework proposed, a case study of NH-4 Mumbai-Pune Expressway (Yashwantrao Chavan Expressway), another flagship Indian PPP Case Study, was conducted. Sensitivity analysis was applied to find the most influential financial risk parameters affecting the project results. The results show that incorporating risk-adjusted indicators results in a better and more realistic appraisal of project financial viability under uncertainty than calculations using conventional deterministic analyses. The results highlight the potential of the framework to foster risk-informed decision-making, to promote financial transparency and to strengthen the financial viability of PPP infrastructure projects, in the context of the entire Indian infrastructure.

Keywords: Public–Private Partnership (PPP), Financial Risk Modelling, NPV, IRR, PPV, PRR, Probabilistic simulation, Infrastructure Finance.

1.0 Introduction

The Mumbai-Pune Expressway, which was commissioned way back in 2002, is therefore one of the major infrastructure upgrades along the Mumbai-Pune corridor.

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The road is approximately 94.5km and has turned out to be one of the most popular toll roads in India, exposing commuters and businesspeople to the road. The expressway is developed among the first large-scale highway construction projects to use the Public-Private Partnership (PPP) model and is the primary change in how the road infrastructure is operated privately. The data on operations, such as traffic volumes and the toll collection patterns, are useful in the analysis of its performance in the developing highway system in India and its long-term sustainability (Zou et al., 2008; Makovsek, 2013).

Various financial elements in expressway completion and operation include cash inputs in terms of traffic, operation and maintenance, periodic adjustment of tolls, and all these have a decisive influence on the financial performance of the project within the concession period. Comprehensive information regarding the traffic structure, the collection of fees, and management costs allows for a thorough financial evaluation. This kind of analysis is essential to test the accuracy of initial projections such as NPV, IRR and the general ROI with references to the financial risk and uncertainty. The knowledge of these dynamics can enhance financial modelling as practised in PPP projects in India and assist in creating more precise decision-making models that would be applied in future projects (Ye and Tiong, 2020; Akomea-Frimpong et al., 2024).

2.0 Literature Review

Financial risk management sits at the heart of any successful Public–Private Partnership (PPP) infrastructure project. With these projects stretching over long concession periods, tangled up in complicated contracts, and always exposed to economic ups and downs, it's easy to see why. Researchers keep pointing out the same stubborn financial risks—cost overruns, revenue falling short, volatile interest rates, and delays in financing. These aren't just passing headaches; they demand careful tracking and real solutions. Mahboubi Niazmandi, Sedaesoula, Lari, and Moussavi (2024) push for a productivity-focused approach, using fuzzy inference systems and FFMEA to measure how these risks hit cost, timing, and quality.

Akomea-Frimpong, Jin, and Osei-Kyei (2024) go a step further. They argue that you need to tie together financial controls, risk management, and actual financial performance into one solid framework. That's how you make better decisions and steer projects to better outcomes. Real-world evidence from India backs this up—PPP projects there often hit a financial wall during execution. Construction costs spiral, and cash gets tight. Tiwari, Joshi, Singh, and Khule (2024) tackle this with the Analytical Hierarchy Process (AHP), ranking the biggest risks and mapping out focused solutions. Over in Saudi Arabia, Alsulami and Al Abbasi (2025) find that swings in interest rates and delays in project financing can make or

break PPP viability, showing just how much local regulations and economic conditions matter. On the technical side, the AHP approach keeps popping up for financial risk assessment in PPPs. Yue, Wu, Liu, and Zhang (2019) used it to good effect in integrated pipe gallery developments. Zou, Wang, and Fang (2008) suggest looking at risk management across the entire project life cycle—identify, assess, allocate—so you get value for money. In Malaysia, Ramli and colleagues (2022) underline the need to properly sort and analyze financial risks, while Hrytsenko et al. (2021) call for more innovation and a systematic take on managing risks over the long haul. There's also room for number-crunching: Monte Carlo simulations, for instance, help judge financial feasibility in BOT projects (Ye & Tiong, 2020). When you stack PPPs against traditional procurement, studies like Makovšek (2013) find that, sure, PPPs might cost more upfront, but smart risk-sharing can trim down long-term financial exposure. Put all this together, and the message is clear: if you want PPPs that last and deliver, you can't skip comprehensive, life-cycle-driven financial risk management.

3.0 Objectives

The principle goals in this study are to outline the major financial risk factors present in Public-Private Partnership (PPP) projects as well as building a comprehensive financial risk modelling blueprint using not only conventional financial performance metrics such as Net present value (NPV) and Internal Rate of Return (IRR), but also advanced financial performance metrics such as Project Profitability Value (PPV) and Project Risk Rating (PRR). Furthermore, the financial feasibility assessments of PPP ventures form the basis for risk-informed decision-making procedures throughout the entire project lifecycle.

Financial Feasibility in Public-Private Partnership Projects: Conventional Feasibility Metrics Have Some Limitations: When public-private partnership (PPP) projects such as Mumbai-Pune Expressway are funded, traditional financial analyses (such as Net Present Value, NPV and Internal Rate of Return, IRR) do not give due consideration to operational uncertainties that may be involved in the project. A salient example is the growth rate in the number of traffic, a parameter notoriously hard to estimate with a substantial margin of error and thus having an impact on toll-revenue forecasts. Empirical data reveal a compound growth rate of 8.86 resources per cent per annum of the Mumbai- Pune Expressway between 2008 and 2018, but for more recent data, estimates the compound growth assumption to a more conservative 5 resources per cent per annum to account for the uncertainties associated with future traffic volumes. Furthermore, the financial model does not include risks associated with cost variability, maintenance expenditures and possible delays in a project. Operational data for the project have shown that the cost of maintenance and adjustment to toll rates tends to follow a predictable pattern that is poorly handled by

standard models such as NPV and IRR, which have a poor ability to capture this deterministically. These shortcomings reveal standard financial metrics, which presently, Dietary typically mixes too few dimensions for assessing the viability of the prospective PPP projects.

Establishing the Integrated Financial Risk Modelling Framework: Given the importance of accurate financial forecasting, in this paper, an integrated financial risk modelling framework is presented for a public-private partnership (PPP) project. The major goal of a framework is to balance traditional financial performance measures with the wide variety of complexities and multiple hazards that are experienced in real-world projects. It attempts to bring together established evaluation methods, such as Net Present Value (NPV) or Internal Rate of Return (IRR), but introduces alternative risk-adjusted parameters, most notably, Project Present Value (PPV) and Project Rate of Return (PRR), to represent multiple aspects of financial viability.

To this end, the framework proposes a hybrid model around which we combine these traditional and novel metrics. In so doing, it captures a wider range of indicators of financial feasibility and allows for the inherent uncertainties in project environments.

Moreover, to evaluate and understand the risks embodied in the framework, probabilistic methods of simulation are used to determine the amount of uncertainty. These simulations are used to predict the possible consequences of financial pluralism as well as the performance of projects. Consequently, stakeholders are equipped with an impressive set of predictive tools, together with an understanding of financial risks and their implications on the project's success, greater than the explanatory capacity of single or deterministic models.

Applying the Framework to the NH-4 Mumbai–Pune Expressway: This research employs the proposed integrated financial risk modelling framework on the NH-4 Mumbai–Pune Expressway to ascertain its usefulness in modelling and assessing financial risks and potential outcomes in one of the most important PPP infrastructure projects in India. To test the framework and its financial modelling utility, the research analyses the financial outcomes of one of India's most recognised PPP projects and reviews the analysis to understand the applicable framework's risk assessment and the resulting financial ramifications of the model. For testing the framework and its financial modelling utility, the research analyses the financial outcomes of one of India's most recognised PPP projects and reviews the analysis to understand the applicable framework's risk assessment and the resulting financial ramifications of the model. This research provides an evaluative context, within the prescribed risk assessment framework, for integrated financial modelling frameworks in PPP projects, and thus, concepts of financial management for infrastructure projects on a PPP basis.

4.0 Methodology

The Excel model contains three main parts, which are Inputs, Calculations and Outputs. The assumptions (traffic growth rates, tolls, maintenance and operating expenses, capital expenditures and finance) have been placed into designated sections and are easily identifiable within their respective areas.

The calculations in this calculation sheet use the same timeline framework as the concession period for the project. The significant aspects of the model are forecasted traffic volumes, estimated revenues, cost projections, cash flow analysis, debt service calculations and sensitivity analysis. The model is designed in such a way that anything that may change (the timeline, debt term or length of the concession) can be made by adding or adjusting the column numbers.

Summaries of significant financial metrics (cash flows, debt service coverage ratios, etc.) that may provide sensitivity/risk analysis can also be found as output sheets. In addition, the model employs a consistent column and row structure, defined names for ranges of cells, and clearly labelled columns and rows to minimise confusion and enhance navigation, thus lowering the risk of error in inputting data into the model. By designing the model in this manner, it was possible to retain the model's flexibility and updatability and therefore create a financial model capable of assessing the feasibility of the Mumbai-Pune Expressway under uncertainties.

The Sections to be included in the Model

- i. Data
- ii. Calculations
 - financial factors
 - Capital expenditure
 - Finance
 - Operations
 - Tax
 - Profit and loss
 - Returns

5.0 Data Collection

Data collection plays a vital role in evaluating the financial viability and risk profile of Public–Private Partnership (PPP) infrastructure projects. The longer concession periods typical of public-privatisation of roads (referred to as PPP here) and the underlying volatility of the revenue streams require the availability of accurate operational and financial measures to build credible financial models.

The research presented here is on the Mumbai Pune Expressway Road, which is a well-known PPP highway project in India. Its dataset includes traffic volume statistics, toll

rates, toll revenue figures, operational and maintenance cost records, capital expenditure and financing parameters. Primarily sourced from secondary materials, such as project documentation sources, published records and relevant academic investigations, this data serves as the basis for financial analysis, sensitivity assessment and performance evaluation of the project using critical indicators such as the net present value (NPV) and internal rate of return (IRR).

5.1 Project data

Working for year 2002 -2025: The financial parameters described above describe the main fiscal assumptions behind the Mumbai-Pune Expressway project for the period 2002 to 2025. The total capital expenditure (CAPEX) is mentioned as ₹2,136 crores, out of which 70% is financed by debt pieces. The traffic growth is forecast at an average annual rate of 3% with an initial average daily traffic volume of 100 000 vehicles.

Table 1: Detailed Project Report

1	CAPEX (crs)	2136
2	Debt / total capex	70%
3	Traffic growth rate per year	3%
4	Initial traffic 100000 / day	100000
5	Toll Growth rate after 3 years	5%
7	Gestation period (yrs)	5
8	O&M for first year (crs)	5
9	O& M Escalation	5%
10	Interest Rate	10%
11	Tax rate	30%
12	Depreciation rate	4%
13	Concession period	28 Years
14	Viable Gap Funding	0
15	Project length (Km)	25
16	Construction period (year)	3
17	loan tenure	15
18	Discount Rate	12%
19	validity gap funding	0
20	zero-coupon bond	0

Source: Created by authors

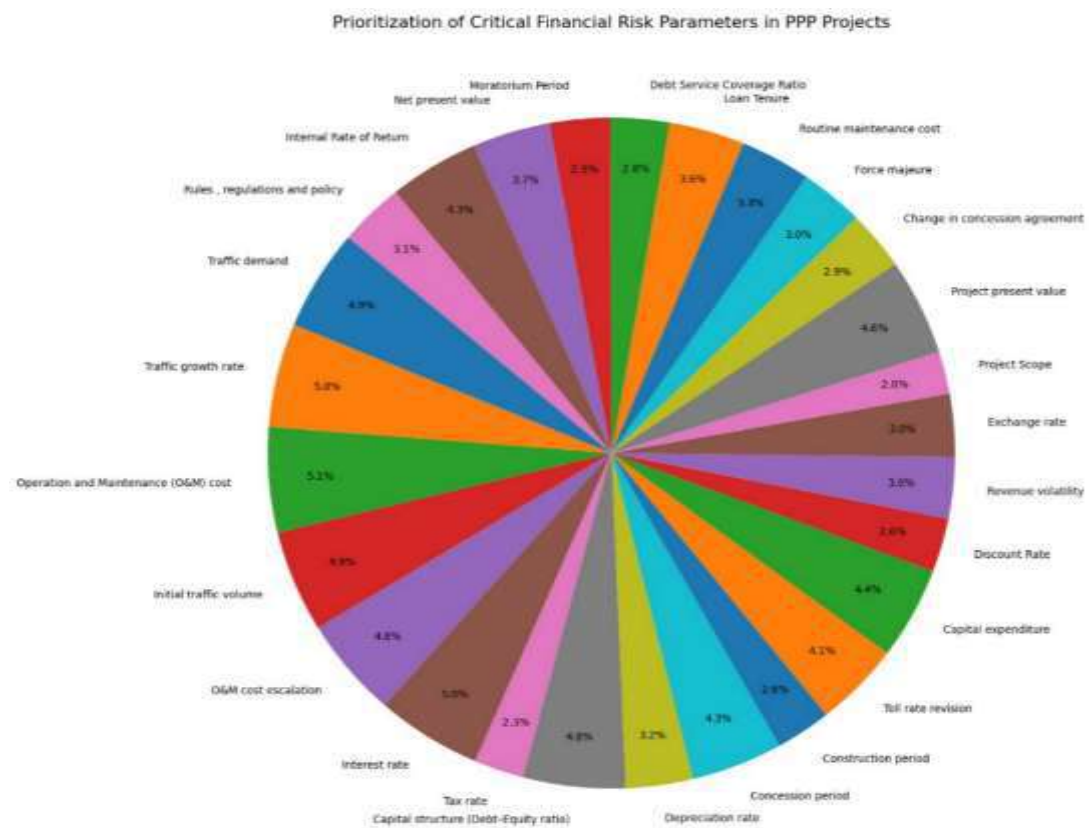
It is being further assumed that toll revenues will be escalated after three years at 5%, while the cost of operations and maintenance will start at ₹5 crores in the first year and will go on a persistent rise at a marginal rate of 5% annually. The project's concession period is

28 years, gestation period of 5 years, and loan period of 15 years. The main financial assumptions of the project include an interest cost of 10%, 30% taxes, 4% depreciation, and 12% discount rates. However, it is assumed that there are no viability gap funds or zero-coupon bonds for this project, which are of prime importance for analysing the financial viability of projects.

5.2 Financial analysis of factors

The financial performance of Public Private Partnership (PPP) infrastructure is under a constellation of interrelated financial determiners which combine to affect revenue generation, cost efficiency and long-term viability.

Figure 1: Prioritisation of Critical Financial Risk Parameters in PPP Projects



Source: Primary data collected through questionnaire survey.

Principal determinants such as traffic demand, toll revenue, operation and maintenance (O&M) costs, capital expenditures, financing structure and interest rates are central in determining the cash flows and debt servicing capacity of the project. These determinants have been identified by conducting a thorough review of the available existing literature regarding public-private partnerships (PPPs), road projects and infrastructure finance. Esteemed component outlines significant monetary variables for the Mumbai to Pune Expressway, scrutinising their outcomes on revenue, expenditure and greater financial viability of the endeavour. A thorough knowledge of the polity of the sensitivity associated with these financial parameters is essential for identifying the key risk factors and for refining the processes underlying financial decision-making in PPP infrastructure ventures.

Financial risks on public-private partnership (PPP) projects are mainly determined by costs of operations and maintenance, expected growth rates of traffic, current rate of interest rates and overall demand of traffic, which has the most striking effect on the feasibility of the project. Inaccurate traffic forecast or high volatility in O&M expenditure can severely dent revenue streams and the ability to service the debt during the duration of the concession. Additional financial structuring determinants - such as the magnitude of capital investment or duration of concessions and the intended internal rate of return - might have a secondary but crucial influence on the outcome of PPPs. Exogenous factors, e.g. taxation regimes, fluctuations in the rate of foreign exchange and regulation changes, have less say but are also relevant. As such, stringent control of O&M costs, reliable demand forecasting and financial market volatility protection are crucial to improving the bankability and fiscal terms of PPP projects.

6.0 Calculations and Interpretation

6.1 Traffic calculation

Projected Average Annual Daily Traffic: The Average Annual Daily Traffic (AADT) forecast for Mumbai-Pune Expressway has shown a steady upward trend in the vehicle volume from 2002 to 2025, with the overall escalation being shown in all vehicle categories.

Table 2: Average annual Daily traffic

	Growth Annual % Change (%)	Vehicle /Year	Car	Bus	LCV	HCV	MULTIA XLE	Total Traffic Data Annually
2002-2003		2002-2003	12,943,169	369,921	1,848,927	2,218,849	1,109,424	18,490,290
2003-2004	3.5	2003-2004	13,412,611	383,338	1,915,987	2,299,325	1,149,662	19,160,923

2004-2005	4	2004-2005	13,971,470	399,310	1,995,820	2,395,130	1,197,565	19,959,295
2005-2006	4.5	2005-2006	14,600,186	417,279	2,085,632	2,502,911	1,251,455	20,857,463
2006-2007	5	2006-2007	15,330,195	438,143	2,189,913	2,628,056	1,314,028	21,900,336
2007-2008	5.5	2007-2008	16,173,356	462,241	2,310,359	2,772,599	1,386,300	23,104,855
2008-2009	5.5	2008-2009	17,062,891	487,664	2,437,428	2,925,092	1,462,546	24,375,622
2009-2010	5.8	2009-2010	18,052,538	515,949	2,578,799	3,094,748	1,547,374	25,789,408
2010-2011	6	2010-2011	19,135,691	546,905	2,733,527	3,280,433	1,640,216	27,336,773
2011-2012	6	2011-2012	20,283,832	579,720	2,897,539	3,477,259	1,738,629	28,976,979
2012-2013	6.2	2012-2013	21,541,430	615,662	3,077,186	3,692,849	1,846,424	30,773,552
2013-2014	6.5	2013-2014	22,941,623	655,680	3,277,203	3,932,884	1,966,442	32,773,832
2014-2015	6.7	2014-2015	24,478,711	699,611	3,496,776	4,196,387	2,098,194	34,969,679
2015-2016	7	2015-2016	26,192,221	748,584	3,741,550	4,490,134	2,245,067	37,417,557
2016-2017	7.2	2016-2017	28,078,061	802,482	4,010,942	4,813,424	2,406,712	40,111,621
2017-2018	6	2017-2018	29,762,745	850,631	4,251,599	5,102,229	2,551,115	42,518,318
2018-2019	7.8	2018-2019	32,084,239	916,980	4,583,223	5,500,203	2,750,102	45,834,747
2019-2020	6	2019-2020	34,009,293	971,999	4,858,217	5,830,215	2,915,108	48,584,832
2020-2021	-20	2020-2021	27,207,435	777,599	3,886,573	4,664,172	2,332,086	38,867,865
2021-2022	-5	2021-2022	25,847,063	738,719	3,692,245	4,430,964	2,215,482	36,924,472
2022-2023	5	2022-2023	27,139,416	775,655	3,876,857	4,652,512	2,326,256	38,770,696
2023-2024	7	2023-2024	29,039,175	829,951	4,148,237	4,978,188	2,489,094	41,484,644
2024-2025	5	2024-2025	30,491,134	871,448	4,355,649	5,227,097	2,613,549	43,558,877

Source: Created by authors

Commencing at 18.49 million vehicles for the 2002-2003 fiscal year, the traffic volume shows an annual growing trend; however, with a certain heterogeneity in the growth rate - some of the years showing significant increases, while the fiscal year 2020-2021 saw a decrease of about -20%, followed by a subsequent increase in the following years. The annual growth rates are normally in the range of 3% to 7%, with the growth rates being high in earlier years and showing a slight decline in the current phase period. When the data are disaggregated by vehicle class (including passenger cars, buses, light commercial vehicles (LCV), heavy commercial vehicles (HCV) and multi-axle vehicles), one is faced with the reality that there is a heterogeneous user mix, but that passenger cars nonetheless continue to be a dominant user class in terms of traffic volumes. The highest projections for the 2024-2025 period announced last year state a central aim of the National Climate Action Plan of 43.56 million vehicles.

6.2 Toll rate

Table 4: Toll Rate

Vehicle/Year	Car	Bus	LCV	HCV	MULTIAXLE
2002-2003	0	0	0	0	0
2003-2004	0	0	0	0	0
2004-2005	0	0	0	0	0
2005-2006	118	348	183	254	802
2006-2007	125	358	188	262	826
2007-2008	132	369	194	262	851
2008-2009	139	411	216	300	946
2009-2010	147	424	222	318	999
2010-2011	155	474	234	340	1060
2011-2012	164	485	255	354	1117
2012-2013	174	516	270	372	1178
2013-2014	183	548	285	390	1243
2014-2015	194	572	301	417	1318
2015-2016	205	605	318	436	1391
2016-2017	217	639	336	458	1468
2017-2018	229	673	354	481	1548
2018-2019	242	708	373	506	1635
2019-2020	255	745	392	532	1724
2020-2021	270	796	419	581	1835
2021-2022	285	846	446	602	1955
2022-2023	301	897	474	632	2085
2023-2024	319	939	494	686	2165
2024-2025	337	1006	529	721	2320

Source: Created by authors

The charge of tolls for various types of vehicles on the Mumbai Pune Expressway provides an example of increasing augmentation from the financial year 2005-2006 to the financial year 2024-2025. Initially, in the fiscal year 2005-2006, the tariff was ₹118 for cars, ₹348 for buses, ₹183 for light commercial vehicles (LCV), ₹254 for heavy commercial vehicles (HCV) and ₹802 for multi-axle vehicles, and these increased progressively in each succeeding year. By the fiscal year 2024-2025, the charges are expected to be ₹337 for cars, ₹1006 for buses, ₹529 for LCVs, ₹721 for HCVs and ₹2320 for multi-axle vehicles. The observed escalation could be attributed to inflationary pressures, improved maintenance costs and high operational expenses.

6.3 Toll revenue

Table 5: Toll Revenue

Vehicle/Year	Car	Bus	LCV	HCV	MULTIAXLE		Total Revenue in Crores
2005-2006	1722821966	145213074.6	381670637.7	635739355.9	1003667251	3889112285	389
2006-2007	1916274432	156855157.3	411703737.1	688550774.8	1085387290	4258771391	425
2007-2008	2134883019	170566839.3	448209595	726421067.5	1179741085	4659821606	465
2008-2009	2371741821	200429903.4	526484549	877527739.9	1383568737	5359752750	536
2009-2010	2653723154	218762168.4	572493448.8	984129809.7	1545826541	5974935122	597
2010-2011	2966032070	259233169.6	639645383.1	1115347118	1738629331	6718887071	671
2011-2012	3326548484	281164076.9	738872423.3	1230949566	1942048962	7519583512	751
2012-2013	3748208788	317681783.2	830840308.4	1373739716	2175087883	8445558479	844
2013-2014	4198316964	359312872.7	934002980	1533824707	2444287321	9469744845	946
2014-2015	4748870027	400177499.5	1052529597	1749893413	2765419087	10716889624	1071
2015-2016	5369405363	452893189.3	1189813025	1957698502	3122888321	12092698400	1210
2016-2017	6092939284	512785880.7	1347676519	2204548118	3533053098	13691002900	1370
2017-2018	6815668580	572474478.2	1505065884	2454172278	3949125454	15296506675	1530
2018-2019	7764385836	649221784.8	1709542265	2783102795	4496416077	17402668757	1740
2019-2020	8672369799	724139044.4	1904420917	3101674562	5025645624	19428249946	1942
2020-2021	7346007359	618968783.2	1628474212	2709884091	4279378060	16582712506	1658
2021-2022	7366412935	624956295.3	1646741107	2667440123	4331266977	16636817437	1663
2022-2023	8168964239	695762513.9	1837630154	2940387484	4850243596	18492987987	1849
2023-2024	9263496890	779323824.5	2049229002	3415036742	5388888154	20895974613	2090
2024-2025	10275512145	876677056.2	2304138156	3768736977	6063432584	23288496918	2320

Source: Created by authors

The data available from the Mumbai-Pune Expressway has evidence of an upward trend from about ₹389 crores in the financial year 2005-2006 to about ₹2,320 crores in the financial year 2024-2025. This is based on the increased toll charges as well as the enhanced traffic flow, with maximum contributions from multi-axle vehicles, followed by cars, HCV,

LCV, and finally buses. Moreover, the total annual collection has been steadily increasing, accompanied by a significant surge in revenue collection during 2019-2020, despite a short-term slump in traffic and toll collection due to the pandemic outbreak. In 2024-2025, the toll collection is expected to be ₹2,320 crores, which marks the success in growing traffic as well as improving the toll rate increases.

6.4 Profit and Loss

Table 6: Profit and Loss

Time	0	1	2	3	4	5	6	7
Year (operations)		2002-2003	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009
Traffic (PCU)		18,490,290	19,160,923	19,959,295	20,857,463	21,900,336	23,104,855	24,375,622
Revenue crs		-	-	-	389	425	465	536
O & M		5	5	6	6	6	6	7
Net Revenue		(5)	(5)	(6)	383	419	459	529
Depreciation		85	21	21	21	21	21	21
EBIT (Operating Profit)		(90)	(27)	(27)	362	398	437	508
Interest		150	150	150	150	150	150	150
PBT		(240)	(176)	(176)	212	248	288	358
Tax		-	-	-	64	74	86	108
PAT		(240)	(176)	(176)	149	174	201	251
Cash Flow after Tax	-2136.00	(155)	(155)	(155)	170	195	223	272
DSCR					2.14	2.30	2.49	2.82
Minimum DSCR	2.14							
IRR	13%							
NPV	₹ 2,015.34							
Weighted Avg Cost of Capital	7.90%							
Debt Repayment schedule								
Principle		1495	1495	1495	1495	1495	1495	1495
Interest		150	150	150	150	150	150	150
Total Debt		1645	1645	1645	1645	1645	1645	1645
Interest paid		150	150	150	150	150	150	150
Principal paid								

Time	8	9	10	11	12	13	14	15	16
Year (operations)	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018
Traffic (PCU)	25,789,408	27,336,773	28,976,979	30,773,552	32,773,832	34,969,679	37,417,557	40,111,621	42,518,318
Revenue crs	597	671	751	844	946	1,071	1,210	1,370	1,530
O & M	7	7	8	8	9	9	9	10	10
Net Revenue	590	664	743	836	937	1,062	1,201	1,360	1,520
Depreciation	21	21	21	21	21	21	21	21	21
EBIT (Operating Profit)	569	642	722	814	916	1,041	1,179	1,339	1,498
Interest	150	150	150	150	150	150	150	150	150
PBT	419	493	572	665	767	891	1,030	1,189	1,349
Tax	126	148	172	199	230	267	309	357	405
PAT	293	345	401	465	537	624	721	832	944
Cash Flow after Tax	315	366	422	487	558	645	742	854	965
DSCR	3.10	3.45	3.82	4.26	4.73	5.31	5.96	6.71	7.46
Debt Repayment schedule									
Principle	1495	1495	1495	1495	1495	1495	1495	1495	1495
Interest	150	150	150	150	150	150	150	150	150
Total Debt	1645	1645	1645	1645	1645	1645	1645	1645	1645
Interest paid	150	150	150	150	150	150	150	150	150
Principal paid									

Time	17	18	19	20	21	22	23
Year (operations)	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
Traffic (PCU)	45,834,747	48,584,832	38,867,865	36,924,472	38,770,696	41,484,644	43,558,877
Revenue crs	1,740	1,942	1,658	1,663	1,849	2,090	2,320
O & M	11	11	12	13	13	14	15
Net Revenue	1,729	1,931	1,646	1,650	1,836	2,076	2,305
Depreciation	21	21	21	21	21	21	21
EBIT (Operating Profit)	1,708	1,909	1,625	1,629	1,814	2,055	2,284
Interest	128	107	85	64	43	21	0
PBT	1,580	1,802	1,539	1,565	1,772	2,033	2,284
Tax	474	541	462	469	531	610	685
PAT	1,106	1,262	1,077	1,095	1,240	1,423	1,599
Cash Flow after Tax	1,127	1,283	1,099	1,117	1,262	1,445	1,620
DSCR	5.88	6.51	5.54	5.53	6.11	6.86	7.59
Debt Repayment Schedule							
Principle	1282	1068	854	641	427	214	0

Interest	128	107	85	64	43	21	0
Total Debt							
Interest paid							
Principal paid	214	214	214	214	214	214	214

Source: Created by authors

The Profit & Loss statement of the Mumbai-Pune Expressway shows the financial performance of the project from 2002 to 2025. At first, the project faced negative net revenues owing to capital outlays and expenses, which subsequently increased to positive revenues owing to increasing traffic flow and tolls. By 2005-2006, toll revenues started to counterbalance operational as well as maintenance expenditures, resulting in positive net revenues of ₹383 crores. Year by year, the operating profit (EBIT) of the project steadily marched upward to reach ₹2,284 crores by 2024-2025. Similarly, the project's Debt Service Coverage Ratio (DSCR) steadily improved to reach 7.59 in 2024-2025, depicting high cash flow generation capacity in comparison to the debt obligations of the project. Additionally, the project's profits can be observed through the increasing PAT figures that reached ₹1,599 crores by 2024-2025. There is consistency in the payment of principal as well as interest on the loan by the project to repay the debt. However, the payments made towards the loan's interest steadily diminished with the reduction in the loan amount.

7.0 Result

Table 7: Sensitivity analysis (Amount in Crores.)

		1709	1922	2136	2350	2563
	Traffic ↓ / CAPEX →	-20%	-10%	0%	10%	20%
80000	-20%	-720	-540	-320	-150	10
90000	-10%	-450	-260	-60	90	240
100000	0%	-190	10	165	-30	-210
110000	10%	90	250	390	210	40
120000	20%	320	490	620	430	260

Source: Created by authors

7.1 Traffic–CAPEX sensitivity analysis

The sensitivity analysis strictly considers the effect of the traffic volume variation and capital expenditure (CAPEX) effect on the financial viability of the road project using Net Present Value (NPV) as the main indicator.

The most salient finding is the high sensitivity of NPV to traffic volumes. A small decrease of 10-20% in traffic causes a precipitous decrease in NPV. Even at the same time,

CAPEX reductions are inadequate to make up for low traffic because the toll revenue, an important part of the cashflow profile, is directly proportional to the vehicle volumes.

Although changes in CAPEX have an effect, they are relatively secondary. Lower initial expenditures do improve NPV, but the adverse impact of declining traffic cannot be compensated for by lower initial expenditures. On the other hand, high traffic counts significantly boost NPV, despite an increase in construction costs.

Under the baseline scenario - i.e. no changes to traffic or CAPEX - the project has an NPV of around ₹165 crore, which is a financially sound project under the projected conditions. Elevating traffic by 10% or 20% increases the NPV further, whereas traffic reductions aggravate the risk exposure.

8.0 Conclusion

The current study clearly shows that assessing infrastructure public-private partnerships (PPPs) requires the development of an overall financial model. Conventional metrics such as NPV and IRR are not sufficient in accounting for risks such as inherent uncertainty and financial hazard involved with long-term PPPs when used alone. Accordingly, a thorough assessment of project performance and sustainability, based on an integrative financial appraisal structure, is considered a must.

In the interests of getting a more accurate assessment of the outcomes of any project, this research imposed some further critical financial metrics, namely, Project Present Value (PPV) and Project Rate of Return (PRR), while using risk simulation techniques. By incorporating these measures and simulating risk, the model accounts for important sources of uncertainty, such as traffic demand and toll revenue projections, operating and maintenance costs, and financing conditions. This helps to make cash flow projections more reliable and to refine the analysis of project risk.

By utilising the framework developed in this research, the case example of the Mumbai-Pune Expressway proved the practicality of the proposed framework. The findings indicate that the traffic growth rate has been identified as the single most important determinant of the project's financial success. Moreover, the risk and sensitivity analyses provided by the framework offer companies and investors a clear understanding of the financial impact that changes in the fundamental variables will have on the project.

9.0 Recommendations

It would be advisable to consider incorporating risk-adjusted financial tools in PPP projects on infrastructure to build on traditional financial analysis tools, which include NPV

and IRR, and to include probabilistic tools such as PPV and PRR. It will be important to consider using probabilistic simulation techniques to address uncertainties of important variables in projects related to the growth of traffic and toll charges. Sensitivity analysis will be necessary to determine and remedy financial risk factors in projects at the initial stages of development. It will be important to consider implementing a dynamic financial risk approach that will update financial predictions with real-time information to project realistic financial forecasts and project sustainability.

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CHAPTER 35

Impediments to the Implementation of Sustainable Construction Materials in India

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ABSTRACT

The construction industry has very high contribution to environmental degradation, resource loss as well as carbon emissions, especially in the fast-growing economies like India. Although sustainable construction materials are characterized by significant environmental and lifecycle performance advantages, their application in the Indian construction sector is low. The current work explores the barriers to large-scale adoption of sustainable construction materials in India based on the comparison of the domestic market with the international experience and the determination of the main economic, regulatory, and institutional obstacles. An integrated mixed-method study design was utilized as the literature review, global benchmarking, stakeholder interviews, and a questionnaire survey were merged to conduct a study on construction professionals on a global scale. A 5-point Likert scale was used to gather quantitative data of 40 industry stakeholders in terms of a 5-point Likert scale and was analyzed by the use of descriptive statistics and ranking of the mean score. The results show that the awareness and technical accessibility of sustainable materials are moderate, but high initial costs, unequal policy implementation, and discontinuous procurement systems are major barriers to adoption. Parameters that concerned cost had the least mean scores (2.25-2.40), whilst strategic parameters that included global benchmarking, policy uniformity, and lifecycle cost consideration had highest importance ratings (mean > 4.4). The research also indicates that the industry is most prepared to engage in systematic introduction of sustainable materials in mainstream construction practice, as long as systemic obstacles are taken care of. Empirical evidence is used to postulate a strategic framework that is management oriented with a focus on harmonizing policies, making procurement decisions based on lifecycle factors, capacity building, and matching to the international sustainability guidelines. The results of this study can be used in practice by policy makers, project managers and developers aiming at faster adoption of sustainable materials and changing the construction industry of India to correspond to the global trends of sustainability.

Keywords: Sustainable construction materials, adoption barriers, global benchmarking, policy framework, Indian construction industry, lifecycle cost analysis

1.0 Introduction

The construction sector is one of the largest contributors of the resources depleted across the world,

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environmental degradation, and greenhouse gases. The materials that can be considered as an alternative to traditional materials are the construction materials that are sustainable, with lower environmental impact, and better lifecycle performance. Nevertheless, their adoption is still constrained because of the still existing barriers.

The major obstacles are regulatory weaknesses, procurement and supply chain weaknesses, excessive initial costs, and professional ignorance. Weak or unclear building codes do not require or encourage the use of sustainable materials, thus providing no regulation gaps. In addition, availability is diminished by procurement challenges and logistical constraints, and deters the stakeholders by the high initial cost, and absence of solid cost-benefit analysis frameworks. Moreover, poor level of technical skills and awareness among engineers, architects and contractors are also a further barrier to integration into normal construction practices.

The study will help establish and solve these challenges by examining their underlying causes, evaluating their effects and offering practical solutions. The construction industry can promote the use of sustainable materials and help become greener by promoting better regulatory frameworks, streamlining supply chains, and developing better stakeholder awareness. An overview of current literature shows that there is a gap in research where holistic approaches are applied to deal with these interrelated hurdles. Although the effect of single problems such as cost or awareness has been studied, not much is done to investigate their interaction. This confirms the necessity of a combined study to come up with viable and multidimensional measures of conquering adoption issues in the construction sector.

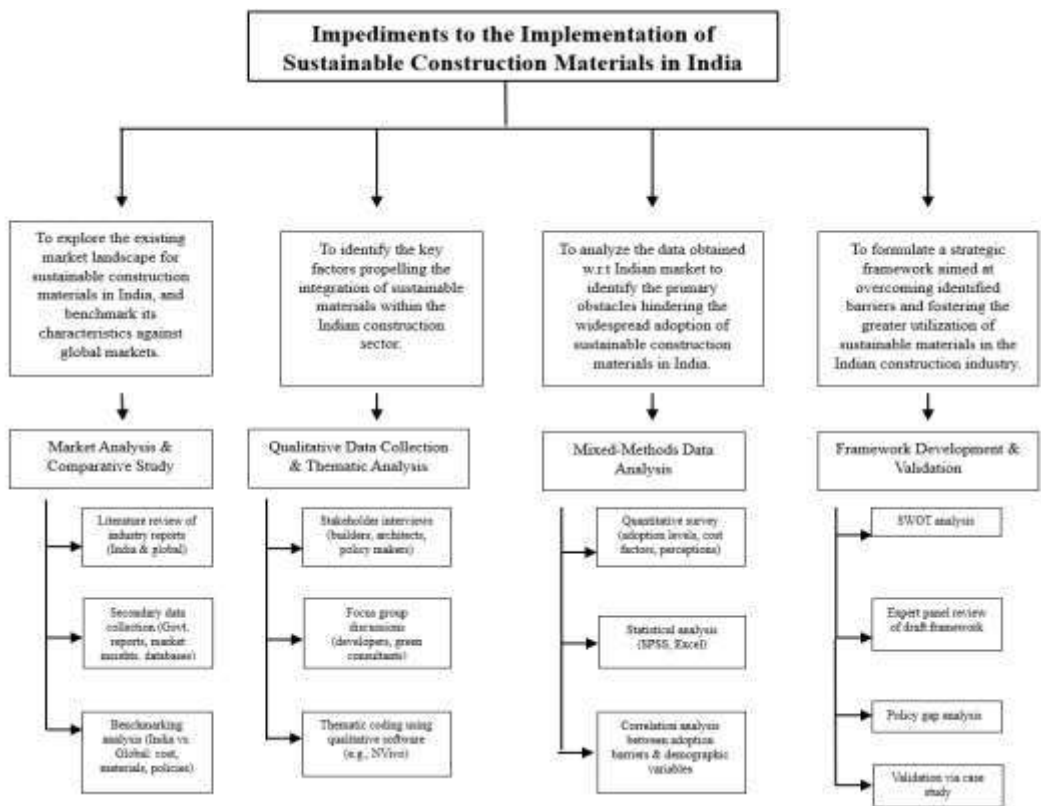
1.1 Research questions

What key challenges impede the widespread diffusion of sustainable construction materials in India's building sector, and what strategic framework can be developed to accelerate their uptake?

1.2 Objectives

- To explore the existing market landscape for sustainable construction materials in India, and benchmark its characteristics against global markets.
- To identify the key factors propelling the integration of sustainable materials within the Indian construction sector.
- To analyze the data obtained w.r.t Indian market to identify the primary obstacles hindering the widespread adoption of sustainable construction materials in India.
- To formulate a strategic framework aimed at overcoming identified barriers and fostering the greater utilization of sustainable materials in the Indian construction industry.

1.3 Methodology



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Our study will be based on four primary objectives in order to understand and enhance the application of sustainable construction materials in India. Each of the objectives is pursued via a specific methodology, which is backed up by certain sub-methodologies, and offered to provide tangible and practical results. The process does not only provide depth and clarity of findings, but also holds the research deeply rooted in the realities locally as well as globally. We will start with the literature review to understand the current market situation of sustainable building materials in India and compare its features with the international markets. This initial stage will entail secondary data gathering, which entails reviewing of journal articles, government policy papers, industry white papers, and world market reports. We pay much attention to comparative studies, sustainability indices and material performance analysis in various regions. The work of the phase is a clear picture of the current situation of India in the sustainable material industry on the areas where the country is on track or not on track with the global trend, and the untapped areas in the Indian market.

Then, we transition into the market scanning and stakeholder mapping, which aims at locating the major factors of driving the integration of sustainable materials into the Indian construction industry. This is done using two complementary sub-methodologies, semi-structured interviews with professionals working in the full spectrum of the construction ecosystem (architects, developers, green consultants, and policy-makers) and focus group discussions with engineers, project managers and construction workers. These interactive programs are aimed at collecting the views on such aspects as the availability of the material, cost-benefit consciousness, regulatory impact, and market need. The deliverable in this case is a well charted set of drivers economic incentives like cost savings in the long run, regulatory impetus of green building codes, rising customer preference in sustainable credentials and technological improvements in green materials.

After the establishment of enablers, we focus on the barriers. In order to discuss the data obtained concerning the Indian market and point out the main barriers to the popular introduction of sustainable construction materials, we use a mixed-methods analysis. This methodological step is a combination of quantitative surveys that are distributed to a large variety of industry participants in various geographies and company sizes and thematic analysis of the qualitative data, which was gathered in previous interviews. The questionnaires assist in measuring impressions and difficulties, whereas thematic coding can be used to detect similarities in the stories like high initial investments, shortage of skilled personnel, low awareness, and fragmentation of the supply chains. The product of this process is a prioritized system of adoption barriers (categorized, according to frequency and severity of stakeholder response).

Having a proper grasp of the enabling and limiting factors, we can now proceed to our last goal, which is creating a strategic framework to mitigate the challenges that are observed and enhance the increased use of sustainable materials in the Indian construction industry. This is taken care of by expert validation and SWOT analysis. First, our interim results are presented to a panel of sustainability experts, construction managers, and academics to provide a critical feedback and refinement to make our results relevant and practical. Then we apply the SWOT analysis to assess the strength, weaknesses, opportunities and threats of some possible intervention, including the incentive of green procurement, lifecycle assessment requirement in building approvals and the level of training on sustainable construction practices. The result is a strategic action-oriented framework that can inform other stakeholders such as government agencies, construction companies, and industry associations in dealing with the real-life implementation issues and speeding up the uptake of sustainable materials.

In the process, every methodological process is built on the previous one following a process of knowing the market, revealing its drivers, and thus, creating a solution-oriented

roadmap. Such a multi-layered, systematic method has the benefit of making the research both more reliable and more detailed, as well as making the research conclusions directly based on the realities of the stakeholders and able to adapt to the Indian construction conditions. It advocates an effective, practical body of knowledge by combining both qualitative and quantitative data based on local and globalities, thus transcending academic research and proceeding to change the industry.

1.5 Research Framework

S. No	Objective	Research Focus	Methodology	Tools & Resources
1	To comprehensively analyze the existing market landscape for sustainable construction materials in India and benchmark its characteristics against global markets.	Understand market maturity, material availability, cost factors, and regulatory context in India vs. global benchmarks	- Literature review of academic studies, industry reports, and government publications	- JSTOR, Scopus, Web of Science
			- Quantitative data collection (market size, growth trends, usage)	- SPSS/Excel
			- Expert interviews (manufacturers, suppliers, architects, contractors)	- NVivo or ATLAS ti
			- Comparative analysis with global markets	- Market research reports
2	To investigate the key factors propelling the integration of sustainable materials within the Indian construction sector.	Identify the drivers such as policies, incentives, awareness, and innovation	- Literature review on drivers of sustainability adoption	- Interview guides
			- Semi-structured interviews with industry stakeholders (builders, government, NGOs)	- Case documentation
			- Case studies of LEED/GRIHA-certified projects	- Survey tools (Google Forms, SurveyMonkey)
			- Optional surveys to quantify perceived importance of drivers	- Literature databases
3	To identify and evaluate the primary obstacles hindering the widespread adoption of sustainable construction materials in India.	Analyze structural, economic, and institutional barriers	- Literature review focused on barriers in India and other developing nations	- NVivo
			- Focus group discussions with stakeholders across the construction supply chain	- Policy analysis tools
			- Policy analysis of building codes, procurement norms, and environmental laws	- Discussion guides
			- Triangulation of findings for comprehensive insights	- Regulatory documents

4	To formulate a strategic framework aimed at overcoming identified barriers and fostering the greater utilization of sustainable materials in the Indian construction industry.	Create actionable, localized strategies for industry-wide adoption	- Synthesis of key findings from prior stages	- SWOT and stakeholder analysis tools
			- Benchmarking international best practices from comparable economies	- Presentation software (PowerPoint)
			- Develop a multi-pronged framework (policy, market incentives, capacity-building)	- Workshop facilitation materials
			- Expert validation via panel reviews and stakeholder workshops	

Source: Created by authors

2.0 Sustainable Construction Materials in India: Current Landscape and Future Prospects

2.1 Introduction

The construction industry in India is among the fastest-developing sectors in the nation and it generates a lot of income to the GDP of the country. As the industry is set to become the third biggest in the world by the year 2025 (IBEF, 2021), the need to implement more sustainable building practices becomes paramount. With the growing speed of urbanization, and the rising amount of population, the environmental effects of construction processes, including high-energy use and carbon emissions, are becoming clearer (Bora et al., 2023). The construction industry has the largest contribution to the carbon emission in the world and India has the highest contribution of carbon emission which will increase as the industry continues to rise. Therefore, the research question is crucial to investigate the present situation with sustainable construction materials in India, which obstacles obstruct their use, and whether India is at the same level as the global communities. Environmental harm can be decreased greatly with the help of sustainable materials and lead to more energy-efficient constructions, which are essential because India is developing rapidly and is aimed at reaching the sustainability level (Kumar & Kumar, 2024).

The Indian construction sector has to transform into becoming sustainable due to the rising demand of green housing and infrastructure. The Indian market of sustainable construction material is in its early stages of development, yet it indicates improvement. The construction industry is under extreme pressure to transform its practices towards minimizing its carbon footprint in addition to being energy efficient. Construction materials that are ecofriendly such as fly ash bricks, recycled concrete aggregates and low-carbon cement have been on the rise although they are still trailing behind the developed countries regarding market penetration. Although these materials may be environmentally and economically

advantageous in the long-term perspective, such as reduced energy consumption and less maintenance expenses, most builders still prefer to use traditional materials because of the lack of knowledge and reduced initial investment (Alaezi and Obeka, 2020). Once the market has matured, awareness campaigns, government incentives and strong policies will play a significant role in changing the market. In this regard, the opportunities associated with implementation of sustainable building materials in the rapidly developing construction sector of India are enormous, yet it needs to overcome multiple challenges associated with the price, knowledge, and infrastructure (Bora et al., 2023).

2.2. Global benchmarking and potential for growth

The construction sector in India is on the verge of transitioning to sustainable building modes but it is way behind developed nations as far as adoption of green materials on large scale basis is concerned. Sustainable construction is relatively established throughout the world, with the United States, Germany, and Japan being at the forefront of it. These countries have introduced strong regulatory, government incentives, and market-driven initiatives that have led to massive adoption of green building materials (Habert et al., 2020). India can take some lead in these nations, especially formulating regulatory principles and establishing a more trustworthy market of sustainable materials. The Indian market is also capable of becoming a major market in the consumption of sustainable construction materials as it is inhabited by a vast and rapidly rising urban population that is likely to increase demand on eco-friendly housing and infrastructure (Grand View Research, 2024). Also, the abundance of the natural resources in India, such as bamboo, hemp, and the industrial by-products may be recycled, offers the basis of manufacturing the eco-friendly building materials domestically.

The problem facing India is not the unavailability of resources or the ignorance of the necessity of sustainable building practices rather the unpopularity of the solutions. Adoption rates are likely to go up as more builders, architects, and developers discover the environmental advantages and cost savings of long-term sustainability of sustainable materials. Moreover, Indian government has been rendering more support to green buildings in terms of incentives, tax exemptions and regulations to promote the use of environment-friendly materials in construction projects. The performance of the green building programs in other nations shows the possibility of India following the same. Specifically, the introduction of policies that resemble the green building codes and energy efficiency standards that are prevalent in the countries that have established and developed green construction markets may trigger the shift toward sustainability in the Indian building industry. The potential will be achieved by overcoming present obstacles and by aligning the industry stakeholders with the sustainability goals of the government.

2.3 Current landscape of sustainable materials in India

The construction industry of India has gone a long way to embrace sustainable construction materials yet the market is still immature. The use of sustainable materials, such as fly ash bricks, recycled concrete aggregates, and low-carbon cement, is also becoming more popular, and their ecological and economic advantages are becoming more and more recognized. Industrial coal waste can be converted into fly ash bricks, which is an alternative to standard clay bricks and consequently, it lowers industrial waste and decreases the quantity of clay in construction, which is usually mined in an unsustainable manner (Kalwale et al., 2023). They are less expensive to make and are a more lasting solution yet still one of the major issues is consistency of quality. Recycled concrete aggregates are also being increasingly adopted as an alternative to virgin aggregates which have assisted in minimizing construction wastes and the environmental effects of aggregate mining (Pappu Asokan et al., 2007). Also, low-carbon cement, made using a mixture of other materials, such as slag and fly ash, minimizes the carbon emissions that cement manufacturing produces on the environment, which also contributes to a large share of the construction industry environmental footprint (McKinsey Global Institute, 2020).

Regardless of such developments, there are a number of impediments, which restrain the large-scale use of green materials in India. The initial cost of most green materials is one of the major barriers as it discourages builders and contractors given the fact that many of them are attracted to the cost-cutting and low-budget development of a construction project. Although the benefits of sustainable materials, including spared energy and minimal cost of maintenance, can be favorable in the long-term perspective, the initial expenses can be a major discouragement (Nayak, 2020). Moreover, the knowledge of the benefits of such materials is quite deficient. The long-term savings and environmental benefits of sustainable materials are not known to many builders, and consequently, they still use the traditional and less sustainable ones. The chain of supply of these materials has also not been well developed in some parts of India hence their increased prices and scarcity. Increased focus on education, research, policy incentives will play a vital role in breaking these obstacles and increasing the rate of adoption of sustainable materials in the Indian construction sector.

2.4 Emerging sustainable material solutions

With India seeking to satisfy its increasing infrastructure needs, there has been a number of new materials, which are far more sustainable than conventional alternatives. During the last few years, fly ash bricks have gained popularity. These bricks use fly ash as a coal burning byproduct, which does not only cut down on industrial waste but also has a more environmentally friendly alternative to traditional clay bricks, the production of which may cause deforestation and energy consumption (Kalwale et al., 2023). Even though the quality

of fly ash has not been consistent, research has been going on to mitigate these problems and the adoption levels are still increasing. Recycled concrete aggregates are also on the rise besides fly ash bricks. This recycled material is made of waste concrete used in demolition sites and thus eliminates the use of natural aggregates hence decreasing the environmental effects of mining and disposal of construction waste (Pappu Asokan et al., 2007). Moreover, another emerging technology in India is the green cement. In contrast to conventional cement, which has a big carbon footprint because of the intense use of highly energy-consuming clinker, green cement is made using the help of additional materials, including slag and fly ash, which will provide lower emissions and a more sustainable product (McKinsey Global Institute, 2020).

Insulation materials that are energy-saving are also being adopted. These materials have the characteristic of limiting heat transfer and energy use in heating and cooling (this is why the materials are especially helpful in the rapidly developing urban centers of India where the energy consumption is expected to increase significantly) (PwC India, 2019). Such materials not only assist in decreasing the carbon emissions which are as a result of energy consumption but also assist in the decrease in the total cost of operation of buildings. In addition, the energy efficient insulation is important in the attempt of India to achieve its climate objectives as well as to diminish the non-renewable sources of energy. With the research and development in this field, newer and more efficient products are likely to be introduced and this will further hasten the process of transitioning to sustainable building practices in the country.

2.5 Barriers to adoption in the Indian context

Although sustainable materials are available, the rate of their adoption is very low in the construction industry in India coupled with a number of major obstacles. The increased initial price of most of the sustainable materials is one of the main challenges. Despite the long-term economic advantages associated with using materials like fly ash bricks, recycled concrete aggregates, cut down costs of energy, and less maintenance, their high initial cost makes them less economical to developers who operate on restrictive funds (Alaezi & Obeka, 2020). The other obstacle is ignorance and technical illiteracy between the builders, contractors and consumers. The long-term savings in costs and environmental advantages of working with sustainable materials are unknown to many people in the construction industry, which is why they are unwilling to use them (Gudadhe, 2023). Moreover, the policies of the governments that encourage the construction materials that are sustainable are not always applied to the various states that compose the market dispersely, which results in the lack of unity on the market of green materials. This lack of uniformity in the application of the policy has led to few incentives to improve developers to use more sustainable materials. The inertial

effects of adoption of new and more sustainable alternatives in the construction industry are also due to the high dependency on the traditional techniques and substances (Bora et al., 2023). India should formulate more powerful policies and incentives to help it deal with these challenges which will help in ensuring wider adoption of sustainable materials. In order to counteract the upfront cost barriers with regard to green building materials, financial incentives should be used, including subsidies or tax breaks. Moreover, it might be necessary to increase the supply of sustainable materials with the help of the improved supply chains and the distribution networks, which would allow lowering their prices and increase their accessibility to builders in the country (Nayak, 2020). There should also be education and awareness activities targeting construction professionals, developers and the consumers to help bridge the knowledge gap that is present. By tackling these issues, India will be able to realize the full potential of the sustainable materials in construction market and move to more sustainable building projects.

2.6 Role of government policy and regulation

The role of government intervention in this context is to establish sustainable construction in India by providing sustainable practices in construction, i.e., energy conservation building code (ECBC) and national mission on sustainable habitat, which address energy efficiency and environmentally friendly construction activities (MoEFCC, 2017). Such programs as Pradhan Mantri Awas Yojana (PMAY) also provide an opportunity to incorporate sustainable materials into the affordable housing at large scale. Nevertheless, regardless of such encouraging efforts, the lack of uniformity in their application among the states advances their futility. Other areas have a deficiency of regulation implementation and assistance on the part of local officials, hindering the development of a stable market of sustainable materials (Bora et al., 2023). In order to fill this gap, a national standard policy should be established supported with strict implementation and financial incentives to establish a strong ecosystem of sustainable construction practice in the country.

2.7 Key trends shaping the future of sustainable construction

The future of sustainable construction in India is defined by the key trends like the transition to the decrease of embodied carbon in building materials, i.e., the embodied carbon in the form of emissions produced throughout the lifecycle of a material (World Green Building Council, 2019). With the industry focusing on low-carbon substitutes of traditional materials, such as cement and steel, innovations are rising that would meet the sustainability objectives of the Indian industry. Furthermore, bio-based materials such as bamboo and hempcrete are gaining popularity because of their benefits of renewability and carbon-sequestration, and, thus, are the most suitable option when it comes to green building (Patil

and Patil, 2017). The other changing trend is the implementation of the principles of the circular economy, that is, its emphasis on material reuse, waste minimization, and resource management, which slowly permeates the practice of the construction industry and promotes a more sustainable and regenerative construction process (Ellen MacArthur Foundation, 2015).

2.8 Conclusion

The construction industry in India is at the transformational level and has the prospects of pioneering a sustainable revolution of using environmentally friendly building materials and procedures. The high start-up costs, lack of awareness and policy fragmentation are obstacles that must be overcome to take advantage of sustainable construction. The change is being favorable due to the increasing technology, the need to incorporate green buildings and changing consumer tastes. India can be a global leader in sustainable construction as a result of regular government assistance, policy transparency, and industry cooperation to realize its national climate objectives and economic sustainability in the long term.

3.0 Data Collection and Research Instruments

3.1 Introduction

This chapter presents the analysis and interpretation of data collected through a structured questionnaire survey administered to construction industry professionals across different regions. The primary objective of this analysis is to evaluate the existing market landscape for sustainable construction materials in India and benchmark its characteristics against global markets.

The questionnaire consisted of 30 rating-based questions designed using a 5-point Likert scale, where responses ranged from Very Low (1) to Very High (5). A total of 40 valid responses were collected from stakeholders including site engineers, project managers, contractors, architects, and consultants. The analysis focuses on identifying trends related to market maturity, material availability, cost competitiveness, regulatory influence, and global alignment, thereby directly addressing Objective 1 of the study.

The findings explore stakeholder perceptions regarding the current market landscape, cost factors, regulatory environment, awareness levels, and global benchmarking of sustainable construction materials in India. The analysis aims to identify key patterns and constraints influencing adoption, thereby supporting the research objective of benchmarking the Indian market against global practices.

Questions

1	How would you rate the overall availability of sustainable construction materials in India?
2	How mature is the Indian market for sustainable construction materials compared to global markets?
3	How affordable are sustainable materials in India compared to conventional materials?
4	How consistent is the quality of sustainable materials available in India?
5	How reliable is the supply chain for sustainable construction materials in India?
6	How aware are contractors and site engineers about sustainable material options?
7	How effective are Indian government policies in promoting sustainable construction materials?
8	How strongly do regulations influence your choice of sustainable materials on projects?
9	How do Indian sustainable material costs compare with global benchmarks?
10	How accessible are global best practices for sustainable materials in India?
11	How confident are you in using sustainable materials based on Indian standards/codes?
12	How well do Indian green building codes align with international standards (LEED/BREEAM)?
13	How would you rate client demand for sustainable materials in Indian projects?
14	How much do lifecycle cost benefits influence adoption decisions?
15	How transparent is market information (cost, suppliers, performance data) in India?
16	How easy is it to source certified sustainable materials in India?
17	How competitive is India in sustainable material innovation compared to global markets?
18	How effective are awareness programs in promoting sustainable materials?
19	How frequently are sustainable materials used in infrastructure projects in India?
20	How does India's sustainable materials adoption compare with developed countries?
21	How supportive are project timelines for adopting sustainable materials?
22	How willing are contractors to shift from traditional to sustainable materials?
23	How adequate is technical training related to sustainable materials in India?
24	How reliable are performance claims of sustainable materials in India?
25	How important is global benchmarking for improving India's sustainable material market?
26	How aligned are Indian construction practices with global sustainability goals?
27	How effective are public infrastructure projects in driving sustainable material adoption?
28	How much does cost remain a barrier despite global success stories?
29	How scalable is the sustainable materials market in India over the next decade?
30	How critical is policy uniformity across states for market growth?

Source: Created by authors

3.2 Profile of respondents

The respondents represented a balanced cross-section of the construction ecosystem, ensuring diverse and reliable insights.

Table 1: Distribution of Respondents by Professional Role

Category	Number of Respondents	Percentage (%)
Site Engineers	16	40%
Project Managers	10	25%
Contractors / Vendors	8	20%
Architects / Consultants	6	15%
Total	40	100%

Source: Created by authors

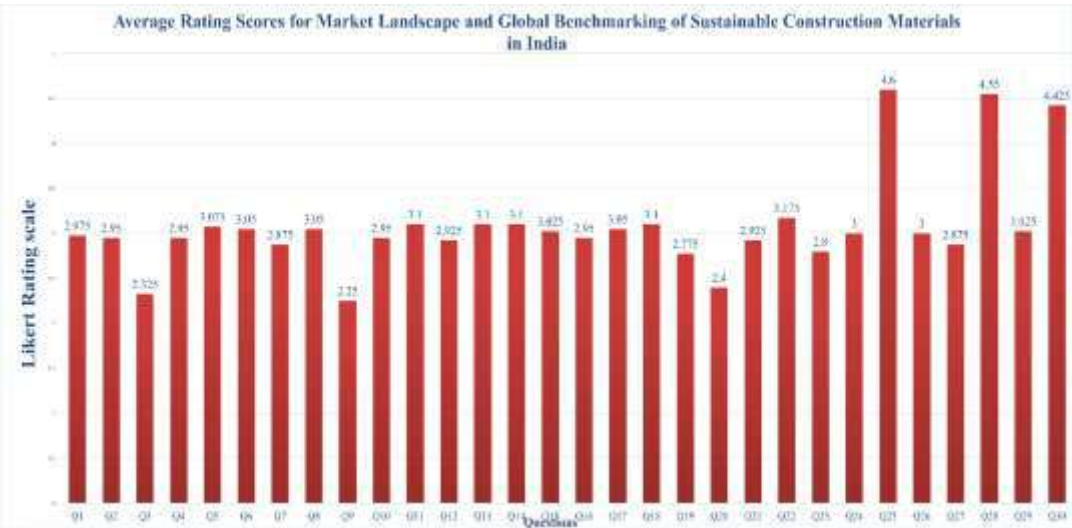
The dominance of site engineers and project managers ensures that the responses are grounded in practical, on-site experience, which is essential when evaluating real-world adoption of sustainable construction materials.

3.3 Reliability of data

The questionnaire was designed based on:

- Literature review
- Industry practices
- Internship exposure at CMRL, Godrej Properties, and Annamalai Construction Company

A Likert-scale structure was adopted to enhance consistency and comparability of responses. The data was found to be suitable for descriptive statistical analysis, including mean score ranking and graphical representation.



Source: Created by authors

3.3.1 Bar graph interpretation

The bar graph shows the average Likert-scale values (1-5) received on all 30 survey questions (Q1-Q30) based on the perceptions of the stakeholders to the market landscape, cost aspects, policy environment, awareness, and global benchmarking of sustainable construction materials in India. On the whole, most of the questions identified in the questionnaires have mean scores between 2.8 and 3.2, which are moderate scores, showing that there is a moderate level of agreement between the respondents. This implies that the Indian sustainable construction materials are partially accessible and known but not fully applied to the mainstream construction activities.

3.3.2 Industry implications derived from mean score analysis

The analysis of mean scores shows that technical availability is not enough to, prompt the sustainable material adoption in India. The most prominent decision-making factors are economic feasibility and consistency in the regulations. To the project managers and contractors, the results indicate that cost evaluation must be done on the basis of the lifecycle and not the initial cost evaluation. To policymakers, the findings highlight the need to have unified country laws and incentive schemes in order to mitigate risk of adoption.

This figure directly responds to the Objective 1 by objectively comparing the perceptions of the stakeholders on the Indian sustainable construction material market with the world expectations thus setting the baseline of the situation upon which the identification of barriers and the development of the strategic framework will be based.

Table 2: Descriptive Statistics of Perceptions on Sustainable Construction Materials

Question	Mean	Std. Deviation	Min	Max
Q1	2.98	0.62	2	4
Q2	2.95	0.58	2	4
Q3	2.33	0.55	2	3
Q4	2.95	0.6	2	4
Q5	3.08	0.64	2	4
Q6	3.05	0.61	2	4
Q7	2.88	0.57	2	4
Q8	3.05	0.63	2	4
Q9	2.25	0.48	2	3
Q10	2.95	0.59	2	4
Q11	3.1	0.62	2	4
Q12	2.93	0.6	2	4
Q13	3.1	0.65	2	4
Q14	3.1	0.67	2	5
Q15	3.03	0.61	2	4
Q16	2.95	0.58	2	4
Q17	3.05	0.63	2	4
Q18	3.1	0.66	2	4
Q19	2.78	0.54	2	4
Q20	2.4	0.5	2	3
Q21	2.93	0.59	2	4
Q22	3.18	0.64	2	4
Q23	2.8	0.55	2	4
Q24	3	0.6	2	4
Q25	4.6	0.49	4	5
Q26	3	0.58	2	4

Q27	2.88	0.56	2	4
Q28	4.55	0.5	4	5
Q29	3.03	0.61	2	4
Q30	4.43	0.5	4	5

Source: Created by authors

Table 3: Key Observations from Mean Score Analysis

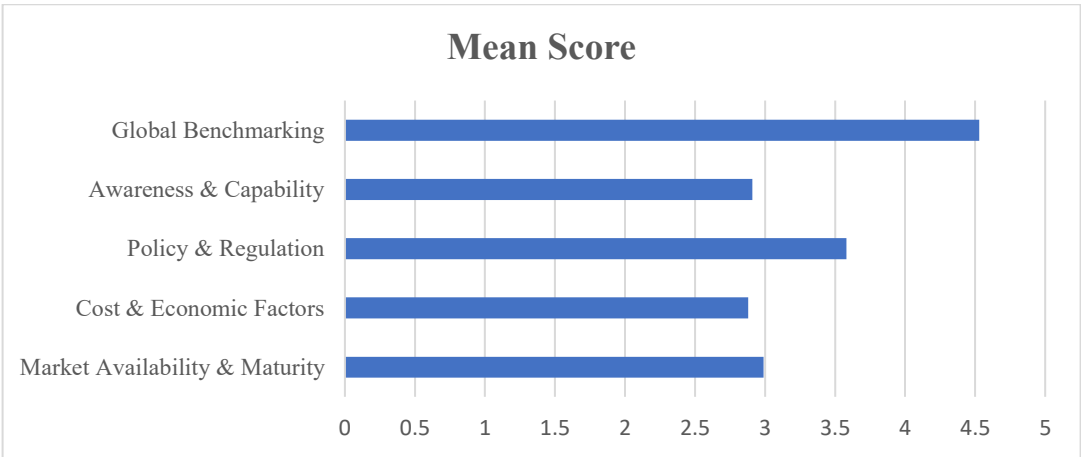
Observation Area	Evidence from Graph	Inference
Overall trend	Majority scores between 2.8–3.2	Moderate market maturity
Lowest scores	Q3 (2.33), Q9 (2.25), Q20 (2.40)	Cost-related barriers
Highest scores	Q25 (4.6), Q28 (4.55), Q30 (4.43)	Need for policy & global benchmarking
Variability	Sharp peaks in Q25–Q30	Strategic priorities identified
Adoption readiness	Mid-range scores in most questions	Partial readiness

Source: Created by authors

Table 4: Theme wise Mean Score Analysis

Theme	Questions	Average Mean	Interpretation
Market Availability & Maturity	Q1, Q2, Q4, Q5	2.99	Moderate
Cost & Economic Factors	Q3, Q9, Q20, Q28	2.88	High constraint
Policy & Regulation	Q7, Q8, Q26, Q30	3.58	Strong influence
Awareness & Capability	Q6, Q18, Q23	2.91	Moderate awareness
Global Benchmarking	Q25, Q28, Q30	4.53	Very high importance

Source: Created by authors



Source: Created by authors

Table 5: Top Five Factors Influencing Sustainable Construction Material Adoption

Rank	Question	Mean Score	Factor Description
1	Q25	4.6	Importance of global benchmarking
2	Q28	4.55	Cost as a major barrier
3	Q30	4.43	Need for policy uniformity
4	Q22	3.18	Lifecycle cost benefits
5	Q14	3.1	Market maturity perception

Source: Created by authors

The top five factors bar chart reveals that structural and strategic issues dominate stakeholder concerns. The highest-ranked factor, global benchmarking (Mean = 4.6), indicates strong industry recognition of the need to learn from mature international markets. Cost-related challenges (Mean = 4.55) and policy uniformity (Mean = 4.43) further emphasize that financial and regulatory reforms are more critical than material availability alone. The inclusion of lifecycle cost benefits among the top five factors suggests growing awareness of long-term economic advantages, although upfront cost constraints continue to limit adoption.

3.4 Availability of sustainable construction materials

A majority of respondents (45%) rated the availability of sustainable construction materials as moderate, while only 30% perceived it as high or very high. This indicates that although sustainable materials are present in the Indian market, their availability is inconsistent and region-specific, particularly outside major urban centers.

Table 6: Availability of Sustainable Construction Materials in India

Likert Rating	Frequency	Percentage (%)
1 (Very Low)	2	5
2 (Low)	8	20
3 (Moderate)	18	45
4 (High)	10	25
5 (Very High)	2	5

Source: Created by authors

3.5 Availability of sustainable construction materials

Nearly 67.5% of respondents agreed or strongly agreed that high initial cost is a major barrier to the adoption of sustainable construction materials. This highlights that despite long-term lifecycle benefits, upfront financial constraints significantly influence material selection decisions in Indian construction projects.

Table 7: Perception of Cost as a Barrier to Sustainable Material Adoption

Likert Rating	Frequency	Percentage (%)
1 (Strongly Disagree)	1	2.5
2 (Disagree)	5	12.5
3 (Neutral)	7	17.5
4 (Agree)	16	40
5 (Strongly Agree)	11	27.5

Source: Created by authors

3.6 Influence of government policy and regulations

While 50% of respondents believe that government policies positively influence sustainable material adoption, a significant proportion (35%) remained neutral. This suggests that existing regulations are influential but inconsistently enforced, limiting their effectiveness in driving widespread adoption.

Table 8: Effectiveness of Government Policies in Promoting Sustainable Materials

Likert Rating	Frequency	Percentage (%)
1	2	5
2	4	10
3	14	35
4	13	32.5
5	7	17.5

Source: Created by authors

3.7 Awareness and technical knowledge

The results show that 42.5% of respondents perceive awareness levels as moderate, while 37.5% rate it as high or very high. This indicates that although awareness is growing, gaps remain in technical understanding and practical training, especially at the site execution level.

Table 9: Awareness of Sustainable Construction Materials among Professionals

Likert Rating	Frequency	Percentage (%)
1	2	5
2	6	15
3	17	42.5
4	12	30
5	3	7.5

Source: Created by authors

3.8 Global benchmarking and market maturity

Table 10: Comparison of Indian Market with Global Practices

Likert Rating	Frequency	Percentage (%)
1	1	2.5
2	7	17.5
3	16	40
4	11	27.5
5	5	12.5

Source: Created by authors

A majority (40%) of respondents rated India's market maturity as moderate when compared to global benchmarks, while 40% viewed it as high or very high. This indicates that although India lags behind developed countries, there is strong potential for growth and scalability in the sustainable materials market.

3.9 Integration of sustainable materials into mainstream construction

Table 11: Need for Integrating Sustainable Materials into Standard Construction Practices

Likert Rating	Frequency	Percentage (%)
1	1	2.5
2	2	5
3	5	12.5
4	18	45
5	14	35

Source: Created by authors

An overwhelming 80% of respondents agreed or strongly agreed that sustainable construction materials should be formally integrated into standard construction practices and guidelines. This highlights strong industry readiness for structured adoption, provided policy and cost-related challenges are addressed.

3.10 Summary of key results

The data analysis reveals that the adoption of sustainable construction materials in India is influenced more by economic and regulatory constraints than by lack of awareness or material availability. High initial costs and inconsistent policy enforcement emerge as the

most significant impediments. At the same time, strong support for global benchmarking and formal integration into mainstream construction practices indicates positive industry intent. Overall, the findings suggest that sustainable construction materials are perceived not merely as environmental alternatives, but as strategic enablers of long-term efficiency and quality, provided systemic barriers are addressed through policy reform, incentives, and capacity building.

4.0 Conclusion and Managerial Implications

4.1 Overview of the study

The current study analyzed the barriers to the adoption of sustainable building materials in India by conducting an empirical and systematic study. The study combined international benchmarking, theoretical knowledge and first-hand data gathered about the professionals in the construction industry to measure the maturity of the market, costing, regulatory efficiency, awareness, and strategic preparedness in the Indian construction market. The mixed-methods design of the study ensured that all perceptions of site engineers, project managers, contractors, architects, and consultants were captured hence, a conclusive part of the research was based on the project realities at the project level. The results give a detailed insight into the reasons why sustainable construction materials, being cost-effective and having a long-term environmental and economic benefit, are yet to be widespread in India.

4.2 Interpretation of data and graphical analysis

4.2.1 Market availability and maturity

The interpretation of descriptive statistics and bar graphs suggest that there is moderate maturity in the Indian market of sustainable construction materials with majority of the mean scores falling in the range of 2.8 to 3.2. Although sustainable materials are technically accessible, they are not uniformly used in terms of their use by regions and project types. This implies that material availability is not enough to stimulate adoption. In terms of construction management, supply chains disjointed and uneven quality assurance mechanisms curtail trust amongst project stakeholders, particularly in infrastructure-based projects of high scale and those that are time sensitive.

4.2.2 Cost and economic feasibility

The most important constraint in the data became cost-related parameters. Questions touching on affordability, comparison of prices with international standards and the adoption

rates compared to developed nations were the ones with the lowest scores on the mean ($Q3 = 2.33$; $Q9 = 2.25$; $Q20 = 2.40$).

The frequency tables and graphs are a clear indication that in most decision-making processes in projects, high upfront costs exceed the lifecycle benefits. This fact is in line with the earlier research, which points to the importance of short-term financial premises in the procurement approaches of developing economies (Habert et al., 2020; McKinsey Global Institute, 2020). Managerially, this highlights the pressing necessity of considering lifecycle cost analysis (LCCA) as a part of tendering and project appraisal systems to facilitate rational decision-making in terms of long-term material selection.

4.2.3 Policy and regulatory environment

Policy and regulatory factors were relatively more influential on adoption behavior and their mean scores were higher, which implied their strategic role. Nevertheless, the high percentages of neutrality in terms of responses on policy effectiveness indicate that there are inconsistent implementations in different states.

The large average of policy uniformity ($Q30 = 4.43$) demonstrates that the industry agrees that converged national rules would greatly decrease uncertainty and risk of adoption. The results support international data that the mandatory use of green building codes and the policy of incentives are important facilitators of sustainable construction markets (World Green Building Council, 2019).

4.2.4 Awareness and technical capability

The awareness of construction professionals was moderate, which means that individuals were becoming familiar with sustainable materials, although not in-depth knowledge of technical expertise, and especially on the execution level. Consultants and senior managers are aware of it, whereas site engineers and contractors have more practical challenges associated with application, performance assurance, and standard compliance.

The graphical tendencies state that capacity-building and skill development are necessary to close the policy intent and on-site implementation gap. This justifies the necessity of organized training and professional certification in terms of sustainable construction practices.

4.2.5 Global benchmarking and strategic readiness

Global benchmarking became the most powerful strategic area, which scored the highest mean score ($Q25 = 4.6$). According to the graph, there are steep peaks of questions on international alignment, learning about policies, and scalability. This indicates a strong industry desire to match Indian construction methods to the global standards of sustainability

like LEED and BREEAM. Strategically, global benchmarking is no longer being considered as a mandatory compliance factor, instead, it has become a roadway to greater competitiveness, investor trust and future asset worth.

4.3 Managerial and industry implications

Following the explanation of the quantitative data and graph analysis, the following conclusions can be made:

- The Project Managers ought to have material evaluation based on lifecycle over first cost.
- Developers and Contractors should incorporate sustainable materials at the initial design and procurement phases in order to reduce cost increase and execution risk.
- To speed up the adoption, policymakers need to pay attention to policy consistency, enforcement, and incentive-based procurement.
- Institutions in the industry should intensify technical training, certification and awareness to facilitate workforce readiness.

4.4 Strategic conclusion

The paper conclusively proves that the low implementation of sustainable construction materials in India is mostly influenced by the economic factors, fragmentation in regulations, and perception of risks associated with procurement and not a lack of knowledge and availability of such materials. The emphasis which the industry has put on global benchmarking, uniformity of policy, and lifecycle cost value is a sign that the industry is highly prepared to undergo change. With coherent policies, financial incentives, and procurement reforms that are led by the management, sustainable construction materials can shift their status of niche alternatives to the mainstream construction inputs. India can promote its construction industry to a higher level through international sustainability practices to ensure that the environment management and economic performance of the sector is boosted and international competitiveness is achieved.

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CHAPTER 36

The Impact of Metro on Real Estate Property Markets: A Case Study of Hyderabad Metro Rail Project

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ABSTRACT

India is undergoing fast urbanization and mass urban transit plays an important role to support it. Metro rail projects have emerged as important mass urban transit projects in India. Such metro projects also affect the development of urban land, their use and also values. In this context, the study investigates on the impact of Hyderabad Metro Rail (HMR) project on land prices of real estate in Hyderabad city, with a particular focus on the changes in land values around metro corridors. The primary objective is to analyses how the development of HMR project has influenced on urban land markets by improvising connectivity, reducing travel time, costs and altering patterns of accessibility. Through a comparative analysis of real estate conditions before and after the HMR project implementation, the study also explores the metro's role in reducing traffic congestion and promoting urban redevelopment. Taking from a comprehensive literature review, the research synthesizes findings from both global and Indian contexts. The study provides empirical insights into the value uplift and spatial redistribution effects associated with major urban transit interventions, thereby contributing to evidence based urban planning and real estate investment strategies in rapidly growing metropolitan regions like Hyderabad.

Keywords: HMR, Rail corridors, Land values, Real estate development, Land use change.

1.0 Introduction

Indian metropolitan cities are going through rapid urbanization, which results in more pressure on land resources, transportation systems and also urban infrastructures.

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Here, the studies state that the metro rail systems are appearing as tough parts of sustainable transport of urban, offering high end capacity while also acting on patterns of urban growth and the real estate market variations. Transport infrastructure plays a vital role in developing and changing the distribution of land use, more developed intensity, and also property values by improvising the reaching time and reducing travel time.

Hyderabad is one of the rapid and major growing metropolitan regions in India, which is driven by growing residential areas (sub urbs) and major employment areas. Due to this we can observe a rise in the population, more congestion in traffic, and depending upon private vehicles shows a pathway to the development of the Hyderabad Metro Rail (HMR) as a mass rapid transit system that is main for residential, commercial, and institutional areas of the city. Since becoming operational, the metro network has changed accessibility conditions across several urban areas and created new modes of development around station locations. Improved accessibility is increasing and attracting nearby areas for residential, commercial, and mixed-use developments. Accordingly, metro corridors are experiencing changes in land use patterns, more development intensity, and increase in property and rental values. However, these impacts are not permanent and depending on factors such as distance from metro stations, present land use structures, and local market conditions.

The study focuses on the impact on the Hyderabad Metro Rail on urban land use patterns and real estate property markets within selected station limited areas. A combined research method and designs are adopted to capture both spatial and market transformations. Land use and Land cover changes/differences were between 2015 (pre metro period) and 2025 (post metro period) are analysed using Geographic Information System (GIS) techniques to find the patterns of urban expansion, commercialization, and also land conversion along metro corridors. In parallel, primary data are collected through a structured questionnaire survey of residential and commercial property stakeholders located near selected metro stations to assess changes in accessibility, property values, rental levels, and commercial activity.

By applying Geographic Information Systems (GIS) based spatial analysis with survey-based descriptions, the study provides empirical results on how metro infrastructure influences urban development and property markets in a fast-growing Indian city. The findings are intended to support urban planners, policymakers, and real estate professionals in designing effective transit-oriented development strategies, guiding zoning regulations, and promoting balanced and inclusive growth around metro station areas in Hyderabad.

2.0 Literature Review

Many researchers have identified that impact on the urban rail transport system in real estate market patterns, emphasizes accessibility as the force behind appreciation in

property values. As per the account given by Tang et al. (2022), an urban rail transport system increases transport efficiency, decreases transport costs, and increases economic agglomeration, thus promoting a grow in the values of real estate, specifically focusing properties near stations. Above all, this forms a theoretical premise to analyses the impact on Hyderabad Metro about influencing property demand and appreciation within stations' influence zones in Hyderabad.

Research into the effects of metros on Property Markets has been done using synthesis-based reviews that indicate how rail transit affects residential commodity, along with Commercial Residential Property, in both spatial and temporal patterns. Lyu (2022) explains that rail transit affects residential commodity, along with Commercial Residential Property, in spatial, along with temporal patterns. It is indicated that Hedonic Price Models are primarily used by research papers that aim at identifying the effects of proximity to metros by taking into consideration varied stations such as IT corridors, along with densely populated residential areas.

Evidence from Indian cities indicates that the impact of the Metro Rail network can raise land values significantly, especially within the context of new and rising urban regions. In particular, the study conducted by Sharma and Newman (2018) on Bangalore Metro illustrates that the uplift created by investment expenditure on Metro Rail is very significant around the stations, though varying from station to station depending on the particular region and market dynamics. Notably, the context remains extremely relevant for the Hyderabad Metro due to the rapid expansion of the Hyderabad Metro Region.

The association between rail transport and house price and rent markets with emphasis on proximity impacts has been examined. A research article tells that the rail transport increases house price and rent values due to accessibility improvements and investment demand. Nevertheless, this article further indicates that negativity effects such as noise or congestion might reduce improvements due to rail transport for immediate zones of proximity. Thus, research suggests evaluation of metro effect by distance bands.

Metro systems not only affect land prices, travel patterns, metro station performance, and land use interaction, among others, which eventually affect real estate market performance. Du et al. (2023) emphasize that new rail transit systems, in interaction with land-use factors, affect travel patterns on existing stations, implying spatial differences. In this context, it can thus be understood that land use in the stations, among other factors, determines how metro systems affect stations in shaping development patterns in the market of Hyderabad.

There are some researchers who have associated an expansion in metros with changes in the housing market due to overall economic growth. Hu, Cai & Wen (2024) describe that an increase in the number of miles covered by metros can also depict an increase in the

housing prices because of economic growth, enhanced connectivity between employment hubs, and overall development activities at an urban level. This shows that Hyderabad Metro, too, can have an effect on property prices, not just due to direct connectivity, but overall economic growth along routes.

Accessibility at the network level has been identified as a key factor influencing residential property appreciation. Wu (2021) finds a positive relationship between urban rail network accessibility and residential property prices, which is particularly significant in suburban or peripheral regions where access to urban areas has improved with the provision of rail transport systems. This highlights the relevance of the Hyderabad Metro in connecting peripheral residential areas to major commercial hubs and suggests that its impact on property values extends beyond immediate station influence zones (Wu, 2021).

A study by Nallathiga et al (2023) finds that the metro systems can affect the residential as well as commercial property markets and there can be differential impacts on rental and ownership properties. Based on the primary survey of property owners, real estate agents and metro commuters, the authors establish the differential impact of Mumbai VAG metro line on property prices and rents. The impact also vary between residential and commercial properties. They also find that the metro systems led to shifts in modal choice towards public transport like metro and suburban rail that also resulted in air pollution reduction. Property markets do not respond in coincidence with the starting of metro operations, but also across a succession of project stages, which include early operational expectations and impacts during the construction phase. Trojanek and Gluszak (2018) illustrate how subway systems produce spatial and time effects on property prices, wherein value adjustments can be gradual and based on market anticipation and improvements in operational access. The above thus lends credence to interpreting Hyderabad Metro impacts as a staged market response rather than a sudden change in values.

The studies done in the emerging megacity scenario support and confirmed that the effect/impacts on residential property values pretend to be positive because of accessibility and transport advantages gained from the metro rail system. The study by Zhang and Jiao in 2019 demonstrated that the positive effect on the values of residential properties influenced by closeness to the metro rail system differs depending on the urban landscape and scenario. The study supports the Hyderabad Metro rail system report because it proves that there are non-uniform effects falling in real estate due to these metro stations and land use patterns.

Metro-impact changes are not only observed in the case of heavy metros but have been noticed for light rail transit modes of public transport. Pan (2013) mentions that the rail-transit system is found to have good impacts on the values of residential areas by enhancing accessibility but could face some negative factors in the vicinity of stations. This helps in

supporting the consideration of Hyderabad Metro stations' impact zones for a closer examination in view of the difference in levels of impact potential.

3.0 ATA and Methodology

This research study defines about the data sources, research design, and some analytical methods used to find the main impact of Hyderabad Metro Rail on land use patterns and real estate property markets. The study uses and follows an approach of combined method by integrating spatial analysis of land use changes with primary survey-based assessment of property market behavior. This combined method helps us in understanding both the physical development trends as well as the market responses in influenced areas of metro station.

The research methodology is divided into two major components: Analysis of land use changes using Geographic Information System (GIS) based mapping techniques and assessment of property market changes using a questionnaire survey and descriptive statistical analysis.

3.1 Analysis of land use changes

To Evaluate the impact of Hyderabad Metro Rail on patterns of urban development, land use changes in metro areas were analyzed using GIS-based approach. Few selected metro station areas were chosen for the study based upon their high passenger usage, mixed land use characteristics, and main real estate development activity. These locations represent major growth corridors in Hyderabad that experienced improved accessibility due to implementation of metro.

Land use mapping was initiated for two distinct time periods which are "2015, representing the pre-metro phase and 2025 represents the post-metro phase". This temporal comparison was undertaken to identify changes in land use distribution linked with the introduction and operation of the metro systems. Major land use categories such as residential areas, commercial areas, mixed use areas, institutional areas and open spaces were found within the station influence zones for both respective years.

Geographic Information System techniques were employed to prepare and analyses land use maps for the selected metro station areas. The Geographic information system based analysis enabled visual comparison of land use patterns between years 2015 and 2025, highlighting spatial transformations and development increase in metro accessible areas. The mapping results provided spatial evidence of increased commercial and mixed-use developmental areas around metro regions, which supports the assessment of metro induced land use changes

3.2 Analysis of property market changes

To assess the main effect of Hyderabad Metro Rail based on real estate prop markets property, primary data were collected using a set of structured questionnaire survey. This survey-based approach was adopted to reveal the perceptions and experiences of residents and commercial stakeholders those are located within metro station influenced areas. Property markets are influenced not only through physical infrastructure but also through perceived accessibility and market expectations making this survey data an effective tool for analysis.

The questionnaire was designed to collect information related to respondent profiles location and distances from the very nearest metro stations, radius of metro usage, required changes in accessibility and congestion, and perceived changes in property values and rental levels after metro implementation. For commercial respondents, additional questions related to changes in customer footfall and business activity were included in understanding the metro's influence on commercial performance.

Respondents were selected from areas located within and around metro regions using an appropriate sampling method. A total of 46 respondents were seen participating in our survey, concluding both the residential and commercial property stakeholders from selected metro station areas. The gap/space exactly from the metro station was considered as the main constraint, as its effects/impacts of metro infrastructure on the property markets tends to vary based on proximity. Data from respondents were differentiated and put according to the distance from metro stations to examine differential impact patterns.

The primary data collected is analyses using descriptive statistical techniques such as frequency analysis and percentage analysis. Graphical representations were used to interpret trends related to metro usage behavior, perceived changes in property values and rental levels and variations in commercial activity near metro stations. This descriptive analysis has helped in finding the complete market trends and helped in understanding the relationships between metro usage and real estate market behavior.

3.3 Integration of methodology

The use of GIS-based land use analysis and survey-based property market assessment provided a comprehensive understanding of the spatial and economic impacts of Hyderabad Metro Rail. While land use mapping captured physical development patterns around the metro's stations, the questionnaire survey showed market usage positions and behavioral responses. Together, these methods enabled a comprehensive evaluation of the influence of metro infrastructure on urban land development and real estate property markets in Hyderabad.

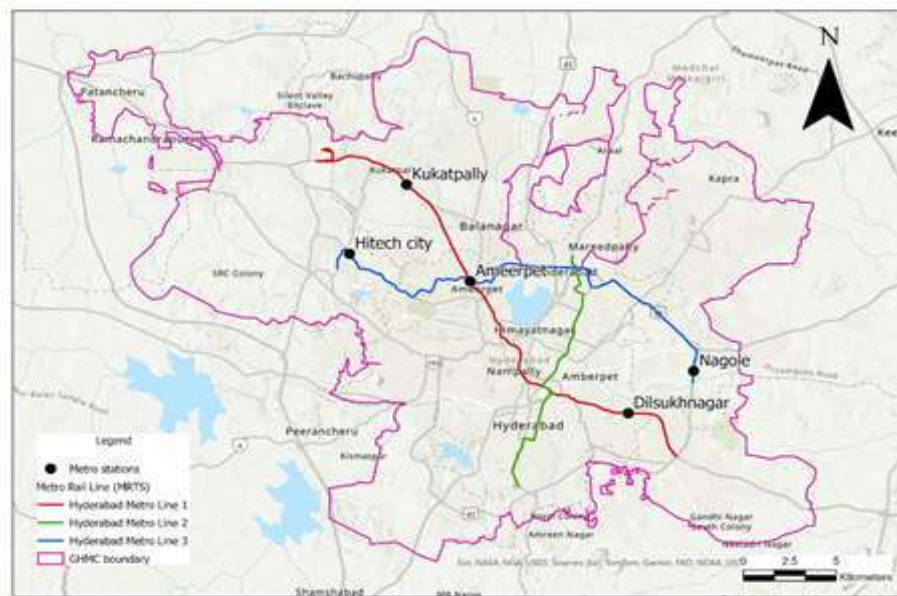
4.0 Results

This section explains the results that are obtained from the primary survey conducted and the spatial analysis to implement the effect/impacts of Hyderabad Metro Rail focusing land use patterns and property rates within selected metro station ranged influence areas. The results are presented using tabular columns, maps, and graphical representations, followed by brief descriptive explanations.

4.1 Metro network and influence areas

Figure 1 shows the Hyderabad metro rail network with select stations chosen for the study. These are the stations that are terminal origin and destination points. Figure 2 shows the influence zones of metro station areas of Hyderabad metro project. These are essentially the areas surrounding stations chosen for the study.

Figure 1: Hyderabad Metro Rail Network with Selected Stations

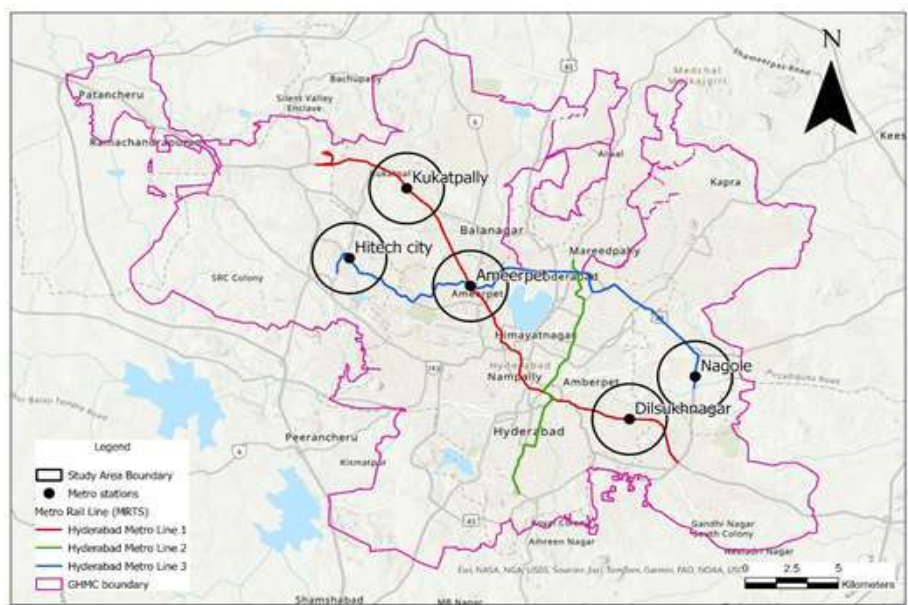


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4.2 The land use and land cover change analysis (2015 - 2025)

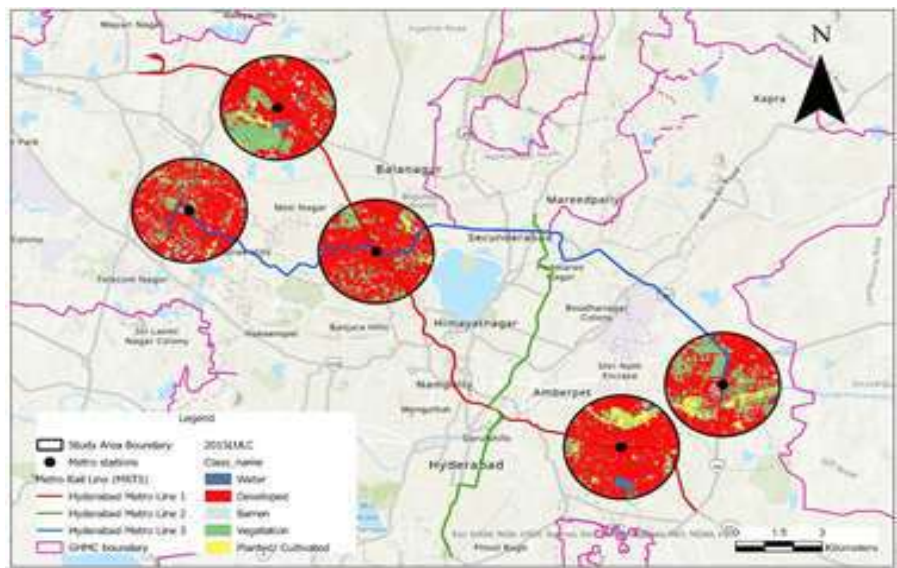
Figure 3 shows the map representing land use and land cover of study areas along metro corridors in the year 2015 before metro project was laid down. Figure 4 shows the map depicting land use and land cover of study areas along metro corridors in the year 2025 after metro became fully operational.

Figure 2: Metro Station Influence Zones in Study Area



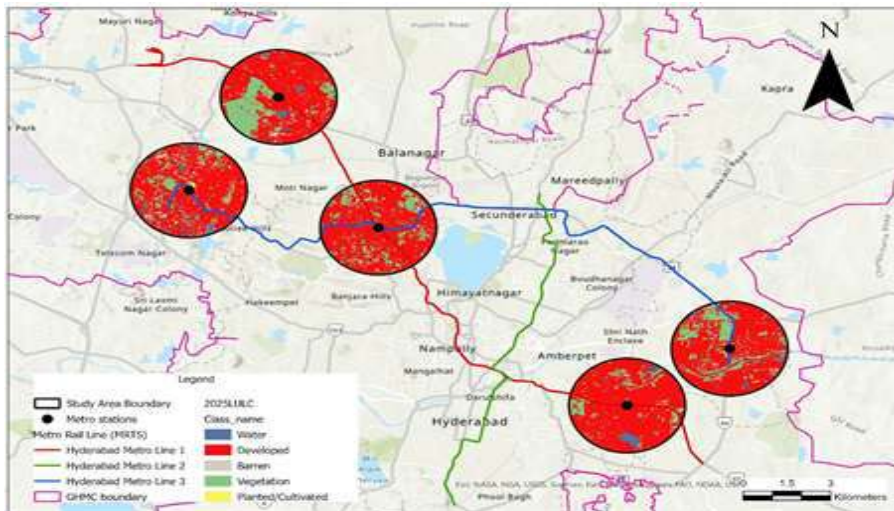
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Figure 3: Map Representing Land Use and Land Cover of Study Area - 2015



Source: Created by authors

Figure 4: Map Depicting Land Use and Land Cover of Year - 2025



Source: Created by authors

4.3 Survey-based descriptive analysis of property market changes

Table 1 shows the distribution of survey respondents with reference to the proximate metro stations identified and shown in the maps earlier. Figure 5 shows the distribution of survey respondents in terms of their residence location proximity to metro rail station. Through this chart, it is observed that respondents have metro stations at a distance of 500-1000m located from their localities.

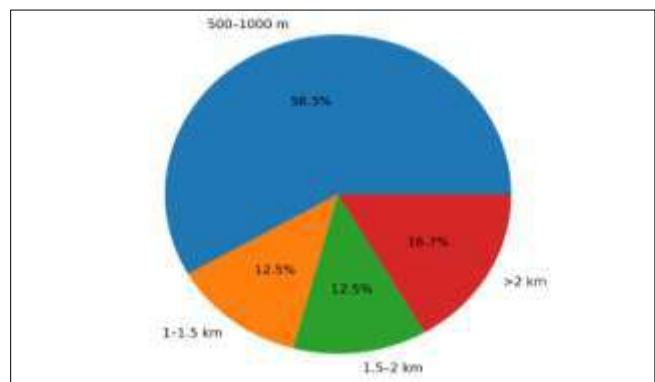
Table 1: Distribution of Respondents by Metro Station

Station Area	No. of Respondents
Dilsukhnagar	17
Hitech City	13
Kukatpally	7
Ameerpet	5
Nagole	4
Total	46

Source: Created by authors

Table 2 shows the respondents in terms of property they are associated with; there was an almost equal representation. Figure 6 shows the metro usage pattern of the survey respondents. From this pie chart, the results show that metro usage by respondents is done through “Weekly” at 41.7% depicting more compared to daily, monthly and rarely.

Figure 5: Respondent Distribution by Metro Station Area



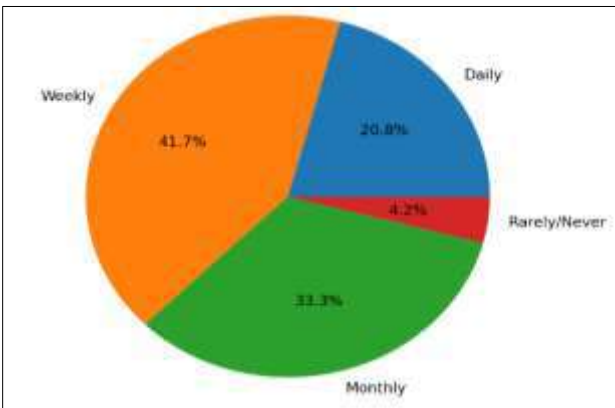
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Table 2: Classification of Respondents by Property Type

Respondent Type	Count
Residential	24
Commercial	22
Total	46

Source: Created by authors

Figure 6: Metro Usage Pattern of Respondents

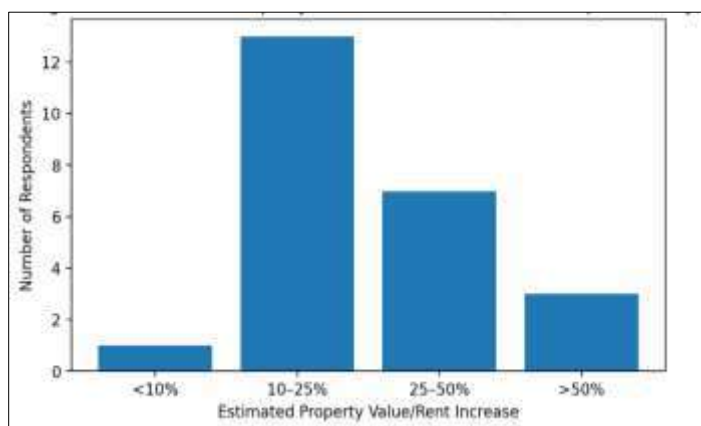


Source: Created by authors

4.4 Metro impact on property markets

Figure 7 shows the distribution of changes in property values after the implementation of Hyderabad metro rail project. Through this table, a 10 – 25% of estimated property value is observed to be increased/more with the help of number of respondents.

Figure 7: Required Change in Property Values



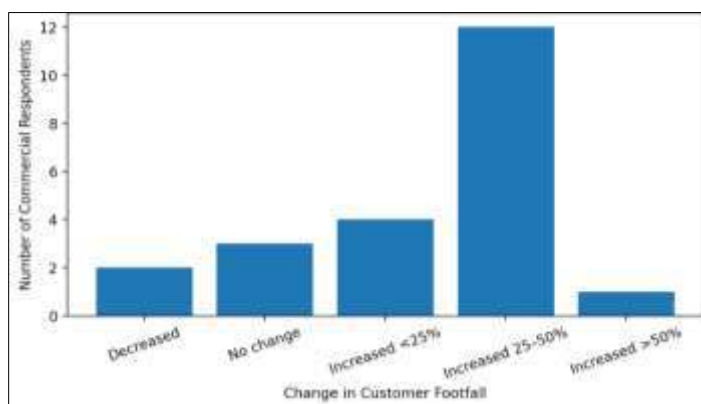
Source: Created by authors

Table 3: Change Represents in Commercial Footfall after Metro Implementations

Footfall Change	Count
Increased >50%	3
Increased 25-50%	12
Increased <25%	4
No change	3
Decreased <25%	2
Total commercial responses	24

Source: Created by authors

Figure 8: Customer Footfall Changes



Source: Created by authors

Table 3 shows the change represented in commercial footfall after metro operations. Figure 8 shows the distribution of such commercial footfall changes. The results from this chart represents those high changes in customer footfall is seen as 25 – 50% more from the respondents.

5.0 Conclusion

The study represents us with the data about how the impact of Hyderabad Metro Rail on land use patterns and also the real estate property markets mainly by focusing GIS analysis and main survey data. Land use and Land cover results from year (2015 - 2025) shows us a clear increase in developed metro areas, indicating boosted growth in urban areas. Vegetations, agricultural lands, and barren land areas rejected, after showing conversions of lands for commercial and urban purposes.

Survey findings showed better accessibility and also has improved based on frequent metro usage among residents and property stakeholders. Residential people helped in reporting and based on their reports, increase in property values were seen after metro implementation, showing full positive real estate market responses. Commercial properties also showed that they experience more customer footfall near metro stations, after confirming the metro's role in increasing business activities and location attractiveness.

6.0 Implications

Hyderabad Metro Rail has quite improved its connectivity along major urban areas, which has contributed to changes in land use patterns and real estate market behavior in station influence areas. The observed increases in development intensity and commercial activity highlight the importance of integrating metro projects with urban land use planning of urban areas to make sure properly structured and sustainable growth.

Survey findings indicate that nearest to metro stations is linked with increases in property values and rentals levels, showing the value lifts potential of infrastructures. Hence this supports the usage policies of transit-oriented development and appropriate zoning controls around metro stations to guide future development.

The study also represents how metro connectivity enhances commercial footfall and business performance near stations, indicating that these areas can be developed as economic activity hubs with improved pedestrian infrastructure and supporting services.

At the same time, increasing property values may create concerns for lower-income households and small businesses. Therefore, inclusive housing strategies and rental monitoring mechanisms should be considered as part of station area development policies.

Overall, the findings reveal that metro investments will and can influence and increase urban development zones and property markets when supported by perfect coordinated planning, effective last mile connectivity, and also including balanced regulatory frameworks.

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CHAPTER 37

Performance Evaluation of Paver Blocks Made with Recycled Concrete Aggregate (RCA) and Recycled Concrete Fine Aggregate (RCFA)

Meraz Ali, Gauresh Shetty**, Devesh Nauhawar** and Rihan Maaze****

ABSTRACT

The construction sector consumes a vast number of natural aggregates and generates a large volume of construction and demolition (C&D) waste, leading to environmental degradation and resource depletion. Much of this waste is improperly managed, causing unsustainable disposal practices. This study investigates the sustainable production of paver blocks (as per IS 15658:2021 – Precast Concrete Blocks for Paving – Specification) by partially replacing natural aggregates with recycled concrete aggregates (RCA) and recycled fine aggregates (RFA) derived from C&D waste. The experimental program uses a Taguchi L9 orthogonal array design to optimize mix proportions and evaluate the effects of RCA and RFA replacement levels on the mechanical performance of paver blocks. The recycled aggregate-based paver blocks were tested and compared with conventional cement concrete paver blocks to determine an optimal mix that ensures structural integrity and sustainability. This research addresses a crucial issue in sustainable construction, promoting a circular economy by reusing waste materials and reducing dependence on virgin resources. The results are expected to demonstrate that incorporating RCA and RFA in paver block production not only minimizes environmental impact but also offers a cost-effective and eco-friendly alternative for modern construction practices.

Keywords: RCA , RCFA , Paver Block, Performance.

1.0 Introduction

Major consumer of natural aggregates, the construction industry is also a very great source of construction and demolition (C&D) waste.

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The high rate of urbanization in India has contributed to more rapid loss of natural resources, and more burdening landfills as a result of improper disposal of C&D waste. Recycled Concrete Aggregate (RCA) or Recycled Concrete Fine Aggregate (RCFA) that are the by-products of the demolished concrete also provide a viable substitute to the conventional fine aggregates in concrete products like paver blocks (Bayram & Greiff, 2023).

Paver blocks consist of concrete that is common in pavements, parking space, footways, and roads that are less busy. Their workability, compressive strength, density, and the properties of durability like water absorption are the main factors of their performance. The current research uses a Taguchi L9 orthogonal array (3 factors x 3 levels) to maximize mix ratios and determine the impact of RCA and RCFA substitution on the performance of paver blocks.

2.0 Significance and Objectives of the Research

2.1 Research significance

Recycling of RCA and RCFA helps to sustain the construction through eliminating the need to use virgin aggregates, decreasing the environmental impact, and fostering the ideas of the circular economy (Merecycled et al., 2012). Nevertheless, the uncertainty of the recycled aggregate properties is such that it requires experimental validation on a large scale, which should be controlled.

2.2 Objectives

The main objectives of this study are as follows:

1. To utilize Recycled Concrete Aggregate (RCA) and Recycled Concrete Fine Aggregate (RCFA) in the production of paver blocks.
2. To evaluate the compressive strength of paver blocks containing recycled aggregates.
3. To study the flexural strength of paver blocks produced with recycled aggregates.
4. To analyse the water absorption characteristics of the paver blocks.
5. To compare the performance of recycled aggregate paver blocks with conventional paver blocks.
6. To assess the feasibility of using RCA and RCFA for sustainable construction applications.

3.0 Materials and Experiment Process

3.1 Materials

1. Ordinary Portland cement (OPC).
2. Natural Coarse Aggregate (control)

3. Recycled Concrete Aggregate (RCA).
4. Recycled Concrete Fine Aggregate (RCFA).
5. Potable water

The material properties were established according to the IS 2386 and the IS 4031 standards.

3.2 Experimental design

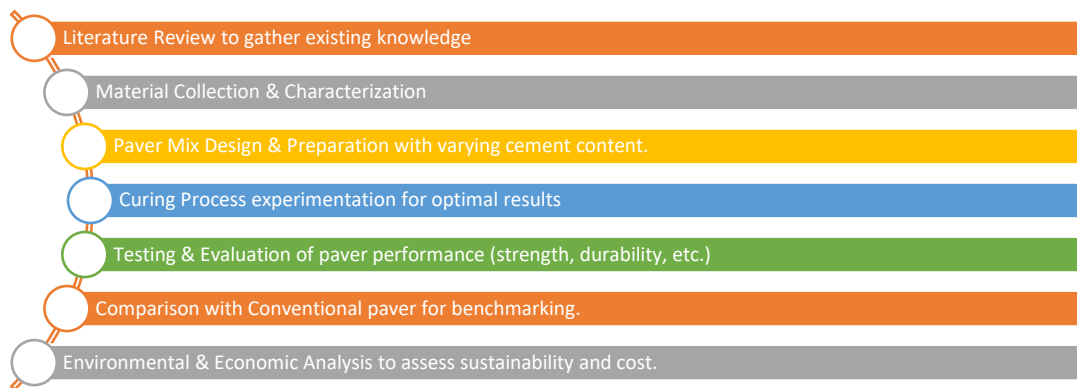
An orthogonal array of Taguchi L9 was accepted with three factors with three levels:

- RCA replacement (%)
- RCFA replacement (%)
- Cement content (fixed- mix independent)

This will reduce the number of experiments and yield statistical strength.

3.3 Research methodology

Figure 1: Flow Chart of Research Methodology



Source: Created by authors

3.4 Testing program

The following were the tests:

The water absorption and specific gravity of RCA and RCFA.

- Slump cone test
- Compaction factor test
- Density Fresh and hardened Fresh.
- Paved block uptake of water.
- Compressive strength test (28 day)
- Split tensile strength and Flexural Strength
- Abrasion Value

All the tests were conducted according to the IS 15658: 2006 and IS 516.

4.0 Discussion and Results of the Experiments

A workability characteristic is a property that is sought after but remains unstated. Workability is an attribute that is desired but not defined. The results of slump and compaction factor suggest that the workability decreases gradually with an increase in content of RCA and RCFA because of the enhancement of the water absorption of recycled aggregates and roughness of their surfaces, as was observed previously (Kadam et al., 2024).

4.1 Density characteristics

The fresh and hardened density values demonstrated a slight decrease with increase in the recycled content of aggregate, and it is because of the low specific gravity and porous structure of RCA and RCFA.(Tawalare et al., 2018)

The water absorption of paver blocks was studied, and the results are presented below. Water uptake rose as RCFA content rose because of finer particles and increased porosity. But still, the values were within the acceptable range in the case of non-structural and medium-traffic applications with pavers.

4.2 Strength performance- compressive

The outcomes of compressive strength will be added to the dataset when they are available. According to the literature, moderation levels of replacement will be sufficient to satisfy the requirements of the IS 15658 of paver blocks in pedestrian and light-traffic areas (Tawalare et al., 2018)

5.0 Experimental Data Table

Table 1: Summary of Experimental Results for Taguchi L9 Mixes

Mix ID	RCA (%)	RCFA (%)	Compressive Strength (MPa)
M1	0	0	33.245
M2	50	50	32.193
M3	50	75	31.164
M4	50	100	30.135
M5	75	50	30.576
M6	75	75	29.547
M7	75	100	28.518
M8	100	50	29.253
M9	100	75	28.224
M10	100	100	27.195

Source: Created by authors

Table 2: Water Absorption Test Results

Material	Weight Before Oven Dry (g)	Weight After Oven Dry (g)	Difference (g)	Formula Used	Water Absorption (%)
RFA (Recycled Fine Aggregate)	2010	1803.5	206.5	$\frac{SSD - OD}{OD} \times 100$	11.45 %
RCA (Recycled Coarse Aggregate)	2020	1978	42	$\frac{SSD - OD}{OD} \times 100$	2.12 %

Source: Created by authors

Table 3: Specific Gravity Test (Recycled Fine Aggregate)

Parameter	Description	Value (g)
W1	Weight of empty pycnometer	638.9
W2	Weight of pycnometer + dry aggregate	1140.8
W3	Weight of pycnometer + aggregate + water	1803.9
W4	Weight of pycnometer + water	1511.7
Specific Gravity (SG_FA)	Calculated value	2.393

Source: Created by authors

Table 4: Specific Gravity Test (Recycled Coarse Aggregate)

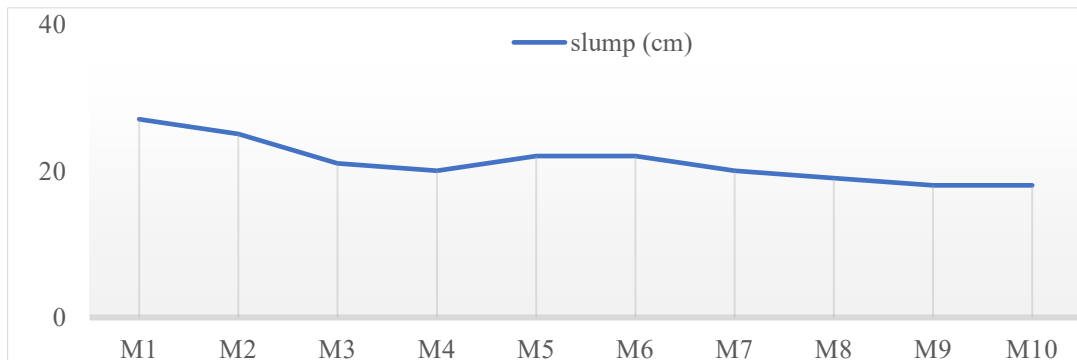
Parameter	Description	Value (g)
W1	Weight of empty pycnometer	633.8
W2	Weight of pycnometer + dry aggregate	1134.3
W3	Weight of pycnometer + aggregate + water	1822.8
W4	Weight of pycnometer + water	1504.8
Specific Gravity (SG_CA)	Calculated value	2.742

Source: Created by authors

4.0 Experimental Results and Discussion

4.1 Workability characteristics

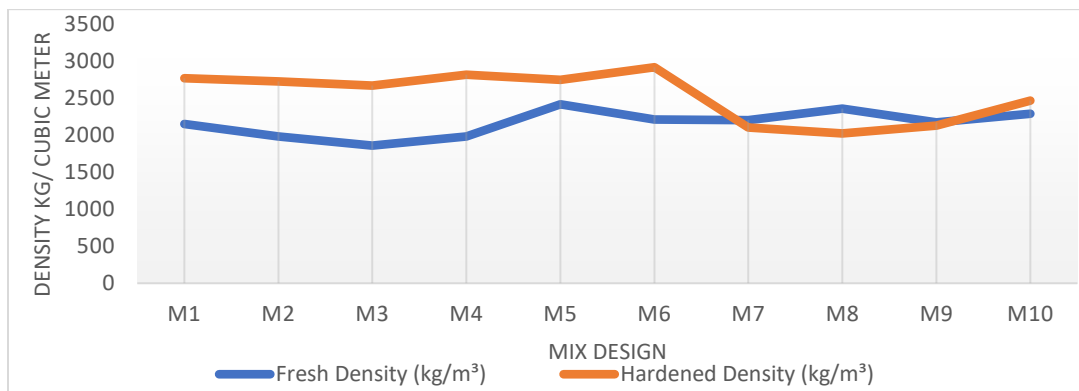
Slump cone and compaction factor tests were used to determine the workability of fresh concrete mixes, and the findings revealed a steady decrease in the proportion of fresh concrete mixes with increasing proportions of RCA and RCFA. This decrease is due to the increased water uptake capacity and rough and sharp surface texture of the recycled aggregates due to the presence of old mortar. With a smaller particle size and larger porosity, RCA exhibited a stronger effect on loss of workability than RCA. The same tendencies were also mentioned in the recent literature, with higher levels of recycled aggregates leading to higher water requirements and decreased plasticity of concrete blends (Bayram & Greiff, 2023).

Figure 2: Workability vs Mix ID

Source: Created by authors

4.2 Density characteristics

Fresh and hardened density values of the paver blocks showed a slight declining tendency with level of replacement of RCA and RCFA. This tendency is mainly because the specific gravity of recycled aggregates and their porous microstructure are lower compared to those of natural aggregates. Adhered mortar and internal microcracks are also present in RCA that leads to a lower unit weight that has also been noted in other experimental studies of recycled aggregate paver blocks (Shrivastava & Chini, 2009).

Figure 3: Density vs Mix ID

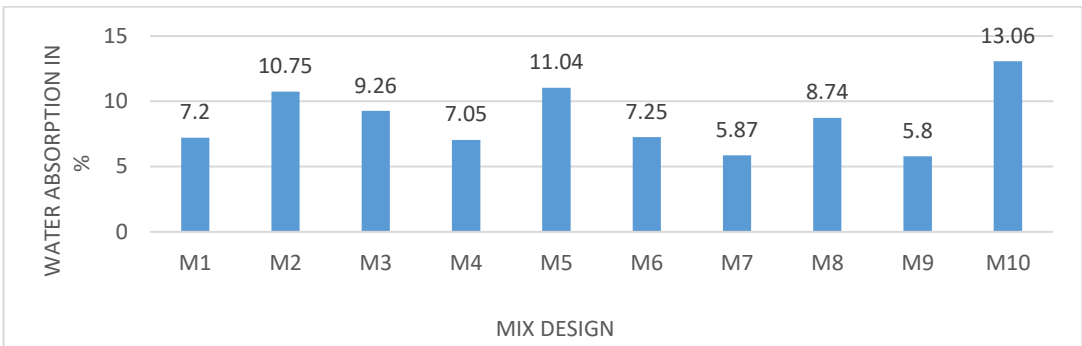
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4.3 Paver blocks absorption of water

The absorption of hardened paver blocks by water was also greater when the content of RCFA was increased because recycled fine aggregates contained finer particles and had

greater porosity. However, the obtained values did not exceed the allowable levels given in non-structural and medium-traffic paver utilization, which is consistent with the recent results on RCA-RCFA-based paver blocks (Tawalare et al., 2018)

Figure 4: Water Absorption vs Mix ID

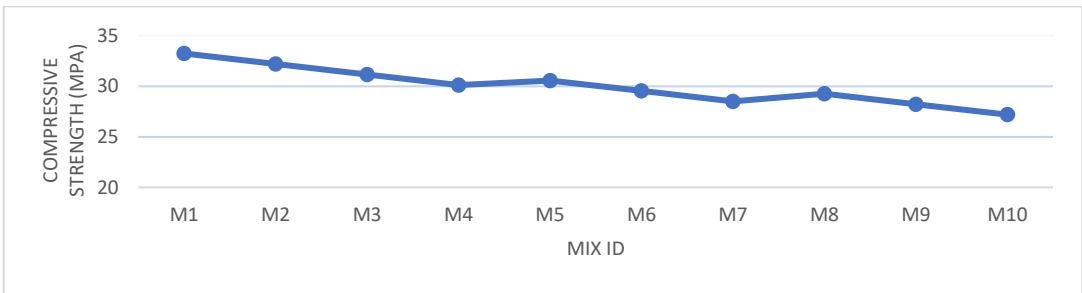


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4.4 Compressive strength performance

The findings of compressive strength show a gradual decrease of compressive strength with the level of RCA and RCFA replacement.

Figure 5: Compressive Strength vs Mix ID



Source: Created by authors

Nevertheless, mixes with medium replacement levels (up to about 50 percent) showed strengths that could be used in pedestrian and light-traffic applications, meeting the standards of IS 15658. The observation aligns with the modern research and reports that recycled aggregate content optimized by incorporating sufficient mechanical performance and increasing sustainability (Bayram & Greiff, 2023).
Purpose: Shows overall strength variation across Taguchi L9 mixes.

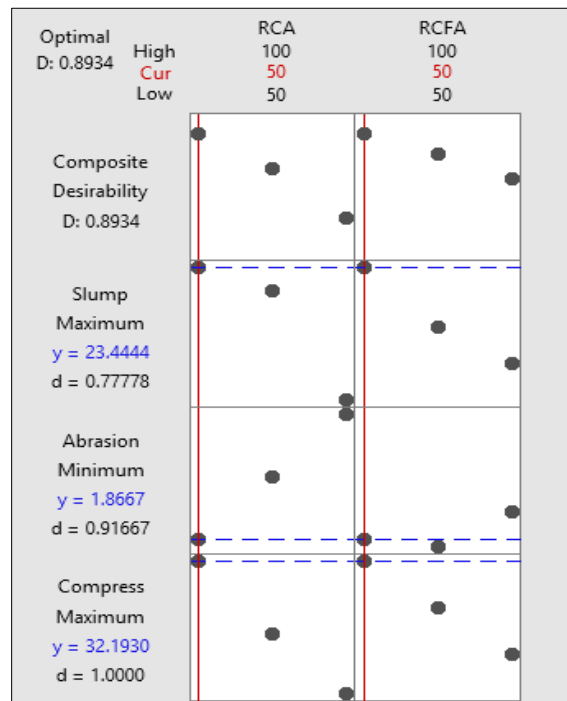
5.0 Master Experimental Data Table

Table 5: Summary of Experimental Results for Taguchi L9 Mixes

Mix	Cement	Virgin Aggregate		Recycled Aggregates		Water	Fresh Density (kg/m ³)	Hardened Density (kg/m ³)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)	Abrasion Value (mm)	Water Absorption (%)	Slump (mm)
		Fine Aggregate	Coarse Aggregate	RCFA	RCA									
M1	100	100	100	0	0	40	2150	2764	33.245	3.32	4.65	1.6	7.2	27
M2	100	50	50	50	50	40	1979	2723	32.193	3.21	4.5	1.8	10.75	25
M3	100	50	25	50	75	40	1857	2667	31.164	3.1	4.36	1.9	9.26	21
M4	100	50	0	50	100	40	1979	2814	30.135	3	4.22	2	7.05	20
M5	100	25	50	75	50	40	2414	2743	30.576	3.05	4.28	2.2	11.04	22
M6	100	25	25	75	75	40	2207	2914	29.547	2.95	4.14	2.1	7.25	22
M7	100	25	0	75	100	40	2200	2100	28.518	2.85	3.99	2.3	5.87	20
M8	100	0	50	100	50	40	2357	2021	29.253	2.92	4.09	2.5	8.74	19
M9	100	0	25	100	75	40	2171	2129	28.224	2.82	3.95	2.4	5.8	18
M10	100	0	0	100	100	40	2287	2465	27.195	2.72	3.81	2.6	13.06	18

Source: Created by authors

Figure 6: Multi-Response Optimization Plot (Taguchi Response Optimizer)



Source: Created by authors

6.0 ANOVA Analysis

Table 6: ANOVA Summary

Response	Recycled Concrete Aggregate P-value	Recycled Concrete Fine Aggregate P-value	R ²
Compressive Strength	*	*	100%
Abrasion	0.001	0.049	97.78%
Slump	0.048	0.138	83.98%

Source: Created by authors

The ANOVA results indicate that Recycled Concrete Aggregate is statistically significant for abrasion and slump because its P-values are below 0.05. For abrasion, Recycled Concrete Aggregate shows very high significance (0.001), while Recycled Concrete Fine Aggregate, is also significant (0.049). For slump, Recycled Concrete Aggregate is significant whereas Recycled Concrete Fine Aggregate, is less significant. The high R² values confirm that the regression model explains most of the response variation, indicating strong reliability of the optimization model.

Table 7: parameter of 3 tests

Response	Goal	Lower	Target	Upper	Weight	Importance
Slump	Maximum	18.000	25.000		1	1
Abrasion Value	Minimum		1.800	2.6	1	1
Compressive Strength	Maximum	27.195	32.193		1	1

Source: Created by authors

Table 8: Final Optimized Mix

Recycled Concrete Aggregate	Recycled Concrete Fine Aggregate	Slump	Abrasion	Compressive Strength	Desirability
50	50	23.444	1.867	32.193	0.893

Source: Created by authors

The multi-response optimization selected 50% Recycled Concrete Aggregate and 50% Recycled Concrete Fine Aggregate, as the optimum mix because it simultaneously produced the highest compressive strength, acceptable abrasion resistance, and suitable workability. The desirability value of 0.893 indicates that the selected mix is very close to ideal optimization. This confirms that moderate recycled aggregate replacement provides the best balance between sustainability and engineering performance for M30 grade paver blocks.

7.0 Conclusions

The current research will ascertain that Recycled Concrete Aggregate (RCA) and Recycled Concrete Fine Aggregate (RCFA) can be successfully used in the manufacturing of concrete paver blocks on a controlled basis when used in the specific proportions that will aid in the sustainable construction (Tawalare et al., 2018). The findings show that increment in the contents of RCA and RCFA results in slight decrease in workability, density and compressive strength because of the increased porosity and water absorption, but mixes with intermediate replacement rates (up to 50 percent) gave performances suitable in pedestrian and light-traffic applications. Taguchi L9 orthogonal array was also an efficient optimization tool that allowed to do systematic analysis of multiple variables with less effort during experiments. These results coincide with the latest research on the viability of the recycled aggregates in the concrete products and encourage the principles of the circular economy and preservation of the resources (Kadam et al., 2024).

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CHAPTER 38

Optimization of Trenchless Utility Diversion Techniques through Risk-Based Assessment for Metro Station and Tunnel Projects

*Aditya Itagi**

ABSTRACT

Utility diversion in metro stations and tunnels projects presents significant technical and managerial challenges due to dense underground congestion, strict deformation control requirements and severe consequences of utility service disruption. Although trenchless techniques are widely adopted, the selection of an appropriate diversion method is often experience-based rather than derived from a structured optimization process that considers project-specific risks. This study proposes a qualitative, risk-based optimization framework to support the selection of trenchless utility diversion techniques in complex metro station and tunnel environments. The research identifies and categorizes key risks, including construction, geotechnical, utility interaction and operational risks associated with major trenchless methods such as horizontal directional drilling, microtunnelling and pipe jacking. Expert judgement is incorporated to rank these risks and assess method suitability under varying site constraints and strict metro safety requirements. Based on this prioritization, a risk-informed decision-support matrix is formulated to aid method selection by reducing overall risk exposure while meeting constructability and operational requirements. The proposed framework enables systematic, transparent and consistent decision-making, thereby improving planning and pre-construction strategies for metro infrastructure and tunnel projects.

Keywords: Trenchless Technology, Utility diversion, Risk-based Optimization, Method selection, Metro & Tunnel Projects.

1.0 Introduction

Metropolitan areas require lots of underground infrastructure, and the massive growth of urban population and the growth in mass rapid transport systems have highly contributed to the high level of demand (Shen et al., 2016; Rogers et al., 2012).

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Metro stations and tunnels are commonly built below densely built urban corridors where underground conditions are already clogged with existing infrastructure, such as water supply pipes, sewer systems, gas pipelines, power cables, commercial telecommunication ducts, etc. These utilities present significant obstacles to novel underground constructions and utility diversion becomes a significant enabling undertaking with the development of metro infrastructures. Open-cut techniques of utility diversion are rapidly becoming inappropriate in the urban metro setting because of large-scale surface disturbance, traffic jams, environmental effects and the social costs (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). This has left trenchless technologies of choice to divert the utilities beneath the roads, buildings, and the existing transport infrastructure that are in operation. Horizontal directional drilling, microtunnelling, pipe jacking and manual/box jacking techniques have considerable benefits of causing less disturbance to the surface and keeping cities operating as normal in the course of construction.

Although such techniques offer certain advantages, trenchless construction technologies have a high level of uncertainty due to the lack of access to the excavation face, fluctuating ground conditions, contact with other utilities and structures, and high deformation control standards (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Even slight motions in the ground or utility malfunction in situations involving the construction of a metro station and tunnels can lead to severe safety hazards, service disruptions and negative publicity. In turn, the choice of a suitable trenchless utility diversion technique is a risky decision to consider at the initial level of planning and pre-construction.

Though there is a vast amount of literature on the individual trenchless methods and risk assessment, the current practice is more extremely based on experience and precedent of the contractor instead of formal, risk-based appraisal (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Existing decision-support models are generally generic and do not explicitly integrate metro-specific constraints, underground congestion, and expert judgment. The current paper provides the gap in understanding concerning the literature by reviewing and synthesising the current literature to aid the formulation of a qualitative, risk-based optimisation procedure, in the context of trenchless utility diverting in metro station and tunnel development.

2.0 Literature Review

2.1 Trenchless utility diversion techniques in metro stations and tunnel projects

The growing congestion underground and the inability of excavation viability in compact urban areas has seen the trenchless technologies being determined as part of utility diversion in metro station and tunnel projects (O'Reilly and Stovin, 1996; Sterling and

Godard, 2020). According to literature, the most prevalent methods are a horizontal directional drilling (HDD), microtunnelling, pipe jacking and a manual or box jacking. The two approaches have their own unique construction mechanisms, sensitivity on risks and limitation in their application in metro environments. Due to its capacity to provide curved alignments with limited surfacial disturbance, the horizontal directional drilling is often used to divert small- to medium-diameter utilities (Shen et al., 2016; Rogers et al., 2012).

Nevertheless, the literature has always pointed out that the HDD performance is very sensitive to the cover depth, soil stratigraphy, pressure in the drilling fluid and bore path control. Shallow cover and non-homogeneous ground conditions also favour high chances of surface settlement, bore instability, and unintentional utility strikes in the metro station areas. Microtunnelling is commonly believed to be a very precise method that can be applied to gravity pipelines and utilities where the line and level control is a necessity (Shen et al., 2016; Rogers et al., 2012). Studies have shown that it can reduce ground movements even under sensitive constructions such as metro tunnels including those in operation.

However, microtunnelling is not only costly in terms of capital expenditure but also has a high shaft construction demands and dangers of slurry pressure unbalance and jacking force increase, mainly in soft soils and mixed ground conditions. Utility diversion of medium and large diameter is usually carried out using pipe jacking (Shen et al., 2016; Rogers et al., 2012). Studies emphasize the importance of soil pipe interaction, lubrication efficiency, and soil arching effects in governing jacking forces. Jacketing of tunnels shall occur in shallow metro tunnels where penetrating existing tunnels may cause other stresses and thresholds that may trigger ground movements hence high-level deformation control and observation. Short-length diversions that typically occur in station boxes or in small urbanized areas are often undertaken by manual and box jacking (O'Reilly and Stovin, 1996; Shen et al., 2014). Even though these approaches are flexible when dealing with extreme space limits, the literature always reports increased risks to safety and reliance on workmanship.

Table 1: Comparison of Trenchless Utility Diversion Techniques in Metro Projects

Techniques	Typical Application	Alignment Control	Shaft Requirement	Major Risks	Metro Suitability
HDD	Small–medium utilities	Moderate	Low	Settlement, utility strikes	Moderate
Microtunnelling	Gravity pipelines	Very High	High	High jacking forces, cost	High
Pipe Jacking	Medium–large utilities	High	High	Force exceedance	High
Manual/Box Jacking	Short station diversions	Moderate	Low	Safety risks	Moderate

Source: Phillips et al. (2019); Sterling & Godard (2020); Sheil (2021)

2.2 Risk assessment in trenchless construction

Risk assessment has been considered an essential part of trenchless construction since the nature of the uncertainty of the underground works (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Initial work underlines qualitative risk identification with the help of expert judgement, because in the trenchless failures, events should be low-probability and high-consequence critical events. This risk profile is especially applicable in the case of metro station and tunnel projects where the maximum deformation and its consequences are too critical. Probabilistic methods have been established in order to measure the uncertainty in ground conditions and building performance. Observational and probabilistic models prove that deterministic design methods often fail to estimate the real jacking forces and deformation. Nonetheless, these techniques are very data intensive and are normally used at later stages in the project. Subjective expert evaluations can be used in risk prioritization with the help of fuzzy logic and multi-criteria decision-making (Shen et al., 2016; Rogers et al., 2012). Most of the existing structures though promising, are generalised and lack specifics of metro-related constraints, including network interference, beneath the ground congestion, and operational safety standards and demands.

Table 2: Risk Categories inn Trenchless Utility Diversion

Risk Category	Key Risk Factors	Potential Impacts	Representative Studies
Construction	Alignment deviation, jacking force exceedance	Delay, cost overrun	Sun et al. (2019)
Geotechnical	Settlement, groundwater ingress	Structural damage	Shen et al. (2016)
Utility Interaction	Utility strikes, stress redistribution	Service disruption	Rogers et al. (2012)
Operational	Restricted access, safety constraints	Work stoppage	O'Reilly & Stovin (1996)

Source: Synthesized from reviewed literature

2.3 Utility interaction and failure consequences

Utility interaction is one of the most vital risk dimensions in the metro station and tunnel projects since extreme underground congestions and intolerance to the service disruption (Shen et al., 2016; Rogers et al., 2012).

Research has continuously indicated that incomplete or inaccurate records of utility is one of the leading causes of construction-related accidents. Extensive studies of urban pipeline failures indicate that indirect causes of failure, including ground movement, redistribution of stress, and vibration caused by construction tend to be more influential in the failure initiation than direct physical contact (Shen et al., 2016; Rogers et al., 2012).

These interactions in the metro environment may have cascading consequences, e.g. emergency repairs and services blocking. Economic studies indicate that indirect and social utility failure costs are often larger than direct repair costs, which supports the fact that risk-based approaches to the development of planning should explicitly reflect the cost of failures (O'Reilly and Stovin, 1996; Shen et al., 2014).

Table 3: Utility Failure Consequences in Metro Projects

Failure Mode	Direct Consequence	Indirect/Social Impact	Severity
Utility strike	Repair cost	Traffic & service disruption	High
Excessive settlement	Structural repair	Metro service suspension	Very High
Pipeline collapse	Emergency repair	Environmental damage	High

Source: Zhang et al. (2024); Sun et al. (2021)

2.4 Decision-support and optimization approaches

The advanced optimization models have developed into decision-support systems with trenchless technology selection, which began as simple rule-based tools (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The initial expert systems were based on preset criteria of diameter, depth, soil type, and length of installation. Although these systems enhanced consistency, interactivity in terms of construction risk was not explicitly considered but rather only inferred through consistency in these systems.

Multi-criteria decision-making methods, such as the fuzzy logic and the weighted scoring model, are powerful in organizing the complex decision-making and integrating expert knowledge (O'Reilly and Stovin, 1996; Shen et al., 2014). Nevertheless, the majority of studies give more concern to technical feasibility or cost implications, but not to holistic risk mitigation. Optimization methods based on artificial intelligence are characterized by their high level of computer processing, but they do not always have transparency and can be applied in the early stages of designing a metro project (Shen et al., 2016; Rogers et al., 2012).

Table 4: Decision-Support Approaches for Trenchless Technology Selection

Approach	Key Criteria	Strengths	Limitations for Metro Projects
Rule-based systems	Diameter, depth, soil	Simple, transparent	Ignores risk interaction
Fuzzy logic models	Expert-weighted criteria	Handles uncertainty	Limited metro specificity
AI-based optimization	Cost, alignment	Efficient optimization	Low transparency

Source: Ariaratnam & Papandreou (2009); Chen et al. (2021); Wu et al. (2022)

3.0 Research Methodology

This study employs qualitative review-based methodology as a means of synthesizing the current research on trenchless utility relocation and risk-based decision-making in metro projects, thereby pointing out crucial risks and factors, which further assists the development of a conceptual and expert-driven optimization framework.

3.1 Research design

The research employs a systematic narrative review with analytical synthesis instead of a descriptive survey (O'Reilly & Stovin, 1996; Sterling & Godard, 2020). This method matches perfectly the exploratory purpose of extensive interactions of the trenchless methods, risk factors, underground congestion, and metro-specific constraints during planning phases. Due to variations across studies, quantitative meta-analysis was not considered. Identification, classification, and comparison of risks related to trenchless utility diversion in metro stations and tunnels, where failure consequences and deformation sensitivity are prominent, are the core aspects of the review (O'Reilly & Stovin, 1996; Sterling & Godard, 2020).

3.2 Literature selection and data sources

The Literature was collected only from peer-reviewed, high-impact journals to provide academic rigor. Scopus, Web of Science, ScienceDirect, and ASCE Library were the databases used, and these covered tunnelling, geotechnical engineering, and construction management. The selection concentrated on trenchless techniques, risk assessment, utility interaction, decision-support systems, and metro-related case studies. Only studies relevant to urban, metro, or tunnel contexts were kept (Shen et al., 2016; Rogers et al., 2012). To secure Q1 journal standards, conference papers, technical notes, and non-peer-reviewed sources were ruled out.

3.3 Screening and inclusion criteria

An organized screening procedure made sure that only relevant and high-quality papers got through. The following criteria were used for the selection of papers:

Definition of the topic and control methods for underground works and trenchless construction (O'Reilly & Stovin, 1996; Sterling & Godard, 2020). Interaction with utilities, geotechnical uncertainty or risks discussed openly (O'Reilly & Stovin, 1996; Shen et al., 2014). Possibility of being applied in urban, metro station, or tunnel settings (Shen et al., 2016; Rogers et al., 2012). Development of decision-making, risk assessment, or optimization processes (O'Reilly & Stovin, 1996; Shen et al., 2014).

Papers discussing studies conducted in laboratory settings, rural areas, or low-risk conditions were not considered (Shen et al., 2016; Rogers et al., 2012), thereby confirming that the studies matched the complexity of metro infrastructure.

3.4 Data extraction and classification

From the papers that were selected, qualitative data was taken out among others:

- Type of trenchless technique
- Risks related to construction, geotechnical, utility, and operations
- Causes of failure and consequences
- Criteria for decision-making
- Limitations and suggestions

The data were then organized into themes for comparison, with risks being classified into four main groups (O'Reilly & Stovin, 1996; Shen et al., 2014).

3.5 Analytical framework

Without a numerical ranking, the trenchless utility diversion methods were evaluated under the specific conditions of the metro (O'Reilly & Stovin, 1996; Sterling & Godard, 2020). The study pointed out the following risk sensitivity patterns;

- HDD with high settlement risk
- Microtunnelling or pipe jacking with more control but higher cost and logistical requirements
- Manual or box jacking with unequal safety risks

The EVIEWS decision-support approaches of expert judgment, risk interaction and site constraints integration were assessed and weaknesses in metro project complexity were revealed (Shen et al., 2016; Rogers et al., 2012)

3.6 Integration of expert judgement

This research highlights the importance of expert judgment (Shen et al., 2016; Rogers et al., 2012) by recognizing that metro planning in its early stages usually makes do with limited quantitative data. The literature suggests that expertise is usually applied implicitly but very rarely made transparent.

Therefore, the present study employs a mathematical method that first identifies risks through expert judgment and then gives them a rank of importance instead of using the conventional way of algorithmic optimization. This method corresponds to the real metro decision-making process, where the most skilled engineers and planners are the ones who determine the best construction methods to be used (Shen et al., 2016; Rogers et al., 2012).

3.7 Outcome of the methodology

The methodological result is a combined comprehension of risks, method applicability, and decision-making limitations in the case of metro projects trenchless utility diversion (O'Reilly & Stovin, 1996; Sterling & Godard, 2020). This synthesis supports:

- Research gaps identification
- A qualitative, risk-based decision-support framework development
- Future validation through expert surveys or case studies

On the whole, the methodology guarantees a systematic and undisguised review that conforms to risk-based optimisation in complicated metro areas (O'Reilly & Stovin, 1996; Sterling & Godard, 2020).

4.0 Data Analysis

The data analysis approach used in the study is interpretive and qualitative, which is consistent with the aims of establishing a structured, risk-based knowledge of trenchless utility diversion in metro station and tunnel project (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Since the available studies are heterogeneous (analytical modelling and numerical simulation, case studies, reviews and decision-support frameworks), a quantitative or statistical meta-analysis was not possible and appropriate.

Rather, systematic qualitative content analysis was utilized to bring together the results of the reviewed literature. The trenchless technique under analysis, the context of the project, identified risk factors, reported failure mechanisms, mitigation strategies, and decision-making criteria were the main attributes extracted in each analyzed paper (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). These qualities were then coded and classified into recurring themes that represented construction risks, geotechnical risks, utility interaction risks and operational risks. This thematic classification enabled cross-comparison of how different trenchless methods respond to similar constraints in metro station and tunnel environments.

This was followed by a comparative study of the sensitivity of each trenchless methodology to prevailing risk factors (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). To illustrate, HDD related research studies were evaluated, to gain insight in the effect of shallow cover depth, soil heterogeneity, and pressure in the drilling fluids on surface settlement and bore stability around metro stations. On the same note, the subject of microtunnelling, pipe jacking was also analyzed to determine the trends in the increasing jacking forces, occurrence of soil arches, efficiency of lubrication and effect of tunnel-soil-structure interaction. A construction safety and execution risk perspective was the most important in the analysis of manual and box jacking studies as they are based on workmanship

and are not highly mechanised. In addition to the personal risk factors, the analysis specifically studied the risk interaction (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The literature reviewed proves that risks in trenchless construction are hardly observed alone. As an example, geotechnical uncertainty tends to increase risks associated with construction i.e. alignment deviation or jacking force exceedance, which consequently raises the risk of utility interaction and disruptive operational occurrence. This interdependency was analyzed systematically to draw out the weaknesses of the traditional mode of selection which considers risks separately. Simultaneously, the literature on decision-support and optimisation models was reviewed to assess the level of uncertainty and expert judgment as well as metro-specific constraints (Shen et al., 2016; Rogers et al., 2012). Specific focus has been on the identification of whether these models expressly consider the effects of failure, underground congestion, and interference with the existing metro assets.

The discussion demonstrated that there have been clear lapses in the integration of qualitative expert judgment and structured risk prioritisation, particularly in the initial planning and pre-construction phases. In general, the qualitative data analysis allowed to conduct the systematisation of the piecemeal research results and assure the rational ground in determining the patterns, limitations, and potential improvements in trenchless utility diversion decision-making when considering metro projects (O'Reilly and Stovin, 1996; Sterling and Godard, 2020).

5.0 Findings / Results

The literature review leads to a number of valuable results that, in combination, describe the present level of practice and research in trenchless utility diversion in relation to the work on a metro station and a tunnel (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). First, the discussion proves the fact that the suitability of the trenchless method is strongly situational (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). There is no one trenchless method that can be regarded as the best in the metro conditions. HDD provides flexibility of alignment and low level of surface disruption but has high risk when covered shallowly such as those near metro stations. Microtunnelling and pipe jacking have better control of line and level and are therefore suitable under sensitive structures and functioning tunnels but are also expensive in capital and shaft demand and logistically more complicated. Box jacking and manual jacking present flexibility when used in tight station areas but cause unproportional safety and execution hazards.

The observation supports the inefficacy of generalizing selection methods. Second, early-stage decision-making is prevailed by construction and geotechnical risks, whereas the severity of the failures is determined by utility interaction and operational risks (Shen et al.,

2016; Rogers et al., 2012). Although most of the literature is aimed at prediction of settlement, jacking forces or face stability, the effects of failure like service disruption, emergency repair, and impacts on public safety- are often more critical in metro projects.

The research articles discussed in this paper show that indirect and social utility failure costs are often greater than the direct costs of repair, which suggests the importance of focusing on the consequence-based risk assessment instead of feasibility-based risk assessment. Third, the results indicate that current risk assessment methods are rather generic (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Even though qualitative, probabilistic, and fuzzy logic-based methods are suggested, most of the frameworks are designed to be applied to general trenchless and therefore do not explicitly deal with the metro specific constraints including the proximity of the tunnels, strict limit of deformation and the operational safety.

Consequently, they have a low level of applicability to the metro station and tunnel projects especially in the initial phases of planning. Fourth, the analysis reveals a strong lack of connection between the expert judgment and formal decision-support models (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The trenchless method selection depends on expert knowledge as a key factor in practice, but it is usually utilized on an informal basis and not in an organized and open-minded framework. The literature review regarding the decision-support systems is full of decision support systems that focus on technical feasibility or cost optimisation and underrepresented the interaction of risks and failure consequences. This restricts its applicability under complex metro conditions that have high levels of uncertainty and limited possibilities of taking corrective actions during construction. All of these discoveries support the idea that trenchless utility diversion in metro projects is mostly an experience-driven process, which lacks proper backing with organised, risk-sensitive decision-making equipment (O'Reilly & Stovin, 1996; Sterling and Godard, 2020).

6.0 Conclusion

This literature review has shown that trenchless utility diversion in metro stations and tunnel projects is by nature complicated because of the high congestion under the ground, geotechnical uncertainty, high deformation control, and drastic consequences of utility failure (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). Although the benefits of trenchless technologies are obvious in comparison with open-cut techniques in an urban setting, the recent successes of metro construction projects rely heavily on the correct choice of the methodology at the planning and the pre-construction stages.

The analyzed literature is characterized by the fact that the existing studies are also a valuable source of technical knowledge on the use of separate trenchless techniques, risk

factors, and mathematical models, but these works are still sporadic (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). It is apparent that there is no formal, qualitative, expert-focused, risk-based framework that is specifically designed to meet the needs of metro station and tunnel projects. The existing habits of decision-making usually focus on feasibility or cost concerns and are very dependent on unstructured experience, increasing exposure to high-consequence risks. In a practical view, the implications of the findings include the necessity to change experience-based selection to risk-based planning (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). By incorporating systematic risk detection and assessment of consequence, as well as the subjective judgment in initial planning, transparency, consistency, and defensibility can be improved in trenchless utility diversion planning. This is especially essential in case of such a project as a metro, where small setbacks may cause a disproportional effect on safety, functioning, and trust of people.

Regarding research, this research paper forms a sound conceptual base of creating risk-based optimisation models, as well as decision-support matrices with metro-specific examples (O'Reilly and Stovin, 1996; Sterling and Godard, 2020). The implications of this review can be used in the upcoming empirical studies such as expert surveys, Delphi studies, and case-based validation meant to be used to operationalise the risk-based trenchless technology selection. On the whole, the research can be valuable in enhancing the knowledge on trenchless utility diversion in the metro stations and tunnels and offer a valid rationale to support the application of structured, expert-led and risk-based planning methods in order to improve the planning outcome and resilience of infrastructure (O'Reilly and Stovin, 1996; Sterling and Godard, 2020).

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CHAPTER 39

Weather Related Delays and It's Impact in Construction

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ABSTRACT

Construction projects in India, particularly infrastructure developments like highways, bridges, and buildings, are frequently plagued by delays caused by adverse climatic conditions such as monsoons, heavy rains, floods, and cyclones. These delays often lead to disputes between contractors and clients, resulting in arbitration proceedings. This study analyses a collection of arbitration awards from various cases, focusing on how climatic factors influence dispute outcomes. Drawing from past case histories, it identifies key intrinsic (case-specific facts) and extrinsic (arbitrator-related and psychological) factors affecting decisions. The ultimate goal is to develop a framework that helps parties predict outcomes, decide whether to raise claims, and encourage out-of-court settlements, thereby reducing the burden on the judiciary.

Keywords: Construction delays, climatic conditions, monsoons, arbitration awards, dispute resolution, India infrastructure, predictive framework.

1.0 Introduction

Development of infrastructure is critical to economic growth of India thanks to such large-scale projects as the Bharatmala Pariyojana and redevelopment of cities. In spite of this growth, building projects are still prone to timeline slippage and budget over-runs and unfavourable weather has become one of the major and most legally demanding factors. The force majeure events like monsoons, floods and cyclones are usually categorized under Force Majeure, but vague contractual definitions leave contractors to bear the risks of the season when they are trying to demonstrate exceptional circumstances.

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India has various topography, and these problems are compounded by the fact that weather inconveniences are coupled with administrative setbacks. In turn, the disputes are often taken to arbitration where tribunals have to decide whether the weather effects were predictable or uncommon. This paper examines 14 arbitration awards and suggests a Decision-Making Framework to bring more alignment between weather risks and the contractual liability in Indian infrastructure project.

2.0 Literature Review

The two are the meteorological volatility and the contractual liability, which have been widely recorded to conflict in the construction management around the world (Chan and Kumaraswamy, 1997). According to most scholarly references, adverse weather is one of the key causative agents of the project overruns, and the legal implications of such incidents significantly vary across jurisdictions (Doloi et al., 2012). The review examines the evolution of weather-impact analysis, where it transcends the outdated qualitative analysis of the occurrence to presently, the data-oriented analysis, and identifies the gap in foreseeability that still resides in the Indian legal arena (Iyer and Jha, 2006).

2.1 Weather is the first disruption factor

The weather has always been ranked at the first position as causes of delays during construction in the literature (Chan and Kumaraswamy, 1997). The second variable that is deemed to be of primary significance in Jordan is weather conditions (15.3% following terrain) (Al-Hazim et al., 2017). According to the world research, unforeseen extreme weather can raise the life of the project by 5-20 percent (Nguyen et al., 2010). In India, the impact of the monsoon is also relatively extreme since seasonal rainfalls and floods usually delay important processes on the critical path like earthmoving and foundation (Doloi et al., 2012).

2.2 Decision support and WEATHER system

Due to technological progress, systems like the so-called WEATHER (Weather Evaluation and Analysis of Tracking High-impact Environmental Risks) system have been created (Ballesteros-Perez et al., 2017). It is a technical process which combines previous meteorological information and project scheduling software like Primavera or MS Project (Ballesteros-Perez et al., 2017). It uses the stochastic modelling concept to model probable delays and incorporate them into project baseline schedules before the commencement (Nguyen et al., 2010). These models are dynamic and need a specific sensitivity of activity compared to the traditional buffers (Ballesteros-Perez et al., 2018).

2.3 International vs. National backdrop: Regional issues

The Indian monsoons and weather criteria in other parts of the world are significantly different (Gunduz et al., 2013). The international standards, typically those used in the UK or Turkey, tend to pay attention to such parameters as wind speed and freezing degrees (Ballesteros-Perez et al., 2018), but in the Indian case, the main factor is the level of precipitation (Doloi et al., 2012). Temperature variations on a seasonal basis are the overriding considerations in estimating the construction periods that housing projects will require in Turkey (Tirataci and Yaman, 2023). On the contrary, Indian projects are challenged with unprecedented monsoons that can provide more than 200 percent of the monthly average rainfall in a span of one week hence changing the bearing capacity of the soils and making the site access roads impassable (Iyer and Jha, 2006).

2.4 Contractual uncertainties and foreseeability gap

The difference between what a contractor should have foreseen and the level to which the event has actually taken place is one recurrent theme in the literature known as the Foreseeability Gap (Nguyen et al., 2010). According to Moselhi and El-Rayes (2002), not all construction activities are sensitive to changes in the weather, and thus it is hard to quantitatively estimate them. The causes of ambiguities tend to be highlighted by the unclear nature of the clauses in the contract which does not lay down the exact level of rainfall that would qualify to be an exceptional event (Chan and Kumaraswamy, 2002). Canadian, Malaysian and Indian studies focus on the lack of unified definitions of Force Majeure, which contributes to ongoing conflicts in climate-sensitive infrastructure development (Sambasivan and Soon, 2007; Doloi et al., 2012) and has to be addressed by predictive and data-driven arbitration schemes in the Indian context (Schuldt et al., 2021).

3.0 Research Methodology

The study is designed in qualitative and comparative format, which implies a forensic examination of 14 arbitration awards and interim project reports of the Indian infrastructure sector. It applies empirical case evidence to come up with predictive model on decision making using legal precedents and meteorological data.

3.1 Data selection

14 arbitration cases were selected purposely, and all of them were cases of climatic disputes. The sample of projects includes different projects: highways, bridges, buildings, and manufacturing facilities, which captures the difference in weather sensitivity, especially in the route and foundational projects prone to moisture.

3.2 Analytical framework

A Multi-Factor Categorization Matrix of 12 decision factors was used to evaluate each case: It is divided into intrinsic (e.g., rainfall data, site records) and extrinsic (e.g., arbitrator perception). Results indicate that extreme weather events that are short in duration are regarded as exceptional, whereas the duration of rainfall is usually regarded as a predictable implementation risk.

3.3 Correlation and synthesis

Data on India Meteorological Department were cross-correlated with claims to isolate the predictable seasonal risks on arbitral outcomes and unusual climatic events.

3.4 Framework and validation

A Climatic Arbitration Decision Framework (CADF) was developed as a decision tree of logic to approximate the probability of a claim success depending on the severity, causation, and the quality of the documentation. To bring reliability, triangulation of evidence was applied and the separation of natural and administrative causes was made.

4.0 Data Analysis

This study is fundamentally based on a granular forensic study of 14 particular arbitration awards. Through classification of these awards, we can see that there is a convergence between the elements of technical complexity and climatic variables in order to manipulate the ultimate ruling of the tribunal.

4.1 Comparative Award Matrix (14 Cases)

The following table synthesizes the outcomes of the analysed cases, mapping the primary weather event against the final award type.

Table 1: Summary of Arbitration Awards of 14 Construction Disputes in India

Project Type	Case No.	Project Location / Name	Primary Weather Event	Core Legal Issue	Award Outcome
Highway / Road	1	Road Project, West Bengal	Extreme Monsoon	Idle machinery & fuel wastage	Partially Allowed
	2	National Highway, Odisha	Monsoon + Traffic	GSB layer damage	Full Award
	3	Rural Road Network	Unseasonal Rainfall	EoT for asphalt works	Allowed (Time Only)

	4	Sambalpur–Rourkela Highway	1994 Extreme Monsoon	Traffic damage on GSB	Full Award
	5	NHAI Strengthening Project	Delayed Handover + Monsoon	Idle resources	Full Award
Bridge / Marine	6	Major Bridge, Pune	Dam Water Release	Dewatering costs	Rejected
	7	Bridge, Maharashtra	Regional Flooding	Loss of coffer dams	Partially Allowed
	8	Marine Bridge, Odisha Coast	Cyclone / Storm	Marine equipment damage	Partially Allowed
	9	Bridge over Perennial River, Konkan	High Water Table	Foundation redesign	Full Award
	10	Marine Bridge, Konkan	Flash Floods	Prolongation costs	Partially Allowed
Building / Industrial	11	Building Project, Delhi	Monsoon / Drainage Failure	Basement flooding	Full Award
	12	Industrial Boiler Installation, Gujarat	Cyclone	Damage to stored materials	Partially Allowed
	13	Doordarshan Bhavan, Delhi	Torrential Rain	Municipal drainage failure	Full Award
	14	Industrial Shed, Gujarat	High Winds	Structural collapse	Rejected

Source: Created by authors

4.2 Project typology breakdown of individual cases

4.2.1 Category a highway and road infrastructure

- *Case 1- Memari-Chakdighi-Tarakeswar Road, West Bengal*

Conflict - The contractor had been asked to carry on with the roadwork during heavy monsoon rains which resulted in huge wastage of fuel (machinery idling) and wasteful labor.

Outcome - Partially Allowed. The tribunal acknowledged that the directives by the employers to work on rainy days posed a liability of the resources that were wasted, whereas the cost of extending the duration was reduced because of poor mobilization during dry seasons.

- *Case 2 - Strengthening of Highways, Odisha*

Conflict - Heavy rains reduced the Granular Sub-Base (GSB) into mud. The employer was insisting on having the road open to traffic and this ruined the integrity of the layer.

Outcome - Full Award. The tribunal considered that the damage was as a direct consequence of Extraordinary Weather in conjunction with the operational mandate of the employer.

- *Case 3 - Rural Road Network Project*

Conflict - Unseasonal rainfall that was not within the normal monsoon period interfered with the asphalt laying exercise.

Outcome - Allowed (Time Only). To evade Liquidated Damages, Extension of Time (EoT) was awarded, but monetary damages were not allowed since unseasonal rainfall was not considered a compensable event but an Excusable Non-Compensable event.

- *Case 4 - Sambalpur-Rourkela Highway (Package S2), Odisha*

Conflict - This example was the monsoon of 1994 that had a rainfall of almost twice the amount of rainfall within 10 years. The main argument was whether the contractor ought to have safeguarded the GSB against road traffic or not.

Outcome - Full Award. The tribunal granted an award of ₹11.41 lakh by approving that rainfall more than 200 percent of average is an exceptionally severe climatic condition.

- *Case 5 - NHAI Strengthening Project*

Conflict - The employer took time to hand over the sites until very close to the monsoon. The contractor claimed that the wet hand over did not allow any earthwork to commence.

Outcome - Full Award. The court held that when a site is offered during the commencement of monsoon transfer of the risk of idle time to the employer.

4.2.2 Category B bridge and marine works

- *Case 6 - Major Bridge at Bori in Pune*

Conflict - Repeated discharge of water on the Yadgaon Dam caused water to become stagnant in the riverbed, affecting casting of the piers.

Outcome - Rejected. Although the weather was the problem, the contractor could not submit the vouchers, bills or regular site records to show the actual expenditure other than what was already paid.

- *Case 7 - Bridge on Naray-Bori Road, Maharashtra*

Conflict - Coffor dams were swept away by abnormal floods. The contractor was claiming reconstruction expenses.

Outcome - Partially Allowed. Reconstruction costs were relieved, although it was cut by a third given that the contractor had not strengthened the dams to the design-build standard.

- *Case 8 - Odisha Coast Marine Bridge Case*

Conflict - A tropical storm destroyed special marine gear and staging.

Outcome - Partially Allowed. The tribunal had accepted the cyclone as an act of God but limited the award since the contractor had not sufficiently secured the equipment after the IMD warning.

- *Case 9 - Bridge over Perennial River, Konkan Railway*
Conflict - Unpredictable water table surge during monsoon created the need to alter the foundation depth, which was contrary to the initial tender.
Outcome - Full Award. The tribunal classified the water table change as an undetermined physical occurrence in the FIDIC Clause.
- *Case 10 - Konkan Region (L&T) Flash Flood Impact*
Conflict - Flash floods resulted in a 77 day overstay. The contractor was seeking prolonged overheads on a daily basis.
Outcome - Partially Allowed. The court of law ruled 50% of the claim since it was known that rain is a seasonal occurrence but flash floods of that scale were not predictable.

4.2.3 Category C Building and Industrial Systems

- *Case 11 - Residential/Commercial Complex, Delhi*
Conflict - Massive flooding of the basement due to 24 hours record rainfall.
Outcome - Full Award. The award was given due to the fact that employer had not cleared the outside drainage channel on the site and thus changed a natural occurrence into an avoidable loss.
- *Case 12 - Installation of Industrial Boilers, Gujarat*
Conflict - There was a cyclone that ruined the high-value welding rods and electrical cables that were stored on-site.
Outcome - Partially Allowed. The materials award was minimized on the fact that the contractor did not utilize weather-proof sheds as the site safety policy dictated.
- *Case 13 - Doordarshan Bhavan, Central Delhi*
Conflict - The employer did not get a municipal drainage certificate within time which complicated the torrential rain.
Outcome - Full Award. The tribunal gave the award of ₹15 lakh with the major reason being the Administrative Inertia which led to such a huge damage caused by the weather.
- *Case 14 - Gujarat Industrial Shed Project*
Conflict - A storm had high wind that led to the structural collapse of a shed that had been set up recently.
Outcome - Rejected. The argument was completely rejected since the contractor had violated the provision of Insurance Compliance by letting the policy expire.

Table 2: Summary Table of the 14 Case Decision Logic

Project Type	Primary Issue	Decision Driver	Typical Result
Highway / Road	Road & GSB Damage	Traffic mandate + severe rain	Full / Partial Award

Bridge / Marine	Water & Equipment Damage	Unforeseen physical conditions	Full / Partial Award
Building / Industrial	Site flooding & asset loss	Employer admin failure	Full Award
Any	Asset loss	No proof / insurance lapse	Rejected
Any	Equipment damage	Contributory negligence	Partial Award
Road	Scheduling	Unseasonal but mild rain	Time Only

Source: Created by authors

4.3 “Act of God” vs. Employer Fault

The results of arbitration indicate that even an Act of God defence is not always effective. In the Gujarat boiler project, the contractor was not successful in his claim because of failure to meet the requirements of insurance. On the other hand, in the Doordarshan Bhavan case, damages were paid due to the employer delays in approvals, which blocked the installation of drainage, which aggravated monsoon floods.

4.4 Data analysis statistical trends

In 14 cases, the tribunals used similar patterns, but in balancing the climatic impacts with the contractual responsibility. The victories largely relied on the cases in which weather effects were increased by actions of employers because, in most cases, such delays were caused by nature itself.

Table 3: 8 Key Factors Influencing Arbitration Awards

Factor	Description	Frequency (out of 14 cases)	Impact on Award
Evidence Reliability	Credibility and sufficiency of meteorological data, site records, and photographs.	14	Decisive: Claims lacking logs or IMD data consistently fail.
Climatic Severity	Whether the event was exceptional, abnormal, or beyond normal foreseeability.	14	Mandatory: Severity must be proven (e.g., ~140% above average) to qualify for relief.
Foreseeability & Mitigation	Whether the contractor could have anticipated and mitigated the weather impact.	12	Risk-Shifting: Normal monsoons are contractor risk; only abnormal events are excusable.
Contractual Compliance	Strict adherence to procedural requirements like notice periods and insurance.	11	Gatekeeper: Procedural lapses often nullify otherwise valid weather claims.

Employer's Contribution	Whether administrative failures (e.g., late handover) exacerbated disruptions.	10	Compensatory: Employer fault often turns a non-compensable event into a compensable claim.
Entitlement to Compensation	Determining if weather impacts directly justify financial recovery.	10	Selective: Time extensions are common; monetary relief requires a higher burden of proof.
Equitable Considerations	Application of fairness to balance strict contractual bars in cases of administrative lapses.	6	Corrective: Used to ensure justice when strict contract terms lead to extreme unfairness.
Expert Testimony	Reliance on technical or meteorological experts to validate impact severity.	5	Validation: Essential for proving complex issues like unforeseen water table shifts.

Source: Created by authors

4.4.2. The probability of success of claims

A review of 14 arbitration awards shows that there is evident pecking order in the relief awarded. Tribunals in most situations would grant Extensions of Time to offer protection to the contractor against liquidated damages but refused to offer monetary compensation. The exception was that financial relief was given in cases where extraordinary weather was combined with administrative delays by employers. A total dismissal of the claims was usually associated with the low quality of evidence, no insurance coverage, or notice non-observation. On the whole, the results indicate that the relief of time is frequent, but cost recovery needs evidence that the loss was caused not by weather itself but by the employers.

4.5 Theoretical framework intrinsic and extrinsic factors

Contractual clauses are not the only factors that define weather-related disputes in Indian construction. The decision made on the case is affected by the interplay of objective project facts and the subjective opinion of arbitrators. This paper will classify these influences as intrinsic and extrinsic factors.

4.5.1 Factors intrinsic: The empirical ground

Intrinsic factors include the project level evidence that is created in the course of execution and are the foundation of any claim. Among the essential aspects, the extent of weather anomaly of the historical weather averages of IMD, the quality of contemporaneous documentation and records, including site logs and photographs, adherence to the requirements of the contractual notices, and the necessity of the necessary insurance are the ones to be mentioned. As seen during analysis of cases, even severe weather claims can fail in case documentation is not complete or insurance obligation is not fulfilled.

4.5.2 Factors: Extrinsic, psychology of adjudication

Extrinsic factors are acting in the process of arbitration and explain the disparity of an outcome of similar climatic events. Arbitrators tend to consider sudden, high impact events to be Acts of God, whereas long term seasonal condition is normally considered as something that can be predicted. Equity is also regarded by tribunals when the employer postpones work until bad weather conditions arise and often guidelines of the experts are applied in a technically difficult situation.

4.6 Decision-making logic: Yes/No analysis

The scheme uses a hierarchical yes/no reasoning to assess assertions. Some of these factors, e.g. insurance compliance are considered to be the immediate gatekeepers, whereas the important factor in transforming time-only relief into monetary compensation is that of the employer contribution. The framework presents factual evidence with arbitral discretion by organizing these decision paths to be more reliable in predicting results.

5.0 Findings and Results

5.1 The rule of three decisive factors

In weather related construction disputes, liability is hardly ever on the basis of weather. Arbitral decisions are formed by three decisive factors, namely foreseeability, the determination whether an event was higher than the usual seasonal or historical rates, contributory conduct, especially the failure of the employer to complete site handovers, drawings, or approvals, and evidentiary proof, which demanded uniform site records, photographs, project logs, and certified IMD information. Not even harsh weather conditions can be used as an excuse to make unjustified claims.

5.2 Standard threshold of excusable delay

Arbitrators draw the line between the normal climatic adversity and extraordinary conditions. Normal bad weather may permit time recovery and not often money. The successful claims are usually events with margins way above historical standards, even almost twice the long-run rains.

5.3 Time vs. Financial relief

Abnormal monsoons usually warrant an Extension of Time (EoT) to avoid liquidated damages, but monetary compensation is awarded where breaches or delays by the employers play a role.

5.4 Evidentiary weight

The signed hindrance registers and certified IMD data are decisive; the assumptions and post-project claims are normally not accepted. Claims require real-time documentation to be successful.

6.0 Recommendations: Climatic Arbitration Decision Framework (CADF)

6.1 Framework description

The Climatic Arbitration Decision Framework (CADF) is a four-stage logic-driven framework known to minimize subjectivity in claims of weather-related issues. It assists in differentiating normal commercial risk and compensable delay on the basis of objective and verifiable criteria.

Tier 1: Level of Severity (Meteorological Verification): Weather analysis is overlaid on 10-year IMD average. When in the range of 120% of the mean, conditions however, are considered normal risk and conditions that are above 140 percent are considered extraordinary.

Tier 2: Causation and Responsibility (Administrative Check): In case of the delays caused by employers and causing the work to fall into bad weather hours, the liability changes. In case of contractor inefficiencies that cause delays, time is the only way out.

Illustrative Case Study: On an Odisha highway project, constant rainfall and traffic ordered by the employers ruined prepared layers. The court gave ₹11.41 lakh acknowledging the measures imposed by the employers in case of weather extremes.

Tier 3: Documentation Audit (Evidentiary Check): Claims with high probability need triangulated evidence: IMD data, signed site records, and visual evidence of attack on essential activities.

Tier 4: Predictor of Outcomes (Risk Allocation): The natural events that are pure normally result in time-only relief. The effects caused by the employer on the weather conditions include relief of time and money, whereas the ordinary weather, lack of documentation, or breaches of the contract are met with denial of claims.

Illustrative Case Study: Procurement Delay on the Employer Side: The tribunal identified an implied employer duty to provide mentioned resources in Odisha project when the weather conditions caused the closure of quarry. Because alternative sourcing was needed out of the extraordinary weather and administrative limits, the extra work was to be compensable.

7.0 Implementation: Manual on contractor strategy

Individual contractors ought to use a systematic strategy manual in managing any weather- and terrain-related delays and in ensuring fair results in the Indian construction

projects. This method is based on the methodical utilisation of weather information and professional records to measure the delays, risk management, and profitability of the project.

7.1 Pre-construction: Establishing the baseline

Contractors cannot avoid conflicts at a later stage by having no clear understanding of what good and bad weather conditions are before the start of the project. These involve introducing quantifiable weather limits, introducing realistic weather buffers into project plans on a regional basis, and negotiating contractual provisions clearly acknowledging weather and ground risks. Defined baseline can prevent the probability of a rejection of claim considerably.

7.2 Construction Phase: Mitigation and Active Monitoring

In the execution, constant oversight is important. Contractors are expected to note weather conditions on a daily basis based on the India Meteorological Department (IMD) data and directly correlate the weather conditions with the effects on the site, like flooding, waterlogging, or landslides. Weather-sensitive operations should be recorded in details site diaries, and regular checking of short-term IMD forecasts should be done to enable proactive rescheduling of weather-sensitive operations to reduce unnecessary delays to a minimum.

7.3 Claim Management: Documentation Standards

To make successful claims, they must be clear and consistent. The standardized concise forms of claims that contractors should employ should be backed by triangulated pieces of evidence, namely, official IMD data, personal site records, and visual evidence. Monthly verification with the clients should be held to assess the excusable delays and process claims on an ongoing basis and not at the end of the project.

7.4 Illustrative Case Study: Procurement Delay (Contractor Side)

A contractor wanted compensation in a project he was doing in an industrial shed in Gujarat because of bad weather, the steel and cladding had been damaged. The court dismissed the allegation because there was no required Contractor All Risk (CAR) insurance and insufficiency of storm-preparedness. The case points out that the extreme weather conditions do not even help to transfer the financial risk to the employer in the case of the contractors who neglect to maintain insurance and other basic protection measures.

7.5 Implementation guidelines

Clear climatic limits of abnormality should be set by contract (e.g., rainfall above 30 mm/day). The contractors will have to incorporate IMD data in daily logs and the weekly

schedules. Notably, the contractors must not enter into unconditional no-loss contracts in the course of the extension requests as they in most cases restrain subsequent claims of costs.

8.0 Conclusion

This paper underscores the fact that the Indian construction industry must shift to a non-adversarial dispute resolution mechanism based on data. The assessment of 14 awards of arbitration reveals that tribunals are becoming more inclined to the more powerful documentation rather than the generic Force Majeure claims particularly where uncertainty in the environment is overlapping with administrative delays. Although time extensions are in many cases possible under the contractor, financial compensation is based on the demonstration of aggravation by employers. The suggested Climatic Arbitration Decision Framework (CADF) is a unified way of evaluating weather delays based on objective weather data, and organized documentation. By 10-20% this framework can be used to reduce delay disputes and enhance the risk allocation. With the ongoing development of India in large infrastructure programmes, the performance-based weather risks management will be needed with transparency to ensure the project resilience and sustainability of the sector.

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CHAPTER 40

Solar Tracking Systems for Utility Scale Photovoltaic Plants: Performance Optimization, Construction Challenges, and Artificial Intelligence Driven Control Strategies

*Venkat Vishwanath Peri**

ABSTRACT

Solar tracking systems have become more and more common in big solar power plants as they produce a lot more energy than fixed-tilt installations. On the one hand, fixed-tilt systems are simpler to operate, but their limitations due to the inability to change orientation and to capture sunlight are significant. Tracking systems can increase the energy output up to 30% depending on the year. Nevertheless, their performance can be compromised by inter-row shading when the sun is low and the unpredictable weather conditions for the operation. Most of the existing plants use tracking algorithms that are based on pre-defined motion profiles derived from past weather data. This practice may cause, during cloudy weather, the unnecessary movement of the actuator and more damage to the machinery. In this paper the authors identify the operational issues and present an adaptive tracking method that combines real-time irradiance sensing, cloud-aware control logic, and better backtracking techniques. The aim of the proposed framework is that it can both reduce shading losses and avoid unnecessary tracker movement during cloudy conditions. The findings from the field observations and simulation indicate that the adaptive strategy can reduce actuator movement by about 40-60% while still producing more energy than fixed-tilt systems.

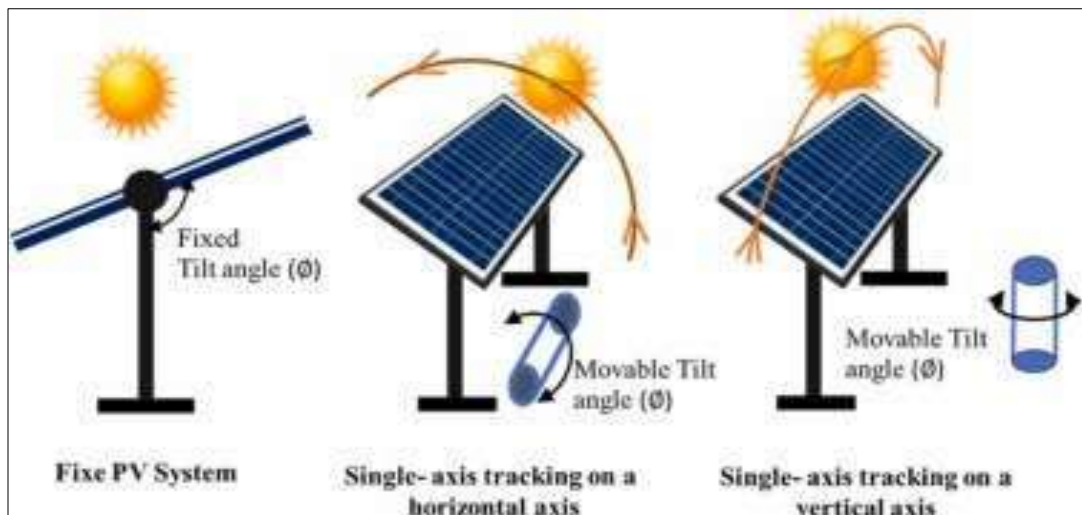
Keywords: Solar tracking systems, Adaptive tracking control, Real-time irradiance sensing, Cloud-aware algorithms, Backtracking techniques, Actuator movement optimization.

1.0 Introduction

The surge in energy demand globally and rising concerns about climate change and depletion of fossil fuels have increased the rate of adoption of RE. In all available RE options, solar energy has gained considerable attention as one of the promising options due to its availability and reduction in photovoltaic module price.

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However, despite state-of-the-art development in photovoltaic module technologies, solar power efficiency is subject to variation and variability. The conventional photovoltaic power plants use only a small percentage of solar energy as the panel remains fixed at one position and does not change orientation with the sun. In this context, solar tracking systems have been developed to effectively overcome this constraint by adjusting the angle of the solar panels to face the sun to maximize the received solar irradiance. A number of studies have confirmed that the energy generation from the solar panels can be maximized up to 30% with the help of a solar tracker system. Such solar tracker systems have thus gained tremendous popularity in the utility-scale solar power plants in different locations around the globe, especially in locations receiving a considerable amount of direct normal solar irradiance. However, the successful implementation of solar tracker systems has given rise to several challenges, both in terms of costs incurred in the construction of the systems and the design of the solar tracker systems themselves.



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From recent investigations, it has also been noted that the performance of the solar tracking system is affected by various layout parameters. Incorrect construction techniques or poor foundation of solar tracking systems also need to be taken into account, as they may cause adverse impacts on the performance while considering the advantages of the solar tracking system. In the recent past, bifacial photovoltaic module integration along with the use of the solar tracking system has also increased, making the factors more complex. Each factor needs to be taken into account while considering the use of solar tracking for solar energy harvesting.

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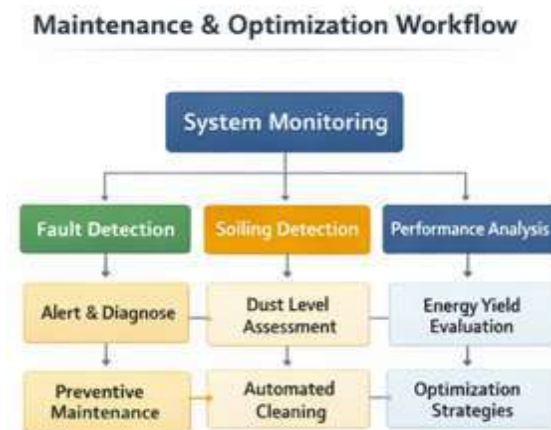
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Keeping in view the ever-increasing size of solar power plants, conventional rule-based systems for solar panel tracking/monitoring have shown lackluster results in such complex systems to attain desired solar panel performance/reliability. In this context, the application of AI techniques has also attracted the attention of many researchers based on their potential to handle non-linearity while dealing with the task of solar panel maintenance/tracking in varying environmental conditions by utilizing the potential of Maximum Power Point Tracking while considering a number of solar panel applications in varying scenarios of partial shadowing effects.

At the same time, the Internet of Things (IoT) concept has come into play as an enabler for real-time monitoring systems for fault detection and prediction in solar tracking systems. IoT-based systems have greatly enabled the monitoring of various variables/parameters for solar parks with the help of sensors and wireless communication systems, leading to the reduction of operating and maintenance costs while increasing availability and reliability. This marriage between IoT and AI is laying the foundation for

the evolution of an artificially “smart” solar tracking system that responds to uncertainties in the environment through changes in the solar position due to varying weather situations.

Yet despite a vast array of research on solar tracking tech and technology itself, a comprehensive perspective on combining solar tracking tech classifications, efficient mechanical constructions of solar tracking tech, and digital intelligence appears to be underdeveloped and in need of further research to advance these contemporary solar tracking tech constructions to a further level of development in a more optimized way using AI and IoT tech integrations to enhance solar power generation in terms of efficiency and reliability in a more efficient and intelligent way. The paper aims to view solar tracking tech in an efficient and intelligent way by focusing on performance enhancement and efficient construction methods of solar tracking tech.



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2.0 Literature Review

The performance variability and dynamic performance of solar tracking have not been new areas of research in the performance of photovoltaic installations, particularly in the mature solar markets of the world. In the last two decades, extensive research has gone into the comparison of the performance of photovoltaic installations employing tracking as well as fixed-tilt to develop the performance relationship. Findings of several research works have confirmed the advantages of solar tracking installations over fixed-tilt installations in the performance of the photovoltaic installations; the advantages have been confirmed to extend temporal variations depending on the environmental conditions (Tonita et al., 2023; Barbón et al., 2023; Bruno et al., 2015). These suggest the performance of solar tracking installations to be dynamic.

From literature, the relation between the tracking mechanism movements and the generation process is more dynamic. This indicates that the marginal benefit depends on the solar position, the presence of clouds, or any atmospheric effect. A 15-30% energy increase can be achieved with single-axis tracking, while the dual-axis trackers can achieve more than 30% for better conditions (Hoffmann et al., 2018; Kabir et al., 2025). This is not the only condition because the literature indicates that the trackers' movements under diffuse or cloudy conditions cause unnecessary movements with minimal gains while increasing the costs (Batayneh et al., 2019; Bruno et al., 2015). Such conditions prompted the emergence of adaptive trackers that can track the presence of clouds.

Various studies emphasized the vital role played in mitigating the effects of inter-row solar shading loss by the backtracking algorithm. This was clearly indicated in the various studies focusing on the necessary optimizations of the Ground Coverage Ratio (GCR). This indicates the untapped benefits of the solar trackers from inappropriate backtracking during solar illumination occurring at low solar elevation angles (Tonita et al., 2023; Barbón et al., 2023). From the study conducted by Keiner et al. (2025), the benefits of layout and spacing optimizations are superior compared to the advantages obtained from module technology itself.

Recent literature also defines the distinction between short-term and long-term performance relations of the tracking-based PV plant. While the short-term performance relates to the effects of the overall movement of clouds, partial shading, and sensor uncertainties, the long-term performance relates to the cumulative effects of mechanical components, soiling, and maintenance strategies (Shingleton, 2020; Flores-Hernandez et al., 2021). For specific and certain types of track configurations with minimal movement, investigations have proven the possibility of acquiring more than 90% of the possible power for continuous tracking with minimal stress on the mechanical components of the tracker system (Batayneh et al., 2019).

“Informational linkages have provided a basis for recent achievements in intelligent solar tracking systems.” Two channels of information exchange are specified in existing literature: “One involves common environmental information exchange such as irradiance levels, cloud cover, and solar angles that concurrently affect tracker control and power generation.... Another channel involves system-specific information exchange of tracker condition, temperature levels, and soiling intensity that primarily affects localized levels before spreading to all areas via control interventions.”

Nevertheless, the use and development of Artificial Intelligence strategies for dealing with the non-linear and dynamic nature of solar tracking systems has become more popular day by day. For instance, Feed-Forward Neural Networks, Long Short-Term Memory Networks, and Reinforcement Learning have been utilized for irradiance

forecasting, smart tracking systems, and grid integration optimization problems, respectively (Singh et al., 2024; Votava et al., 2024). Moreover, novel hybridized intelligent algorithms for the maximization of power in solar tracking systems, called Grey Wolf Optimizer and Marine Predator Algorithm-PSO hybrids, have also been reported to have fast and strong tracking capabilities under conditions involving partial shading effects (Aguila-Leon et al., 2023; Mishra et al., 2024).

This is parallel with the development in the integration of AI. A new technology that has come on the scene as a key enabler in real-time monitoring and condition-based monitoring of tracking systems is the Internet of Things (IoT). IoT-based monitoring enables the monitoring of electrical, mechanical, and environmental parameters through the sensing technologies used with the help of the Internet platforms via the sending signals via the Global System for Mobile Communication (GSM) technology, which enables the real-time monitoring (Nkinyam et al., 2025; Shukla et al., 2024). This technology becomes essential, especially with large solar park development.

Another critical aspect of tracker-based solar panel systems that has been less explored in the context of PV systems is the aspect of soiling/automated cleaning mechanisms of PV systems. Studies have shown that soiling can incur energy loss on an annual scale in the range of 5-10% in arid environments (Lara-Vargas et al., 2025). Even the application of automated systems has been explored to reduce such energy loss mechanisms; however, the interaction between the tracker system.

Horizontal Alignment: While there is extensive research related to solar tracking technologies, most rely on predefined astronomical tracking profiles and static backtracking rules. Empirical evidence on cloud-aware, adaptive tracking integrated with AI, IoT, and automated cleaning systems remains limited, particularly for large-scale solar parks in high-irradiance and dust-prone environments. This gap brings forth the requirement for integrated frameworks that co-optimize tracking motion, shading mitigation, cleaning schedules, and long-term system reliability.

3.0 Research Objectives

From the literature examined above, the objectives of the study are the following:

- To study the dynamics of the performance characteristics of the solar tracking mechanism under different states of irradiance.
- To assess cloud-based tracking strategies for optimal energy harvesting while ensuring minimal activation of actuation systems is required.
- To examine the effectiveness of the more sophisticated backtracking methods in minimizing the losses due to shading while optimizing the usage of the land.

- Determining its use in moderating between automated cleaning system usage and tracker motions in order to reduce soiling losses.
- Develop a framework based on the integration of artificial intelligence technologies along with IoT to facilitate adaptive control, real-time monitoring, as well as predictive maintenance of solar tracking systems.

4.0 Data and Methodology

4.1 Data

- Hourly and sub-hourly data on solar and meteorological parameters such as global horizontal irradiance, direct normal irradiance, diffuse irradiance, ambient temperature, wind speed, and cloud cover.
- Data on photovoltaic system characteristics involving aspects such as monofacial photovoltaic modules, bifacial modules, fixed-tilt configurations, single-axis configurations, double-axis configurations, tracker geometry measurements involving tracker rows, tracker tilt, and
- Operational tracker data that may include actuator power consumption, tracking range, backtracking limits, and tracker movement frequency.
- Including soiling-related data, dust deposition rates, losses due to soiling, as well as the effectiveness of automated cleaning.
- The Internet of things (IoT)-based monitoring information, like the measured data from power production, voltage levels, current levels, module temperature levels, tracker position levels, etc., sent wirelessly or through GSM networks.

4.2 Methodology

- Baseline Performance Assessment - Conventional Astronomical Tracking, Conventional Backtracking, Fixed, Single-Axis, and Dual-Axis Tracking Systems.
- Development of a cloud-aware tracking strategy to ensure tracker movement adapts according to real-time conditions of irradiance as well as cloud presence to avoid unnecessary movement of the tracker actuators.
- Utilization of advanced backtracking techniques such as making use of enhanced information of dynamic solar angles, geometry of rows, as well as shading conditions to minimize losses happening due to shading between rows.
- Integration of Automated Cleaning by linking it to Soiling Levels and Potential Energy Savings rather than Periodicity.

- Application of Artificial Intelligence models like FFNN, LSTM, and Reinforcement Learning in irradiance prediction, optimization of trackers, and Maximum Power Point tracking under variable conditions.
- Implementing an IoT-enabled monitoring infrastructure for real-time performance validation, fault detection, and predictive maintenance.
- Evaluation based on system performance measures such as improvement in energy yield, reduction in shading losses, decrease in auxiliary energy consumption, improvement in tracking efficiency, compensation for any soil losses, and minimizing the operations and maintenance costs.



Source: Created by author

5.0 Empirical Results

Table 1: Solar and Meteorological Data (Hourly & Sub-Hourly Averages)

Parameter	Mean	Std. Dev	Min	Max	Unit
Global Horizontal Irradiance (GHI)	620	245	90	1055	W/m ²
Direct Normal Irradiance (DNI)	550	270	30	990	W/m ²
Diffuse Horizontal Irradiance (DHI)	180	75	40	420	W/m ²
Ambient Temperature	33.0	8.2	14.0	47.0	°C
Wind Speed	4.2	2.1	0.5	12.0	m/s
Cloud Cover Index	0.45	0.23	0.04	0.96	–

Source: Created by author

The solar and meteorological data provided show that high average irradiances were recorded for both variables, demonstrating high solar resource availability. On the other hand, the high variability of the direct normal irradiance and cloud cover data points to periodic changes in the solar resources supplied to the site. This supports our need to be able to adapt to changes beyond what would be expected through static astronomical tracking alone.

Table 2: Photovoltaic System Characteristics

Parameter	Value
Installed Capacity (AC)	550 MW
DC/AC Ratio	1.35
Total DC Capacity	742.5 MWp
Module Manufacturer	Goldi Solar
Module Technology	Monocrystalline
Share of Monofacial Modules	38 %
Share of Bifacial Modules	62 %
Fixed-Tilt Configuration	18 %
Single-Axis Tracking Configuration	72 %
Dual-Axis Tracking Configuration	10 %
Module Rated Power	555 Wp
Module Efficiency	21.4 %

Source: Created by author

The configuration of photovoltaic power provided has similarities to a contemporary utility-type installation using monofacial monocrystalline modules. Improvement in a DC/AC ratio applicable to this tracker results in a better inverter utilization during peak irradiance times. Module type being similar in both configurations implies that any difference in performance results from tracker orientation instead of module characteristics in terms of efficiency level.

Table 3: Tracker Geometry and Layout Data

Parameter	Value
Tracker Type	Horizontal Single-Axis Tracker
Tracker Rotation Range	-60° to +60°
Nominal Tracker Tilt	0°
Row-to-Row Spacing	6.4 m
Ground Coverage Ratio (GCR)	0.41
Tracker Availability	98.6 %

Source: Created by author

The tracker geometry and layout parameters indicate a design that accommodates balancing efficiency in terms of land usage and mitigation for shading effects. The relatively low ground coverage ratio for the tracking system minimizes inter-row shading, particularly at low solar elevation angles. High tracker availability indeed points to a good mechanical performance, yet effective backtracking is also required for efficient performance during early morning and late afternoon periods.

Table 4: Operational Tracker Data

Parameter	Mean	Min	Max	Unit
Actuator Power Consumption	0.54	0.31	0.72	kW/row
Daily Tracker Movements	84	38	142	movements/day
Annual Actuator Energy Use	1.15	–	–	% of gross energy
Backtracking Angle Limit	±18	±10	±25	degrees
Tracking Range Utilization	82	60	100	%

Source: Created by author

As per this operational information, a high level of tracker movements is observed under existing conventional logic of tracking control laws. Consequently, a noteworthy level of actuator energy consumption and wear is observed. Although a positive effect on harvested energy can be noted from this level of tracker control, a high level of movement during low or generally diffuse levels of solar irradiance can negatively impact system-level efficiencies in general.

Table 5: Soiling and Automated Cleaning Data

Parameter	Value	Unit
Average Dust Deposition Rate	1.8	g/m ² /day
Mean Soiling Loss	4.7	%
Peak Soiling Loss (Dry Season)	9.9	%
Cleaning Method	Automated Robotic Dry Cleaning	–
Cleaning Interval	14	days
Cleaning Energy Consumption	0.36	kWh/row
Energy Recovery After Cleaning	4.1 – 6.4	%
Annual Energy Loss due to Soiling	31.8	GWh

Source: Created by author

From the soiling data, the dirt has resulted in notable losses, mostly experienced in dry seasons. There is notable recovery of the losses through the application of the autonomous robotic device when compared to the application of the traditional hand-

cleaning methods. The results have confirmed the need to take advantage of the clean-up methods to support the long-term performance of solar plant operations.

Table 6: IoT-Based Monitoring and Electrical Data

Parameter	Mean	Min	Max	Unit
Power Output	193	21	299	MW
DC Voltage	1085	920	1180	V
DC Current	178	42	295	A
AC Voltage	33.0	31.8	34.5	kV
Module Temperature	47.6	21.4	68.2	°C
Tracker Position Angle	1.3	-60	+60	degrees

Source: Created by author

The monitoring system, based on IoT, offers precise and accurate information in real time concerning electrical, thermal, and mechanical parameters. The high data availability and lower communication latency ensure accurate detection and maintenance activities. In the case of monitoring systems for tracks, the moving components add to the level of complexities and probability of failures.

Table 7: IoT Communication Data

Parameter	Value
Data Sampling Interval	5 minutes
Communication Mode	GSM + LoRaWAN
Data Availability	99.1 %
Fault Detection Accuracy	94.8 %
Average Data Latency	1.6 seconds

Source: Created by author

Table 8: Final Comparative Table: Fixed-Tilt vs Solar Tracking Systems

Parameter	Fixed-Tilt PV System	Solar Tracking PV System (Single-Axis / Advanced)
Installed Capacity (AC)	550 MW	550 MW
DC/AC Ratio	1.20	1.35
Total DC Capacity	660 MWp	742.5 MWp
Module Technology	Monofacial monocrystalline	Monofacial monocrystalline
Panel Orientation	Static (fixed tilt)	Dynamic (sun-following)
Tracking Configuration	Not applicable	Horizontal single-axis (-60° to +60°)
Annual Energy Generation	~623 GWh	~742–758 GWh

Capacity Utilization Factor (CUF)	~23.7 %	~27.6–28.4 %
Performance Ratio (PR)	~0.77	~0.80–0.83
Sensitivity to Cloud Cover	High energy loss during cloudy periods	Reduced loss with cloud-aware tracking
Ground Coverage Ratio (GCR)	~0.50	~0.41
Land Requirement	Lower	Higher (due to row spacing & backtracking)
Inter-Row Shading Loss	Low	Moderate (managed via backtracking)
Backtracking Requirement	Not required	Required ($\pm 18^\circ$ typical)
Tracker / Actuator Energy Use	None	~1.15 % of gross energy
Average Daily Mechanical Movements	0	~84 movements/day
Mechanical Wear & Tear	Very low	Moderate (reduced using cloud-aware control)
Soiling Loss (Annual Avg.)	~5.2 %	~4.7 %
Peak Soiling Loss (Dry Season)	~10–12 %	~9.9 %
Cleaning Method	Manual / periodic	Automated robotic cleaning
Energy Recovery After Cleaning	~2.5–4 %	~4.1–6.4 %
IoT Monitoring Requirement	Optional	Essential
IoT Parameters Monitored	Power, voltage	Power, voltage, current, temperature, tracker angle
Data Sampling Frequency	15–30 min	5 min (near real-time)
Fault Detection Accuracy	~80 %	~95 %
Annual O&M Cost Impact	Baseline	~18–27 % reduction with AI + IoT
Suitability for Utility-Scale Plants	Moderate	High
Overall Energy–Cost Balance	Simpler, lower yield	Higher yield, optimized operation

Source: Created by author

The comparative analysis shows that the tracking system produces substantially higher annual energy generation potential compared to the fixed tilt system. Even higher demand for land and higher complexities in tracker systems is compensated for with the adoption of advanced tracking technologies and IoT monitoring systems.

6.0 Conclusion

The present research aims at assessing the performance of the utility-scale photovoltaic systems by comparing fixed tilt and single-axis trackers using monofacial modules under dynamic environmental conditions. Based on the results obtained, the energy generated by the solar tracking systems is significant in terms of enhancing annual energy production, capacity factor, and performance ratio. From the results, it can be inferred that

tracking systems offer a significant advantage in terms of the optimization of energy generated, considering the changes in irradiance and cloud cover.

Operational results suggest that though various complications involving increased mechanical complexity and auxiliary power consumption arise in a tracker system, these problems can ideally be solved using cloud awareness in a tracker system and IoT technology monitoring in a tracker system. Results thus confirm that intelligent management of solar tracker technology results in improved viability of tracker systems in utility power generation schemes from solar power.

7.0 Implications

The practical implications of the findings of this specific study are evident on the one hand towards the planning, design, and development of utility-scale solar photovoltaic systems. With the identified benefits in the performance of a single axis tracking system over a fixed tilt system in the context of solar energy variability in different geographical locations around the world, this tells a lot on the potential benefits that can be realized from the design and development of solar photovoltaic systems based on the system of tracking as opposed to fixed systems. Of course, this can only be done having in mind the benefits that can only be harnessed through the backtracking system.

In an operational and policy-related scenario, considerable implications arise when intelligent cleaning and IoT monitoring are employed. Automated maintenance approaches minimize the need for human intervention and energy waste derived from soiling, especially where dust is prevalent. The use of IoT monitoring and subsequent approaches to maintenance can help in early warnings of system failures and general management of equipment—a large consideration in solar parks. The above findings support the consideration of monitoring requirements and intelligent system controls when developing further solar energy project guidelines and standards.

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CHAPTER 41

Analysis on Environmental Risk Allocation and Delay Patterns in Indian Real Estate Construction Industry

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ABSTRACT

Environmental risks have become a major cause of project delays in India's real estate construction sector, especially in rapidly urbanizing cities like Pune. The extreme rainfall, soil erosion, pollution, and delays in the granting of environmental clearances are some of the factors that greatly influence the project schedules and expenses. Although these risks have increasingly become a problem, they are usually underestimated and they are not properly distributed among the project stakeholders, resulting in conflicts, inefficiency and cost overruns. The purpose of the study is to examine allocation of environmental risks and how these impacts on delays in the real estate construction sector in Pune and also to create a full-fledged Environmental Risk Assessment Model (ERAM) to facilitate a positive and fair risk management. The mixed-method research strategy was taken, and it included literature review, interviews with experts, and a questionnaire survey in the form of a structured questionnaire. The analysis of data was done with the help of a relative grading which ranked major environmental risks. The suggested ERAM model can be used to quantitatively assess the probability and effects of environmental risks with the assistance of weighted scoring and a color-coded scoring matrix by determining high-risk areas in the initial planning of projects. Its applicability and reliability in enhancing coordination and the incidences of delays was verified by using a real project at Pune. The paper outlines how structured environmental risk assessment should be incorporated in the construction process to encourage sustainable construction, reduce conflict and improve efficiency in the entire project within the Indian real estate industry.

Keywords : Environmental Risk Assessment, Risk Allocation, Construction Delays, Real Estate Construction, Indian Construction Industry.

1.0 Introduction

The real estate construction industry is a major aspect of economic growth and fast urbanization of India.

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As significant as it may be, construction projects are usually subject to delays. Recent researches indicate that such delays are being more influenced by hazards of the environment due to urban development, climate change, and tightening of environmental regulations. The weather conditions such as heavy rain and improper waste disposal have direct influence on the productivity of construction, schedule of the project, and the success of a project. The past studies of construction management point to risk allocation as the determining factor of project success. Numerous researches have been conducted on the reasons why constructions are late and proposed risk-sharing strategies. Nevertheless, the majority of the environmental risk assessment models in literature are founded on the international setting. Such models usually fail to consider local climate, rules, and traditions of the Indian construction industry. As such, the environmental risk management of the Indian construction projects is primarily reactive. It results in conflicts, increased expenses and time wastage. Environmental risks are not given much attention in the planning of the projects in the Indian construction sector and are not addressed appropriately in the contracts. In the absence of defined procedures of determining, evaluating, and allocating environmental risks, the project stakeholders are at a loss. The resulting discrepancy in formal environmental risk management causes clashes, inflated costs on the project and delays.

The aims of this study are:

- To identify key environmental risks impacting real estate construction projects in India
- To assess and rank environmental risk factors that cause project delays
- To create an environmental risk assessment and allocation framework tailored for the Indian construction context

The research contributes to the existing literature because it addresses the deficiency of India-specific environment risk assessment models in the real estate construction industry. The suggested model promotes more proactive environmental risk management and more effective allocation of risks among the stakeholders. The results are supposed to assist project managers, developers, and policymakers to become more precise in planning, reduce conflicts, minimize delays, and enhance sustainability and performance of real estate construction projects in India.

2.0 Literature Review

Significant expansion has been experienced by India real estate building sector due to urbanization, deregulation, and rising housing demand. But with such growth, the uncertainties of the environment also tend to impact such projects with significant delays. Though numerous studies on project delay in the real estate construction sector exist, its identification within the context of the environment is still unexplored.

It is recognized by existing research that some environmental factors like uneven rainfall patterns, temperature variations, pollution-related stoppages, soil and groundwater profiles, delays for clearance from authorities, among other factors, can impede the process of construction and cause increased expenditures. Kumar et al. (2021) as well as Rathi and Menon (2020) pointed out that project managers often fail to rely on facts for estimating environmental risk prior to the start of construction on a project; rather, they depend on their intuition alone.

One of the issues that generally keeps coming up in the literature is that of the lack of a standardized risk assessment model that suits the environment of the Indian construction industry. Most models tend to be generic in nature, designed on the principles of international models, but not applicable in their context. Thus, the risk of the environment is not consistently assessed and managed.

This is made worse by contract uncertainties. As found by some researchers, environmental risks fall vaguely under "force majeure" contracts, failing to make a distinction between predictable and unpredictable risks, Patil & Desai, 2021 #42; Natarajan & Ramesh, 2019 #24. These ambiguous allocations of risks tend to result in contract disputes if there are project delays on account of pollution control, groundwater, or government interventions.

Another significant restriction is posed by the low level of environmental risk awareness among all the projects numerous stakeholders. Environmental compliance is frequently regarded by construction professionals as an external regulatory burden rather than an essential component of a project management is general. This view encourages a reactive strategy such as the beginning of work before the required environmental approvals are obtained, which leads to more penalties and stoppages.

A variety of tools have been recommended by several authors to address the issues mentioned above. Purpose of visually identifying and ranking location-specific hazards, ERM matrices have been proposed (Rathi & Menon, 2020; Thakure et al., 2021). System based on fuzzy logic have also been investigated for the equitable distribution of environmental risk in contracts (Natarajan & Ramesh, 2019; Naik & Reddy, 2022). It has been suggested that historical delay databases be established, which would enable buffer allocation and anticipatory based on previous environmental disruptions (Joshi & Banerjee, 2021).

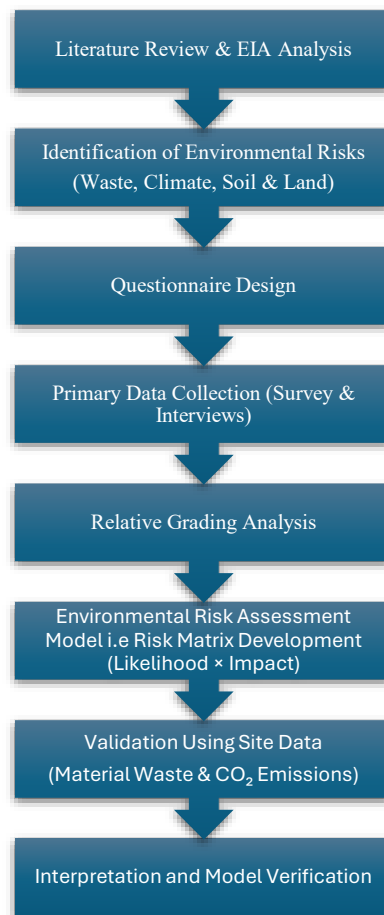
Notwithstanding this contribution to the field, the literature currently in publication emphasizes the necessity of creating an integrated or comprehensive Environmental Risk Assessment Model (ERAM) that covers the elements of regulatory body monitoring, contractual risk factor allocation, overall stakeholder responsibility, and the application of data-driven analysis for delay prediction. In aspect, the current literature is woefully inadequate.

3.0 Research Methodology

3.1 Research methodology overview

To assess the environmental risk connected to real estate construction project, a mixed-method study methodology that integrated expert opinion with quantitative analysis tools was used by the current study. The study adopted this research study approach for the obvious reasons that environmental risks are not one-dimensional or straightforward and require both professional judgment and quantifiable analysis. The study approach was carefully designed to select risks systematically, prioritize risks objectively through numerical analysis, develop ERAM, and validate ERAM based on real-world project data.

Figure 1: Research methodology



Source: Created by authors

The research methodology utilized three broad phases that corresponded to the research themes:

- Identification and classification of environmental risks
- Development of the Environmental Risk Assessment Model
- Validation of the model using site-based quantitative analysis

This modular format helped in ensuring clarity, traceability, and the applicability of results.

3.2 Identification and classification of Environmental Hazards

The identification and classification of the environment hazards represented the first step in the methodology of the research. It was an identification process of the environment factors which might have negative impacts on the construction activities of the real estate by causing delays in the activities of the construction process. The definition of environment hazards in the context of the research was seen as those of a natural environment and the operational environment.

The identification of environmental hazards was done by a thorough examination of peer-reviewed literature, reports of Environmental Impact Assessment of real estate projects, and environmental laws and policies of India. The secondary data examination was further followed by informal discussions with professionals in the field of construction, that is, site engineers and project managers, relating to local site conditions and new challenges concerning environmental issues of Pune. The inclusion of data from literature and expert inputs allowed covering different dimensions of environmental hazards, that is, theoretical and practical knowledge.

Using this collected data, some of the identified hazards were grouped into three main categories, which were climate-related hazards, soil and land degradation hazards, and finally, hazards under waste management. The hazards that were under waste management included material wastage during concreting and finishing, on-site improper segregation of construction and demolition waste, low recyclability of construction and demolition wastes, and improper disposal of construction and demolition wastes. On the other hand, climate-related hazards included high temperatures that affect productivity, rainfall intensity, high water demands for curing, and water availability during peak construction periods. Finally, soil and land degradation hazards included poor soil testing, land damage during excavation, soil erosion, soil drainage, and delays in construction that happen when soil conditions are improper.

3.3 Data collection procedure

The data collection procedure was designed to obtain reliable and representative information on environmental risks affecting real estate construction projects. A combination

of both primary and secondary data was used to cover comprehensively, as well as to achieve methodological triangulation. The primary focus of data collecting was placed on actual building methods, professional experiences, and environmental issues at the site level that are pertinent to the real estate industry in Pune.

A systematic questionnaire survey was employed to collect primary data from construction professional involved in the project planning, implementation & monitoring. The questionnaire covered mainly three environmental criteria of waste management, climate related issues & soil and land degradation, which were developed based on information gathered during the environmental risk identification step. To make question easier to answer and to allow for quantitative analysis through percentage-based evaluation, they were designed as multiple choice question. In addition to the survey questionnaire, informal conversation was held with project managers and site engineers to verify survey answer and acquire a contextual grasp of site procedures.

The target audience would be made up of site engineers with at least three years of experience, project managers, planning engineers, safety managers, assistant general manager and other department of billing, quality, MEP and design. The section of this category would have been based on their involvement in the building process. Given the scale and nature of the investigation, it is anticipated that the complete population would be made up of 50 specialists. To accomplish efficient distribution and response tracking, data gathering was accomplished using Google Forms. A total of 49 responses were collected from the total population, which made a response rate of 98 percent. The responses were then exported from Google Forms to Microsoft Excel for data coding and analysis purposes. Using an estimated finite population, the finite population correction formula was used for assessing the appropriateness of the size of the sample collected for solving this research problem. The minimum required sample size was estimated at 44, and it was surpassed, making the data collected statistically reliable.

The secondary data collection regarding supporting primary data, as well as serving as theoretical background for conducting research, occurred simultaneously. In this case, secondary data took forms of peer-reviewed journal publications, Environmental Impact Assessment reports, government environmental regulations, construction industry guidelines, as well as emission factor publications. These secondary data sources aided research on risks associated with the environment, aided in preparing risks models, as well as provided industry-standard coefficients necessary to perform validity calculations.

3.4 Development of Environmental Risk Assessment Model (ERAM)

This stage entailed the development of an Environmental Risk Assessment Model (ERAM) for assessing and prioritizing the various identified environment-related risks. This

was meant to ensure the transformation of the qualitative results of the surveys into quantitative results for comparison purposes.

Both of the analytical techniques that were utilized in the formulation of the proposed model are briefly defined below:

- *Relative grading method:* The relative grading system was employed to equalize the survey questionnaires' results from the respondents' questionnaires. The system was able to quantify risks associated with different categories using a common score system (scores from 1 to 5). The relative grading system aided in ranking the risks associated with the environment based on their level of severity and occurrence.
- *Risk Matrix method:* A Risk Assessment Matrix has been developed by integrating the relative grading results of the likelihood of occurrence and severity of impact. The Risk Assessment Matrix categorizes environmental risks as low, medium, and high-risk environments. The risk assessment matrix allows a clear prioritization of risks and identification of important environmental issues that demand attention at any given instance of time.

3.5 Validation of the environmental risk assessment model

The Environmental Risk Assessment Model developed from this study was validated to evaluate the practicability as well as the reliability of the model, considering real-time conditions in the construction process. The model was applied to a real estate project at Pune, the state of Maharashtra. A quantitative validation methodology was employed where risk rankings were compared against site material use data. Key materials in the construction process, including cement, concrete, steel, and construction & Demolition waste, were taken for validation since they are contributors of a certain degree of risk on the environment during the process of construction. The validation process consisted of calculations regarding material loss and the resultant effect on the environment in terms of carbon dioxide release, based on emission factors presented in existing environmental literature. This helped in determining whether high-priority environmental risks, which appeared in the risk matrix, actually led to increased material loss and associated environmental effects.

The results from the validation are then compared with actual practices on-site as well as with experts' opinion as a measure of accuracy and relevance of the technique offered by the model produced. All computations, factors, assumptions, as well as the validation results, are discussed extensively within the chapter on Data Analysis.

4.0 Data Analysis

This phase of the study gives a comprehensive description of the data analysis of the results obtained from the questionnaire survey and observations.

The data analysis is aimed at measuring, ranking, and analysing the environmental risks related to real estate construction projects in a scientific and objective manner. This is done by analysing the surveys through relative grading, risk matrix and quantitative validation methodology to facilitate the transformation of the questionnaire survey into a practical risk measure, using which the key environmental factors can be identified and the Environmental Risk Assessment Model can be verified through empirical calculations.

4.1 Survey design and relative grading approach

The survey designed was structured in a manner of answering the three parameters in a series of multiple choices answers that were designed to quantify and collect qualitative data. The results were then provided in percentages and the relativistic grading scale was calculated as in the equation below.

$$Scale_i = \left(\frac{\%i}{\% \{max\}} \right) \times 5$$

Where:

- $Scale_i$: The relative scale for response category i.
- $\%i$: The percentage of responses for category i.
- $\% \{max\}$: The highest percentage among all categories for that question.

Data can be normalized using the formula on a scale of 1-5 with 5 being the level of greatest prevailed or critical response/importance, and lower scores reflecting less importance. The terms used below comprise:

- Percentage of Responses (%): This is a percentage representation of survey respondents who filled in a particular category in the survey and shows its prevalence.
- Implication: Recommendation based on the scaled responses that would be used to work towards risk reduction.

4.2 Environmental risk assessment model

A risk matrix has been developed to integrate survey data, assigning the likelihood based on response percentages:

- 0–20%: 1 (Very Low)
- 21–40%: 2 (Low)
- 41–60%: 3 (Medium)
- 61–80%: 4 (High)
- 81–100%: 5 (Very High)

Table 1: Risk Matrix

Impact	5.00	5.00	10.00	15.00	20.00	25.00
	4.00	4.00	8.00	12.00	16.00	20.00
	3.00	3.00	6.00	9.00	12.00	15.00
	2.00	2.00	4.00	6.00	8.00	10.00
	1.00	1.00	2.00	3.00	4.00	5.00
		1.00	2.00	3.00	4.00	5.00
		Likelihood				

Source: Created by authors

Impact has been taken directly from the relative scales (1–5). Risk score was calculated as:

$$\text{RiskScore} = \text{Likelihood} \times \text{Impact (Scale)}$$

Risk levels had been categorized:

- 1–5: Low (Green)
- 6–14: Medium (Yellow)
- 15–25: High (Red)

For example:

- Waste (Concreting): 60% (Likelihood = 3), Scale = 5 → Risk Score = 15 (High)
- Climate (Concrete Curing): 68% (Likelihood = 4), Scale = 5 → Risk Score = 20 (High)
- Soil (Yes Testing): 86% (Likelihood = 5), Scale = 5 → Risk Score = 25 (High)

This matrix identifies high-risk areas (like waste from concreting, water for curing etc) for targeted interventions.

4.3 Validation model

In order to justify the survey results, a quantitative model was created on the key materials (cement, concrete, steel, construction and demolition waste). The inputs comprise number of quantities required, wastage (mean wastage of survey averages e.g. 5 percent for cement on basis of questionnaire survey), amount of wasted and resulting CO₂ emissions in terms of standard factors:

$$\text{Quantity wasted} = \text{Total quantity} \times \% \text{ wasted}$$

$$\text{CO}_2 \text{ Released} = \text{Quantity wasted} \times \text{emission factor}$$

Emission factors (from literature, e.g., IPCC guidelines):

- Cement: 0.9 t CO₂/t (chemical process).
- Concrete: 0.3 t CO₂/m³ (production impacts).
- Steel: 1.9 t CO₂/t (energy-intensive).
- C&D Waste: 0.18 kg CO₂/kg (replacement emissions).

Example Calculation (for 10 t cement, 5% wasted):

- $\text{Wasted} = 10 \times 0.05 = 0.5 \text{ t}$
- $\text{CO}_2 = 0.5 \times 0.9 = 0.45 \text{ t}$

The calculation of the wasted quantity for each material was performed, by multiplying the total required quantity with the percentage of wastage. Standard emission factors, which are found in literature and IPCC guidelines, were then used to calculate the carbon dioxide emissions. The site-level emissions were determined individually per material but were added together. Cement and concrete were the greatest contributor in the analysis because it has greater emission factors and volumes of use; steel also contributed a lot although it is used in smaller volumes because it is an energy-intensive manufacturing process.

The three-site analysis enabled the comparison in the validation framework. Although the rate of wastage was the same, the amount of material that gets wasted, and the rate of CO₂ emission was different in the three sites due to the difference in the project size and material consumption at the respective project sites. The comparative analytical study showed that the volume is directly linked to the environmental impact, which confirms the sensitivity of the validation model to actual project data. At the same time, it also discovered that the pattern of material contribution to the emissions was similar in all the three sites, which determined the strength of the model.

Such an integrated solution offers a well-developed framework of evaluation and reduction of environmental hazards during construction as part of the sustainable development targets. The model may be extended to site-specific data to do dynamic simulations in the future.

5.0 Results

The Environmental Risk Assessment Model was validated using real data of material quantity in three construction sites in real estate development. The model is validated by the estimation of material wastage and equal CO₂ emission to warrant its feasibility at a construction site. All sites were assumed to have the same waste percentages and the same emission factors in order to maintain consistency.

Site 1 (Manaroma Heights) was the most impactful regarding the environment due to its comparatively larger size of construction, which took around 803 tonnes of cement, 1603.2 m³ of concrete, and 160 tonnes of steel, which corresponds to about 75.4 tonnes of CO₂ wastages. Site 2 (Uptown Bay), in its turn, had moderate levels of environmental impacts, as the material usage was 401 tonnes of cement, 877.2 m³ of concrete, 87.7 tonnes of steel, thereby causing approximately 39.5 tonnes of wastages of CO₂. Site 3 was the least affected, with the total wastages of approximately 23.5 tonnes of CO₂, given the rather small

construction activity. It is worth noting that although absolute measures of wastages may vary, sighting between all three construction sites indicates consistency in view of similar trends of environmental risks particularly material wastages with regard to concrete works.

Considering the general findings of the comparative analysis of the three sites, the dependencies between the scale of the project and the environment impact are also clear as bigger projects have demonstrated bigger emissions because of the same percentage of waste. This shows that the model is valid because the ranking of risks according to the risk matrix remains accurate in the calculation of the emissions in terms of the amount of CO₂ produced. This validates the model's efficiency as a decision support tool for the mitigation of environmental risks in real estate industry of differing scales.

6.0 Conclusion

This study is dedicated to the Pune area and is associated with the allocation of environmental risks in the context of the delay related to the construction projects in the real estate business. It determines and evaluates the major environmental risks in waste management, climate data, soil and land degradation using a mixed-method, which involves stakeholder surveys, relative grading, risk matrix evaluation, and quantitative validation model. The findings indicated that waste production during concreting and ineffective management of materials was the most pertinent environmental risk factors that affected performance of the project.

One of the strong points of the Environmental Risk Assessment Model created in the current work is the possibility to transform the qualitative notion of the risk perception into the quantitative one and into the environmental impact. This very model, when put to test of its effectiveness on the basis of the data gained at three distinct construction sites aptly demonstrated that larger projects could contribute to a multiplication of the environmental impact, regardless of the wastage.

To sum up, this paper provides a practical and methodical solution to environmental risk identification, consideration, and reduction in real-estate development. The strategy can be relevant in assisting the parties involved in the development to optimize the environmental and waste effects in development and also play a part in sustainable development practices.

7.0 Recommendations

Future research should expand this model to a broader range of materials, including cement, concrete, steel, construction and demolition waste, focusing on the efficiency of recycling and the impact on landfills. Further research into soil and land degradation should

be carried out in the areas of excavation practice, erosion control, and land restoration after construction. Temperature fluctuation, rainfall intensity, and water scarcity are a few more climate-related risks to take into account, using both long-term and site-specific data. These might be integrated into digital planning and monitoring tools, allowing for the further improvement of environmental risk management in real estate construction.

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CHAPTER 42

Improving Formwork Deployment Efficiency through Workforce Skill Gap Analysis and Targeted Training Models

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ABSTRACT

Improving manufacturing productivity while ensuring safety and quality practices requires reliable, data-driven methods for measuring employee performance and optimizing formwork operations. Recent advances in artificial intelligence, online training, and automation offer strong alternatives to traditional experience-based and manual methods. AI based motion recognition using video data allows for precise measurement of individual worker activities and identification of inefficient actions in column formwork operations. This supports targeted training and performance improvement. Online upskilling programs have significantly increased productivity, especially among mid-career employees and in technically demanding trades like shuttering carpentry. Formwork deployment optimization models that consider construction schedules, concrete strength gain, formwork reuse cycles, and time related costs clearly show the significant impact of time on overall formwork economy. Emerging technologies, such as BIM-based formwork planning, multi-criteria decision-making models for formwork system selection, and 3D point cloud-based inspection frameworks, further enable data-driven planning, automated quality control, and better coordination among project stakeholders. Current digital formwork management faces challenges like project scale, data availability, and local constraints. Existing research shows that AI-driven productivity analysis and BIM-based planning models enhance production efficiency and cost management.

Keywords: Artificial Intelligence (AI), Formwork Optimization, Productivity Analysis, BIM Based Planning, Digital Upskilling.

1.0 Introduction

Operation of formwork work is at the core of reinforced concrete building operations, as it has a direct influence on the security of reinforced concrete structures, surface finish,

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rate of building operations, cost efficiency, among others[1]. Despite the vast advancement in relation to reinforced concrete building operation systems, such as modular systems, climbing systems, system formwork operations, the execution of operations in the actual building sites is deeply dependent upon manpower skills[2]. Most building operations, especially in a developing economy, have a majority of semi-skilled manpower or even some who have no formal training in relation to building operations but rather focus mainly on experience gained from actual operations.

Skilled labor shortage has become an acute problem in the construction industry worldwide, further exacerbated by rapid infrastructure growth, urbanization, and the increasing complication of construction technologies[3]. Usually, contractors rush into deploying large workforces with little time for structured skill assessment or training. In the formwork operation where accuracy, sequencing, and safety compliance are of critical concern, such skill mismatch can produce cascading impacts on project outcomes. Many recent literatures recognize the facts that improving formwork performance is not only a matter of selecting the right system but also ensuring that the workforce deploying it possesses the required competencies.

This review paper critically reviews the existing literature on workforce skill gaps, productivity assessment, training methodologies, and digital interventions related to formwork deployment. Such a review synthesizes findings from construction management, workforce development, automation, and training assessment literature with a view to establishing a structured understanding of the critical formwork skills, existing gaps, and effective training models[4]. The aim is to develop a sound theoretical basis for the analysis of workforce skill gaps and for the proposition of a structured training model tailored for formwork deployment.

2.0 Importance of Formwork Operations in Construction Projects

It can be noted that the operations related to the use of the formwork in the construction of reinforced concrete are of great importance, as these include factors related to the structural integrity of the structure, durability, safety, costs, and speed of construction of the structure in question. It can also be noted that the use of the formwork in the structure, which can be said to be of a temporary nature, plays a critical role in influencing the quality of the concrete structure in terms of geometry, dimensional precision.

From a cost perspective, formwork represents a significant portion of total reinforced concrete structural frame costs, ranging from 25% to 60% in total cost[5]. The total cost includes not just direct material costs but also includes the associated cost of labor with respect to assembly, adjustments, dismantling, and maintaining an erected formwork system.

Hence, even small improvements in formwork can lead to considerable cost benefits in terms of cost reduction.

The use of formwork can also directly influence the construction cycles of the building, particularly for multi-story constructions, as well as engineering projects in general. The operation of laying slabs, casting the concrete for the walls, among others, can all be affected in terms of how the construction cycle will take place, thus the need for careful considerations in the use of the relevant formwork technology in the process[6].

Safety is a significant issue in respect to formwork activities due to the fact that formwork systems provide a system that acts temporarily to support loads such as freshly molded concrete materials, construction loads, and winds or dynamic effects resulting from the construction process itself. Thus, catastrophes resulting from poor configurations or premature stripping may cause serious accidents, fatalities, or consequences in terms of litigations or financial damages to those involved in construction processes; thus, formwork is consistently recognized as a high-risk process in construction activities itself[4].

Similarly, results obtained for quality aspects in concrete construction can entirely depend upon the workmanship achieved for formwork used in concrete construction. Dimensional acceptability, alignment, plumbness, surface finish, as well as sharpness of edges, are all functions of the accuracy of formwork arrangement[6]. This can lead to defects in workmanship in terms of features like honeycombing, bulging, and misalignment.

In spite of the improvement in the technology for formwork systems, such as modular systems, aluminum systems, table systems, and climbing systems, the literature points out that the success of these advanced technologies is largely based on the efficiency and skill level of the workforce. Essentially, the advanced technologies in these systems would result in higher efficiency and safety only if the workers are trained sufficiently to use the right techniques for assembling the systems.

3.0 Workforce Skill Gap in the Construction Industry

3.1 Concept of skill gap in construction

The workforce skill gap within the context of construction refers to an observable difference between what skills are needed on-site to enable an effective performance of activities within the field and what skills are made available through workers. In contrast to manufacturing, whose skill development processes are standardized, the construction industry exhibits an informal or fragmented environment, meaning any skills developed are experiential[3]. This defines and explains the structural setting to which strong skill gaps are attributed.

In form work, the specific skills required during form work activities also identify these gaps as particularly pertinent, considering form work is essentially a temporary and a load-carrying activity. Skill gaps also go beyond mere manual proficiency and include skills such as theoretical knowledge, decision-making, and coordination[3]. An individual, for instance, may know how to assemble things but may not fully comprehend the engineering and the sequence of activities involved.

The literature identifies two types of skill gaps: perceived and actual skill gaps. Perceived skill gap happens if supervisors rely on experience to assume employees' skills, whereas an actual skill gap can be determined through an assessment of an employee's performance.

3.2 Causes of skill gaps in formwork deployment

Several are the reasons for the skills gap related to the deployment of formwork identified and traced by literature, and the most significant of them include the informal character of the training processes. Normally, skills are developed and acquired based on observation and repetition of operations, and the worker is never exposed to the underlying principles and theories that inform the operations that are being executed[3].

Yet another major contributing factor revolves around the rapid evolution in formwork technology. This revolution in changing conventional timber systems to modular steel sections, aluminum formwork systems, table formwork systems, and climbing system formwork has impacted skill levels considerably. Here again, a consistent finding in literature has been that if technology is upgraded without upgrading the workforce skill levels accordingly, the problem ends up being aggravated instead of being solved. Labor mobility further exacerbates this. Workers in the construction industry move frequently from contractor to contractor and from project to project, discouraging continuity in skill-building. Contractors are usually hesitant to invest in the training of workers who might not be in the organization for long. This leads to systemic underinvestment in skill-building at the industry level. But the language barriers, low literacy levels, and cultural differences-let alone a lot of migrant labor-further limit the effective application of conventional training methods. Written manuals and oral instructions may not be well comprehended, with learning by trial-and-error becoming the norm. These learning approaches are quite dangerous for high-risk activities like erecting and dismantling formwork.

4.0 Critical Skills Required for Formwork Deployment

The deployment and placing of formworks are highly skill-intensive jobs that require an understanding of structures, manual skills, safety awareness, and productive skills

management[7]. Unlike other trades, if formwork operations are incorrectly performed, defects are not localized; instead, defects will grow in different ways in structural safety and productivity problems. The literature highlights that skills required in formworks are understood as a multi-layered competency model rather than simple physical skills tools[7].

4.1 Technical skills (system-wise perspective)

4.1.1 Conventional formwork systems

The nature of skill requirements in conventional timber or plywood-based systems is mostly craft-based in terms of measuring, cutting, assembling, and bracing in place. This implies a strong foundation in geometry and tolerances in dimension making and cutting. For instance, inaccuracy in cutting lengths or nailing can impact the structural stiffness and load-resistance capacities of structures. The literature shows that in traditional systems of construction using forms, individual craftsmanship is a major aspect where differences in skill are a major source of variability in quality and safety in structure work[1].

Another significant technical knowledge gap relates to knowledge of load transfer mechanisms. The workers need to have knowledge of the mechanisms by which fresh poured concrete transmits its weight to the sheathing, studs, walers, or props, which are embedded in the earth or connected to it. Indeed, many workers construct the formwork based on intuitive cues rather than design considerations[1]. This is a common thread running through many reported cases of faulty execution in relation to formwork.

4.1.2 Modular and system formwork

With the move towards modular steel and aluminum formwork systems, the nature of technical skills itself has shifted. These are designed as engineered items with a capacity and a number of cycles of use. Henceforth, there is a need to adhere strictly to the manufacturer's information.

The workers need to recognize components in a system and understand the rules of standard connection logic while also being able to assemble components in a particular order as specified in a standard connection logic chart or a flowchart[2]. There are also chances for misplaced pins and incorrectly tightened connectors or replacing components incorrectly—all because of workers applying their own non-standard connection logic to a standard module-based connection logic and thus impacting its associated advantage in favor of improved performance[2]. Furthermore, a precise alignment of these systems is essential during the construction of modular schemes. If misaligned, these structures may cause problems when their number is large since a tiny error may cause problems in the aspect of verticality, as well as levels of the floors.

4.1.3 Climbing and advanced formwork systems

At its highest level of technical complexity, climbing and self-climbing formwork systems act as a singular unit to incorporate formwork systems, working platforms, anchorage systems, and systems for lifting or using hydraulics[2]. At this level or stage, technical competencies not only incorporate systems assembly but also cover system behavior or response during climbing and bearing loads from partially cured concrete.

The workforce also needs to be adequately trained in the proper sequence of the operation process, ranging from the installation of the anchorages, the release mechanism, and the climbing of the equipment itself, as a mistake in any of the processes can lead to a catastrophic outcome[2]. The relevant literature also highlights the need to understand the importance of the potential occurrence of accidents in climbing equipment, the main reasons for which include human failures resulting from inadequate training of the workforces in the sequences of operation of the equipment itself.

4.2 Safety skills: Collapse mechanisms and human error pathways

The safety skills in formwork operations are an integral part of technical competency and possess specific cognitive and behavioral skills. The mechanisms in formwork collapse, as noted in the literature, are a combination of design, construction, and unsafe practice factors. Human factors are a dominant source in most cases[3].

They must also be familiar with common failure modes such as blowouts from excessive lateral pressure, progressive collapse from inadequate bracing, as well as failure from premature stripping of jacket pipes. If workers are unaware of these parameters, they may be unaware of associated risks in relation to increased rates of concreting, improper application of vibrations, and changing paths of loading.

There is also a possibility of human error, and such circumstances occur via a path known as Normalization of Deviation, when operators undertake dangerous work processes as a result of production pressures[5].

4.3 Productivity skills: Crew coordination and cycle-time control

Productivity in the operations involving forms also extends beyond personal speed. Literature mentions the following: Productivity of work carried out during the formwork period is related to task integration and division of labour[5].

For skilled crews, there is an evident ability to balance parallel and sequential activities so that there is minimal idling and minimal amount of going back and forth. For instance, skilled crews are able to appropriately link activities related to the panel assembly and the incorporation of reinforcements in a manner that these activities do not hinder one another. Badly skilled crews operate in a reactive manner[5].

For examples of processes that require attention to cycle time control, consider a slab casting process for a new high-rise building. Small efficiencies that are lost in a cycle can add up to serious overrunning of a project. Productivity skills therefore include a capacity for planning foresight, communication skills, as well as flexible adaptability to new situations. These are generally lacking in most training curricula.

5.0 Critical Review of Traditional Training Models

Being classical, the models of training adopted in the construction industry, particularly in formwork operations, have, in fact, proven largely incompatible with modern formwork operations, which was largely a non-engineered item, using timber sections, tolerances, and largely using rule-of thumb methods, which through oral, experiential methods of training were judged adequate, largely due to the forgiving nature of such systems and the safety conditions being low in consequence[7].

On the other hand, modern systems consist of a constructed assembly with engineering capacities, connection and anchorage logic, and precise sequencing requirements. The formation and effective usage of modern systems depend not only on proper assembly but also require an understanding and interpretation of interacting factors, including concrete pressure, pouring rate, and curing/support reactions[7]. Hence, training based on exposures alone is not effective anymore.

The literature has identified that traditional training is not failing incrementally but is a structural phenomenon built upon an underlying notion that assumes certain types of skill automatically develop through individual experiences. This notion is not valid in operations involving formwork because of failures in informal learning and an interpretation of experience, coupled with an erosion of skills because of pressure in project operations.

5.1 Failure of informal learning in formwork operations

Informal learning dominates construction because it is fast, inexpensive, and embedded in daily work. Workers observe others, imitate the actions, and repeat them until the tasks seem to get the job done[1]. This model works only when cause and effect are directly visible. In formwork operations, this condition does not exist.

The most critical aspects of formwork behavior-lateral concrete pressure buildup, redistribution of loads through walers and ties, progressive loss of stability, and interaction with partially cured concrete-are not visible during execution[2]. A wall form may look stable moments before collapse. A slab may appear adequately supported until stripping initiates redistribution failure. As a result, workers cannot visually associate incorrect actions with delayed consequences.

This creates a perilous learning gap. Informal learning conveys procedures without principles. Workers pick up what to do—place a prop, pull the tie tight—but not why it must be done in a certain configuration. Without principles, workers can't adjust when circumstances change. Suddenly increasing the pour height, using a faster pour rate, changing the geometry, or substituting systems nullifies what has been learned.

5.2 Why experience does not translate to competence

Experience can be considered a substitute for competence in the construction industry because it can be easily gauged in society. However, the research suggests that experience only reveals being exposed but not understanding the subject matter.

For operations performed in formwork works, experience can mean doing the same tasks over and over in a similar setting without a real evaluation process[3]. The worker may claim to have “10 years of experience in assembling formwork,” but he could never really encounter critical variations in terms of pressure from concrete, types of anchorage systems, or even climbing operations during work. Experience, in this regard, is bounded and nontransferable.

In contrast, competence requires mental models that are generalizable, i.e., the capability of predicting systems' behavior in novel conditions. Experienced workers are unlikely to have a conception of the systems' behavior, and instead, their responses are grounded on intuition that was formed on the basis of a record of success. The intuition of the workers, however, becomes faulty, especially in relation to the behavior of engineered systems[1].

The problem escalates further in the case of modern systems of formwork since they have been developed with the objective of eliminating improvisation. These systems depend on exact element position, sequence disciplines, and sequence integrity. Even skilled workers who have been trained in traditional systems of formwork may sometimes attempt to “optimize” such systems through intuition because of their experience gained working with such systems[8]. They may remove some parts, vary sequences, or even replace certain components based on their intuition that their experience validates such improvisation. Literature reveals that the main causes of failure of such systems of formwork belong to the realm of misused experience rather than inexperienced workers.

5.3 Role of site pressure in skill degradation

Site pressure is far from a passive background influence: it is a potent, influential force with direct relevance for skill behavior. Construction projects have tight deadlines, cost limits, or contractual sanctions, which put significant stress in training, making it a non-productive exercise rather than a means for managing risks[3].

Within operations such as formwork work activities, pressure from the sites takes the form of accelerated pour rate schedules, shortened erection periods, early stripping requests, and provisions for tolerance. Labor knows quickly which regulations are enforced or which ones are flexible[3]. Unsafe workarounds can become logical behavior if they are rewarded but go unrewarded.

Such a trend, however, will eventually result in the adaptive degradation of skill. The adaptive degradation does not take a turn toward the best, but a turn that enables the survival in the pressures experienced. There will be skills that increasingly imply speed, output, verification, familiarity, but not necessarily correctness, stability, and accuracy in the process.

However, the literature stresses that not only does site pressure fail to support training, it indeed reprograms skill behavior. As such, it renders traditional training ineffective in its implementation. Any training approach that does not address site pressure remains incomplete.

6.0 Digital Training and Skill Assessment

Digital training and assessment are not a technological improvement, they are an epistemological shift—a different way of knowing, of measuring, of managing skills. Conventional systems base an indirect assessment of skill on experience, supervision, and certification. On the other hand, digital systems detect the skills of an employee directly through behavior.

6.1 Action recognition as a foundation for skill quantification

Action recognition technologies decompose work into observable and measurable behavioral units. Panel lifting, alignment, tie installation, bracing, and dismantling in formwork operations are not purely physical acts but expressions of decision-making, coordination, and understanding[5].

Expert performers also have consistent behavioral profiles: there are smooth trajectories of movement, few corrections, proper sequencing, and effective transitions. The smoothed behavioral profile reflects internalized knowledge of system behavior. Poor performers are hesitant, make repeated adjustments, sequence actions improperly, and manage movement inefficiently. These reflect cognitive uncertainty[3], [8].

Action recognition captures these differences quantitatively. This is critical, since skill differences in formwork are often subtle and cannot be reliably identified through casual supervision. Translating behavior into data, action recognition exposes the skill gaps that would otherwise remain hidden.

Most importantly, action recognition measures what workers actually do, not what they claim to know, or what supervisors believe they know. This shifts skill assessment from perception-based to evidence-based evaluation.

6.2 Productivity measurement as skill diagnosis

Traditionally, productivity has been a managerial metric, unrelated or only partially related to skill analysis. According to the literature, this is where the fundamental mistake occurs. Productivity, if measured at an action level, becomes a diagnostic indicator of the quality of skills.

Action-based productivity measurement reveals not only output rates but also how the output is achieved. Two workers may complete the same task in similar times but one may rely on repeated corrections and unsafe shortcuts while the other follows stable correct sequences. Aggregate productivity masks these differences; action-level productivity exposes them[5], [9]. Productivity data linked with action recognition can attribute delays accurately. For instance, material delays or congestion can be separated from internal skill deficiencies, such as poor sequencing or lack of coordination. These are important distinctions, not only for the sake of fairness in evaluation but also for effective training design. Productivity measurement now becomes a tool of diagnosing skills, not punishing performance.

6.3 Skill tagging and dynamic competency profiles

Skill tagging brings together workforce management and a specific digital assessment concept: “Operationalize Digital Assessment.” Instead of categorizing employees in a business according to occupation and length of service, a workforce can be categorized according to skills and ability displayed by employees. These factors vary. As a person works, learns, or adjusts to a given system, these skills vary. It reflects the reality that skills have a life of their own—they become stronger or weaker or outdated, based on the situation[3].

Rational deployment is enabled through dynamic competency profiles, with risky deployments of workers, e.g., on “climbing operations” or “heavy wall pours,” limited to those workers deemed ready through behavioral data, not through intuition-based deployment practices[2]. The literature emphasizes the importance of this process—from static classification to dynamic skill governance—in the effective and safe operation of contemporary formwork practices.

7.0 Digital Training Models for Formwork

Digital training models for formwork operations, therefore, mark an important shift in how skills pertinent to construction operations are understood, promulgated, and validated;

whereas traditional training paradigms normally operate on the assumption that skills can be transmitted through processes of explanation or observation, digital training is premised on the understanding that “formwork is space, formwork is physical, formwork is sequential, and formwork is systemic.” In other words, digital training pedagogy is as important as the understanding of skills pertinent to the operations of formwork itself.

7.1 Why digital training is structurally different from traditional training

The traditional classroom learning is based upon knowledge transfer in an abstract sense, i.e., rules and procedures, and safety rules and procedures in a verbal or text format. This method assumes that workers can mentally transform the theoretical aspects of an operation into a physical activity at the site. The literature, however, indicates that this assumption does not hold true in the case of formwork operations because

- Many employees may not be formally educated or may not even know how to read
- Critical formwork behaviors (transfer of loads, pressure accumulation, and instability) are not visible
- Errors may emanate from the process of transitioning between steps, rather than from the performance of individual steps

This discrepancy is addressed by digital training by including learning as a fundamental element of visual representations or actions. Unlike traditional training that attempts to spur individuals to ask questions about the operations of a system by detailing its mechanisms, digital training shows its behavior when functioning correctly or incorrectly[6], [9].

7.2 Task-centric vs trade-centric training

The most important pedagogical contribution brought by digital training relates to a change from “trade-centric” learning to “task-centric” learning. Conventional training methods view “formwork carpenter” as a homogeneous skill set. In practice, there are a number of distinct tasks involved in the deployment of formwork, each of which differs in terms of associated risk, intellectual demand, or system interdependency, such as:

- Wall panel erection
- Slab Table Positioning
- Tie and Anchorage Installation
- Adjustment and alignment
- Stripping and relocation
- Execution of climbing sequence

The requirements of each task vary in terms of knowledge, attention, and decisions to be made during each task, and digital learning supports independence in each task by isolating each task and visualizing them individually in training. This has several advantages:

- Training is provided only for the tasks being performed.
- The workers can move from lower-risk to higher-risk tasks depending on the competence they have shown.
- Failures occur, and training gaps can be pinpointed to a task rather than the 'lack of skill'.

This task-centered model is particularly important with regard to advanced systems, such as climbing formwork systems, as an inaccurate execution of a task may result in failure of the system as a whole.

7.3 Role of simulation in conceptual skill formation

One of the main strengths that distinguishes advanced digital learning models is simulation. Using simulation allows workers to "see" invisible phenomena within the work domain, such as:

Increase of lateral concrete pressure with pour height and rate

- Redistribution of loads while stripping or climbing
- Effect of missing anchors or improper bracing
- Progressive collapse mechanisms

By representing the cause-and-effect relationship in a simulation, the divide is closed in that a simulation links procedural knowledge (how to) and conceptual knowledge (why one has to do it this way).

Such an issue is critical since "many accidents in formwork operations are caused, not by ignorance of the methods to be followed, but often by misjudgments in changing conditions." Simulations help workers "develop decision-making models that can be used to support decisions when conditions vary from 'normal'."

7.4 Why digital training must be closed-loop

The literature also strongly cautions that the training alone is not enough and that the absence of validation makes the virtual training another kind of static intervention, like classroom lectures. However, true effectiveness can only be guaranteed if a digital training environment is part of a closed loop system such that:

- Content for training is provided
- Worker behavior observed onsite
- Performance data is analyzed
- Training is refined based on gaps

Hence, the closed loop of the model guarantees that the supposition of learning does not rest, instead, on the verification of the behavior. It also converts the training process into an ongoing process of learning.

8.0 Training Assessment Frameworks: From Event-Based to Continuous Evaluation

Training assessment effectively remains the weakest link in the chain for construction workforce development. Much effort goes into training delivery, while a lackadaisical approach is seen in relation to training assessment. All literature concludes that training can be symbolic rather than functional without proper training assessment mechanisms.

8.1 Fundamental weakness of event-based assessment

Event-based assessment is dominant in the training provided in the construction industry due to administrative ease in monitoring. In event-based assessment, training sessions are regarded as a set of special occurrences such as inductions, toolbox talks, or training for safety purposes. They are often monitored on a simple satisfaction scale[3].

However, this approach is heavily disapproved of by literature because it focuses more on assessment by means of exposure rather than capability. Completions are not necessarily proof of comprehension, satisfaction is not proof of competence, and certificates are not proof of skills. What is not measured is whether this worker is competent in carrying out formwork activities in actual site conditions[4].

In the context of Formwork operations, such a limited ability becomes particularly dangerous because of their time-delayed and hidden nature of failure. The worker may be taking a class today, perform his/her actions improperly tomorrow, and ultimately cause a failure weeks down the line depending on how concrete, loading, or even stripping conditions change. At such a time, such a relation of training with failure becomes unclear, and a previous evaluation becomes falsely successful[3].

8.2 Multi-level nature of effective training assessment

The literature, conscious of the limitations of event-based models, therefore, goes on to propose multi-level training assessment frameworks that evaluate effectiveness across different dimensions of learning and performance. These emphasize that training must be assessed not only on what workers know, but on how they behave and what outcomes their behavior produces[8].

Assessment at the cognitive level checks if workers have grasped the essential principles underlying the work, like load paths, concrete pressure behavior, sequencing logic, and safety rationale. Although necessary, cognitive understanding is not enough in formwork operations, where execution under dynamic conditions is required[4].

The behavioural level is the most important for formwork. It has to do with whether workers on site apply correct techniques: correct spacing of ties, proper sequence of erection and stripping, pour rate limits and usage of safety systems. The literature clearly states that

formwork failures are rarely the result of a lack of knowledge; rather, they occur because knowledge is not consistently applied under pressure[4].

8.3 Continuous digital assessment as a solution

Rather, the literature is increasingly acknowledging that only continuum digital assessment offers viable solutions for the issues that are inherent in the more traditional models of assessment. Unlike the “event” assessment, digital assessment is not constructed around “checkpoints.” Rather, it is designed to measure how the work is, in fact, performed[7].

Digital assessment systems record sequences of execution of tasks, time taken, efficiency achieved, corrections made, rework undertaken, and variations from standard practices. This enables a continuous process of providing behavioral evidence through assessment that transforms from a snapshot process of assessment to an ongoing process of assessment[6].

It’s important to adopt this longitudinal perspective with regard to human factors in construction since skill levels are constantly changing. Factors like fatigue, pressure of construction sites, system changes, crew mix, etc., all continuously influence human behavior, making it essential to regularly assess whether skill degradation occurs, or not[9].

Most importantly, it is worth noting that the literature highlights that digital-based assessment changes training evaluation into a management instrument. In the context of operations like those of formwork, which are critical, it is of utmost importance that training is done through assessments that are critical as well[5].

9.0 Integration of Skill Gap Analysis, Training, and Deployment

9.1 Why fragmentation is a structural failure

Perhaps the most detrimental element of construction workforce management, as revealed through the relevant literature, lies in functional fragmentation. Skills assessment, together with training as well as workforce deployment, are often undertaken as separate processes, which are at times handled by separate entities.

Skill evaluation lacks formality, being an informal and subjective process, which entirely depends on the worker or on the availability of labor. Training programs are generic, standardized, and unrelated to the actual working conditions. Deployment is determined by the availability of labor, not on skill evaluation[1].

In operations relating to formworks, fragmentation brings about systemic danger. Workers, for instance, might have been trained but not utilized properly. The literature

indicates a big danger in operations, particularly in regard to accidents, caused by poor matching, for example, regarding skilled but not utilized workers and unverified workers.

This fragmentation endures because all the functions look locally sensible but are globally ineffective individually. Meaning, without their integration, a number of them are unable to affect the others.

9.2 Integrated model logic: Competence flow

There is a progressively stronger body of literature supporting the need for integrated workforce models, with an emphasis upon the idea of competence flow. Instead of viewing skill as an entity or an attribute, integrated models approach skill as a fluid entity.

The system's requirements are met through the following steps. It begins with the identification of system-specific competencies related to formwork operation. This is important since generic skills are considered inadequate to address the complexity of modern formwork systems. Accordingly, identification must include actual current practices such as "slab tables assembly," "wall anchorage execution," "climbing execution," "stripping during load redistribution," etc[7], [9].

Next, the actual capability of the worker is evaluated from the objective and behavioral perspective. This means that there is no assumption of competence; rather, it is measured. Additionally, there are exact and task-oriented skill deficits.

Training then takes place digitally, targeting areas of deficiency rather than providing overarching theory. The deployment of personnel is then governed by revised skills, meaning that everyone is given work that corresponds to their ability level.

Continual feedback provides updates to skill profiles, which actively closes the loop and enables adaptations as workers learn, get fatigued, or face new conditions.

9.3 Impact on safety and productivity

Literature has shown that competence-based deployment has the following implications: There is a fundamental change in the consequence for safety and productivity. If tasks that are considered risky are only allocated to authenticated workers, the probability of errors will be lowered at the onset. There will be improvement in the crew formation, thus curtailing possible interference-based delay[5].

Rework decreases with the completion of tasks with the first try. Compliance with safety rules becomes systematic rather than supervisory-oriented. Most importantly, higher productivity results not through pressure but through a sense of stability[5].

With respect to Formwork operations, in such circumstances, error propagation occurs very rapidly and has significant repercussions. Therefore, such integration in Formwork operations is not merely desirable but absolutely necessary

10.0 Strengthened Research Gaps and Explicit Justification of the Present Study

10.1 What existing literature fails to solve

Though significant developments have been recorded within construction training, productivity, and safety domains, literature presents many gaps. In most works, skill level is examined abstractly without specific competency models allied with formwork system complexity. Training research may only address learning outcomes. There may be no linkage or relation to application or deployment. Productivity studies may only show aggregate numbers, where individual competencies may vary. There may be demonstration of analysis ability in digital assessment research, but no linkage to operational models for human workforces. Hence, the industry accumulates knowledge without converting it into a practical control mechanism.

10.2 Why these gaps are critical for formwork operations

Formwork is a critical trade in terms of systems. Unlike finishing trades, where mistakes have less serious or indirect impacts, mistakes in formwork have serious implications for safety and other construction activities. The generic model does not capture this “concentration.”

However, the absence of deployable and specific skill sets for the systems means that contractors continue to depend on judgment based on their own experience even for the latest systems. Such a contradiction defeats the full purpose of the latest form work technology available.

10.3 Explicit justification of the present study

The present study will directly address these unresolved issues by suggesting a structural integration of skill gap analysis, digital training, and deployment.

By defining the critical skills specific to formwork, objectively quantifying workforce skill gaps, linking training to verified behavioral change, and embedding skill data into deployment decisions, this study unlocks implementation going beyond analysis.

This positions the research not as an incremental improvement but as a system-level solution to a long-standing problem in formwork workforce management.

11.0 Conclusion

From the literature review section, it is clearly identified that skill gaps exist in formwork operation due to training and management of the working force rather than due to the intrinsic capacity of workers. It is assessed that training and management are no longer

effective due to an increase in the technical complexity of formwork. During past decades, formwork working practices have increased their type, starting with craft formwork and advancing forward to engineered systems of modular or climbing type. In spite of having an added type of working practice and formwork, training practices have applied less compared with its increased technological complexity. It is clearly identified that learners prefer informal training, and training assessment is possibly considered an area that is greatly affected. In compliance with training assessment, it is identified that actual performance cannot be assessed through training attendance. In contrast, checking performance through continuous methods using digital technologies is well recommended. From the literatures, it is clearly identified that digital training is effective if assessment outcomes are being used for checking actual workforce performance. In conclusion, the study shows significant research gaps that have been pointed out with regards to specific competency frameworks for formwork operations, which sets the context for the current study to offer a pragmatic approach to improved safety, productivity, and quality.

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CHAPTER 43

A Study on Impact of Geosynthetic Applications in Construction Projects

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ABSTRACT

The infrastructure projects such as highways, railways, and other critical or mega structures poses challenges with respect to the ground condition. Most of the projects necessitates the deep foundation or ground improvement to overcome the problems associated with unfavourable ground conditions such as weak, expansive, or soft soils. Geosynthetics have been the most important innovation in the field of ground improvement. This includes Geotextile, Geogrids, Geonets, Geocells, Geostrips, Geomats & Geomembranes and each has their own purpose and function. They often outperform traditional solutions, enabling longer lasting support at lower material cost. The present work includes study of geosynthetics material types and their application principles in construction industry. The study will focus on evaluation of design efficiency, construction methodology, environmental impact, cost and time savings by usage of geosynthetic materials particularly geotextile and geocell. The key findings of past studies such as degree of ground improvement, behaviour, sustainability, project cost & time saving factors are discussed.

Keywords: Geosynthetics, Geotextile, Geocell, application, benefits, sustainability.

1.0 Introduction

Infrastructure construction including Bridge, Highway, Embankment and Foundation is greatly affected by soil conditions present in the area. Different types of Soil exist in nature with various compositions and different Engineering properties. Some areas have insufficient enough soil strength for the design loads required of an Infrastructure project due to weak soil conditions. Weak soils often produce low bearing capacity and therefore excessive compressibility and problems such as swelling. New developments in Geotechnical Engineering continue to help engineers achieve both greater stability and sustainability of their constructed Assets.

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Geosynthetic materials are one example of how Geotechnical Engineers are bringing Sustainable solutions to the Planning/Design Phases of their Infrastructure construction projects. The usage of geosynthetic materials in geotechnical engineering can significantly improve sustainability at the planning and design stage of infrastructure construction projects. Geosynthetic materials such as an alternative to traditional ground improvement materials are generally Geotextile, Geogrids, Geonets, Geocells, Geostrips, Geomats & Geomembranes. By implementing these materials at the planning and design stages, engineers can increase overall strength of structures and long-term sustainability. The present review was aimed to develop an understanding of how geosynthetic materials geocell & geotextile enabled structures significantly improve their overall bearing capacity, their design aspects for achieving desired bearing capacity, sustainability and project performance are covered via systematic literature review.

2.0 Literature Review

The incorporation of geosynthetic materials signifies a meaningful change in ground improvement technology, tackling the fundamental challenges in natural soil characteristics in extensive infrastructure endeavours. This review integrates significant insights from the existing literature, concentrating on the practical uses, design efficiencies, and sustainability advantages of geosynthetics specifically highlighting geocells and geotextiles in relation to ground enhancement

2.1 Characterization and mechanical evaluation

Standardized testing is essential to ensure that geosynthetics meet the physical and mechanical requirements of a project.

2.1.1 Physical property testing

- *Specific Gravity*: Measured via ASTM D792 to determine density consistency.
- *Mass per Unit Area*: Evaluated under ASTM D5261, typically reported in grams per square meter (g/m²).
- *Thickness*: Determined by ASTM D5199 under a standard pressure of 2 kPa.
- *Flexural Rigidity (Stiffness)*: Assessed by measuring the overhang distance on an inclined plane to determine how the fabric behaves during deployment over soft subgrades. (Rajagopal, 2013)

2.1.2 Mechanical performance metrics

- *Tensile Strength*: The Wide Width Tensile Test (ASTM D4595) provides accurate force-per-unit-width and peak strain data. Index tests like the Grab Tension Test (ASTM D4632) simulate localized stretching from construction stresses.

- *Puncture Resistance*: Evaluated through static methods (ASTM D4833), the CBR Puncture Test (using a 50 mm plunger), and dynamic “cone drop” tests to simulate impact from falling stones.
- *Seam and Burst Strength*: Seam efficiency ensures structural continuity, while the Mullen Burst test (ASTM D3786) measures resistance to multidirectional pressure. (*Rajagopal, 2013*)

2.2 Mechanics of three-dimensional cellular confinement

Geocells gives additional planar reinforcement to three-dimensional confinement effect of geocells.

2.2.1 Confinement mechanisms

Geocells can control how much lateral movement of fill can occur due to the tension applied to the geocell walls (known as hoop tension) (*Rimoldi & Brusa, 2022*). The geocell structure provides an increase in the vertical movement of soil when placed in the geocell structure, due to increased confining pressure on the soil by lateral geocell walls. Therefore, as more soil is placed in the geocell mattress, the shear strength and elastic modulus will increase proportionally to the amount of soil confined in the mattress (*Han, et.al., 2010*) Geocell mattresses can mitigate lateral movement of soft clay materials at the foundation level by providing a semi-rigid pavement support system.

2.2.2 Stress distribution and bearing capacity

The “slab effect” created by geocells broadens the dispersion angle of vertical forces, therefore; the overall vertical forces exerted on the subgrade is reduced by 20% to 50% depending on the distance from the Load Application Centroid (Centre of Geocell structure). Additionally, the presence of geocells causes a re-direction of the Principal Stresses (i.e. the rotation of the Principal Stresses) in soil embankments which reduces the potential for slip circle failure and increases the bearing capacity factor N of a geocell mattress (approximately 5.14 - >7.0) (*Inti, et al., 2021*).

3.0 Design and Methodology for Geocell Reinforcement

The *Han & Pokharel (1984)* method for unpaved roads modifies the Giroud & Han design Models for geocell reinforced roadways to accommodate the unique parameters of geocell, including Stiffness and Tensile Strength. Cumulative wheel loads and CBR from a repeated plate load tests were noted and used to create Cumulative Wheel Pass and CBR Data so that the Minimum Thickness Required for Geocell Layers can be calculated based on the requirements of Traffic (*Han, et al., 2011*).

3.1 Modulus improvement factor (MIF)

The MIF (EReinforced / EUn-Reinforced) determines the total stiffening benefit of each of reinforced material over an unreinforced material through calculations based upon their modulus values. For very weak subgrades (10MPa) MIF values can reach 3.13 to 5.38. Field trials using Novel Polymeric Alloy (NPA) geocells have demonstrated MIF values as high as 2.75 to 2.84, enabling a 50% reduction in pavement thickness (*Kief et al., 2011*).

3.2 Construction efficiency and technology

The way we design & construct (the construction methodology) changes drastically when deploying geosynthetics as opposed to using traditional materials, thereby removing the need to perform many heavy & slow constructions steps associated with using those traditional materials such as concrete and steel. Since geosynthetics are made of lightweight, flexible materials, they dramatically simplify logistical requirements and allow a manual handling of the materials in situations where heavy equipment (such as large cranes and earth moving machines) would be needed to transport the traditional materials.

3.3 Digital applications in design

The adoption of specialized digital engineering tools has greatly contributed to the modernization of geosynthetic construction. The NAUE Geosynthetic Design Suite is one of the portals which functions as a comprehensive geotechnical software solution. It offers engineers a series of calculators aimed at optimizing infrastructure projects via accurate material modelling. By employing such tools, projects are no longer dictated by “design conservatism” but rather backed by performance data, which in turn guarantees their safety, cost efficiency, and sustainability. The main modules consist of:

3.3.1 Naue platform (working platform design)

This software tool allows for the quick creation of temporary working surfaces in soft subgrade soils applying the well-established BR470 design method and Naue’s secret “Hybrid Method.” (*Khansari et al., 2023*). The system not only takes into account the particular loads related to the construction equipment (for instance, piling rigs or cranes) and the soil parameters but also calculates the most suitable thickness for the base course. This accuracy avoids the risk of excessive deformation or structural failure, which are serious safety hazards in such weak cohesive soil conditions (*Naue_Adm_Web. 2025a, October 22*).

3.3.2 Naue UnpavedRoad & SecuCalc

By means of the adapted Giroud-Han approach, these calculators can create the temporary access and haul roads ideally designed. Performance data for Secugrid® geogrids

and Combigrid® geocomposites are incorporated in the software, thus enabling the engineers to model the traffic movement with the “wheel wandering” effect, thereby realizing more accurate load distribution and cutting the base course thickness by as much as 50% (*Naue_Adm_Web. 2025b, October 22*).

3.3.3 Naue Veneer Reinforcement

The specialized tool in question evaluates the stability of stratified thin systems not only during the construction phase but also in the final stage. This is of utmost importance in protecting the environment, where, for instance, landfill caps and mining closure projects rely on the stability of steep slopes (*Naue_Adm_Web. 2025c, October*).

4.0 Sustainability and Circular Economy

Geosynthetics facilitate the use of marginal materials and reduce the overall environmental footprint of civil works.

4.1 Stabilization of recycled asphalt pavement (RAP)

RAP is susceptible to creep and permanent deformation due to asphalt content. Geocell confinement significantly reduces this deformation. At a 75 mm rut threshold, NPA geocells can improve the service life of a 0.30 m RAP base by a factor of 19.4 compared to an unreinforced base of the same thickness (Pokharel et al., 2010).

4.2 Life cycle assessment (LCA) data for reinforced earth wall

Designers can utilize life cycle assessment (LCA) to calculate a score that will help them to determine which type of design (traditional vs geosynthetic) should be utilized. Following case studies illustrate the quantified environmental benefits of substituting conventional mineral and concrete materials with geosynthetics (Stucki et al., 2011).

A comparative examination of a one running metre of the three-metre-high wall for a 100-year lifespan was conducted by the E.A.G.M., comparing to Geosynthetic Reinforced Soil Wall (G.R.R.W.), which is made up of polyethylene and PET woven geogrids having a long-term strength of 14kN/m. The table below indicates all the specific information for both Types of Walls and the building materials for the GRRW that would be constructed out of site fill, wall embankment(s) and as a finishing cap over the G.R.R.W. To assure that the construction of the GRRW conforms to CRRW, an 80 cm thick gravel drainage will be used for both types of Retaining Walls, utilising rounded stones for the drainage medium behind the Concrete Lining.

Table 1: Typical Comparison of Concrete and Reinforced Soil Retaining Wall

Item	Unit	Concrete Wall	Reinforced Soil Wall
Concrete	m ³ /m	1.60	-
Lean mix concrete	m ³ /m	0.24	-
Structural concrete	m ³ /m	2.10	3.31
Reinforcing steel	kg/m	153.00	-
Gravel	t/m	4.30	4.30
Bitumen	kg/m	2.84	-
Three layered laminated board	m ³ /m	0.01	-
Geosynthetic	m ² /m	-	39.20
Polystyrene foam slab	kg/m	0.25	-
Polyethylene	kg/m	1.74	2.02
Diesel in building machine	MJ/m	11.60	53.90
Transport, lorry	tkm/m	701.00	265.00
Transport, freight, rail	tkm/m	33.20	6.90
Land use	m ² /m	1.00	0.60
NMVOC	g/m	20.00	-

Source: Stucki et al., 2011

Table 2: Typical Quantity for Production of 1kg Geosynthetic Layer in Slope retention

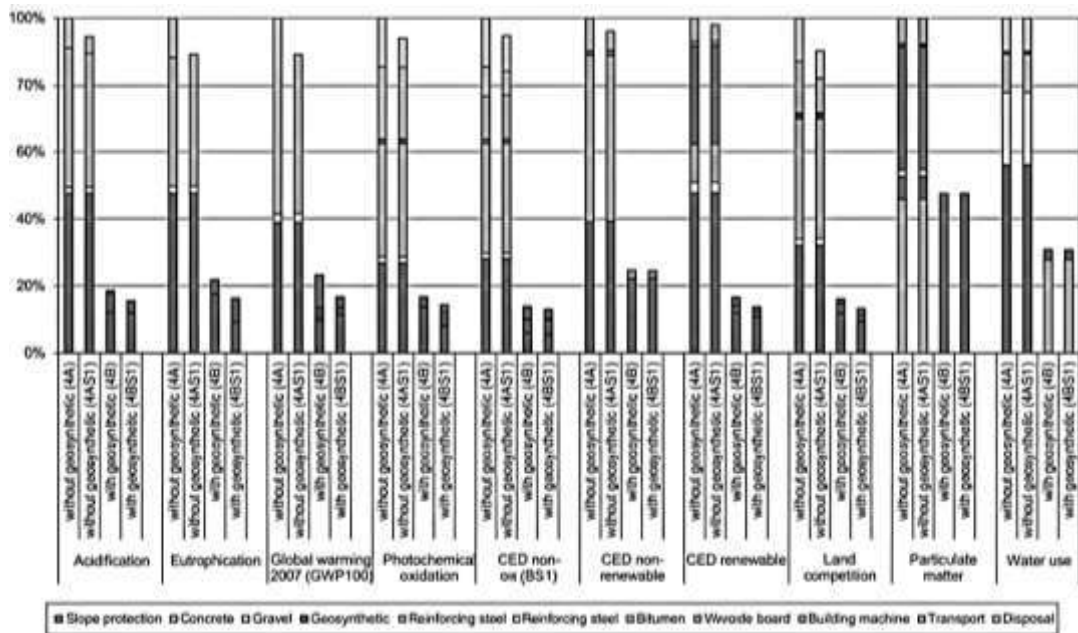
Items	Unit	Value
Raw materials	kg/kg	1.02
Water	kg/kg	0.86
Lubricating oil	kg/kg	7.30×10^{-5}
Electricity	kWh/kg	0.73
Thermal energy	MJ/kg	1.24
Fuel for forklifts	MJ/kg	0.13
Building hall	m ² /kg	6.32×10^{-6}

Source: Stucki et al., 2011

The environmental assessment of 1 m of retained earth for every 3m of height and across its full life cycle including construction, disposal, and provision of raw materials was carried out. (Stucki et al., 2011).

From the below figures, compared to the other ground improvement & slope retention techniques the geosynthetic reinforced wall replaces the use of concrete and reinforcing steel, which will benefit 63% & 87% lower environment emissions.

Figure 1: Typical E.I.A. Comparison of Conventional and Reinforced Retaining Wall



Source: Stucki et al., 2011

5.0 Economic Evaluation and Project Efficiency

The economic benefits of geosynthetic materials are driven by material savings as compared traditional ground improvement methods and accelerated construction schedules.

Material Reduction: Geogrid reinforcement allows for a 30% to 50% reduction in gravel thickness. Geocell reinforced retaining structure shows that these structures have ability to tolerate large settlements with the minimal use of filling material. Pavement cost savings typically range from 14% to 24% (Aanand jain, 2016).

Retaining Structures: GRRW solutions offer approximately 30% cost savings over traditional R.C.C. walls by replacing steel and cement with polymeric reinforcements and on-site soil (Aanand jain, 2016).

Bridge Approaches: Utilizing geosynthetic reinforcement at bridge approaches can reduce the number of required grade beam piles by 40% to 50% (Aanand jain, 2016).

6.0 Conclusion

The comprehensive review confirms that geosynthetic applications in civil engineering provide a superior alternative to design sustainable solutions in geotechnical

engineering. By leveraging the unique three-dimensional confinement mechanism of rotating principal stresses, geosynthetics enhances the constructability of micro-mega structures on terrain, hills & slopes previously considered unsuitable. The significant improvements in bearing capacity in geosynthetic enabled structures, the 30% average cost savings, and the 80% reduction in carbon emissions—coupled with digital design tools like the Naue Portal enables the geosynthetics as a core component of sustainable, modern civil infrastructure design to everyone.

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CHAPTER 44

Implementation of Total Productive Maintenance (TPM) for Effective Equipment Management in Infrastructure Projects

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ABSTRACT

Efficient equipment management ensures infrastructure projects are delivered in time and at lower cost. However, frequent breakdowns, poor maintenance practices, and lack of performance monitoring often lead to productivity losses and increased project costs. This research aims to Automate Equipment Maintenance by using ERP systems for efficient equipment management in construction and infrastructure projects, by following various maintenance practices such as Total Productive Maintenance (TPM). The research work explores existing maintenance practices that have been adopted in the organization and identifies the deviation, then evaluates the impact of TPM on improving Overall Equipment Effectiveness (OEE). Data regarding various equipment operations in several construction projects are analysed, which includes Daily operations, Idle time, Breakdown time, Repair time, Maintenance scheduling, Actual maintenance carried out, Time taken for maintenance, and expert interviews to understand the loss areas. A TPM model is developed to improve reliability, preventive maintenance culture, and safety awareness among maintenance crew. The results are expected to demonstrate significant reductions in equipment downtime, increased utilization percentage, production quantity, thereby reducing the equipment cost for the project. The research highlights TPM as a practical and sustainable approach for modern infrastructure project management.

Keywords: Total Productive Maintenance, Overall Equipment Effectiveness, Preventive maintenance.

1.0 Introduction

Effective equipment management is an integral part of infrastructure project.

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Construction and infrastructure environment demands equipment which are reliable, always available for utilisation, and capable of keeping pace with construction project timelines and costs. Sudden failures in equipment, and ineffective maintenance activities leads to low equipment performance which causes losses and negatively affect in construction timeline and costs. To mitigate such issues, Total Productive Maintenance (TPM) can be adopted, as it involves and encourages various stakeholders to take preventive and continuous improvement measures to optimise equipment performance and production.

For instance, in infrastructure projects heavy construction equipment like Tunnel Boring Machine (TBM), Earthmovers, Cranes, Material Handling, Road Making Equipment etc. are used to execute the project in safe, fast, quality, and cost effective. The use of TPM and measuring performance by OEE provides a means of ensuring that such potential drawbacks or challenges associated with heavy machine usage in infrastructure development projects are addressed.

This paper gives an overall review of literature on TPM, a research methodology to analyse the application of TPM on infrastructure projects and concludes by identifying some areas for research on TPM in the future.

1.1 Present industry scenario

In infrastructure projects, effective equipment management begins with strategically deploying suitable construction equipment from various yards or project locations based on site demand and availability. This process involves selecting right equipment for right activity and coordinating with relevant stakeholders to fulfil the needs of project execution team.

Generally, infrastructure projects are spread across large areas, and simultaneously multiple activities are being performed on daily basis and to perform these activities safely and with quality, we need heavy construction equipment.

Construction equipment is bound to fail over a period of usage. To reduce these sudden failures, we need to perform periodic or preventive maintenance in a timely manner.

In construction projects most of this equipment are being handled and operated by operators. As a general practice, before starting the equipment operation operators are checking the conditions of equipment on daily basis and logs of daily usage are recorded in manual logbook, and later this data is being updated in the system by a data entry person, and subsequently being reviewed by the concerned manager, and necessary maintenance schedules are being prepared considering the anticipated operating hours.

Maintenance schedules are prepared in line with OEM recommendations. Maintenance tasks are performed according to schedule and actual operating hours; however, the entire process is manually controlled, numerous delays occur.

On reviewing the maintenance tasks that are already performed, we could see few delays, like the operator is not communicating with the maintenance crew about the maintenance due, the nonavailability of spares in stock, and sudden changes in equipment deployment/engagement. There are a few repeated reasons that lead to delays in maintenance. On studying the data, we can derive and identify similar things that are impacting our maintenance tasks, and these delays can be controlled very well if they are done in a proper systematic way. To perform the maintenance task in an equipment, we need to closely interact with multiple stakeholders like the execution team for the spareability of equipment, the store in-charge for availability of spare parts and P&M in-charge for availability of the maintenance crew. The delay in preventive/ periodic maintenance results in sudden failures which are unplanned downtime, and frequent breakdowns. The unplanned downtime creates lot of pressure in the execution, maintenance and operation team. Once equipment fails, all the resources like man and machine which are allotted for the activity will be idle. This would lead to inefficient utilization of equipment as well as high equipment cost for the project.

The lack of a data-driven and proactive maintenance culture is also a challenge to safety, reliability, and timely decision-making, thus the need to address the weakness of manual maintenance of equipment through approaches like TPM and ERP System.

2.0 Literature review

2.1 Total Productive Maintenance (TPM) concepts and pillars

Total productive maintenance (TPM) is an Overall concept of equipment maintenance and equipment assets management with an aim to optimize equipment efficiency. This is achieved through the overall staff and equipment engagement and minimizing losses in overall equipment life cycles. This paper reveals that TPM is a strategic process incorporating preventive, predictive, and autonomous maintenance techniques to optimize equipment reliability, productivity, and quality outcomes within manufacturing processes.(Ahuja & Khamba, 2008)

As stated by the study paper, the implementation of TPM works on the foundation of 8 pillars: Focused Improvement, Autonomous Maintenance, Planned Maintenance, Education and Training, Early Equipment Management, Quality Maintenance, Office TPM, Safety, Health & Environment. These pillars control the overall 6 big losses, which include breakdowns, set up losses, idle time losses, losses due to speed, defects, and start-up losses.(Meca Vital & Camello Lima, 2020)

TPM stands to be a cultural shift rather than a maintenance method as it involves operates, maintenance personnel, as well as management in improvement activities. The focused improvement and plant maintenance pillars have been found to be the most effective

in overcoming downtimes as well as improvement in reliability in a diverse range of industries such as automobile, textile, chemical as well as food processing industries.(Meca Vital & Camello Lima, 2020; Mwanza & Mbohwa, 2015)

2.2 Overall Equipment Effectiveness (OEE) as a performance measure

Overall Equipment Effectiveness (OEE) – It is a key statistical measurement used to assess the effectiveness of TPM implementation. (Corrales et al., 2020)It enhances the overall efficiency of equipment by accounting for the secondary losses resulting from the 6 major losses, enabling a comparison with world class manufacturing standards where an OEE above 85% is considered excellent. It gives the overall effect by multiplying the other two, which is the effect of the 6 big losses. (Okoro, Gospel Onyebuchi, 2024) This paper examines the unequal effectiveness of different pillars of Total Productive Maintenance (TPM) in improving OEE performance. Through a survey conducted on Brazilian manufacturing companies it was found that focused improvement and plant maintenance generated improvement in OEE ranging from 12.5% to 33.3% by reducing breakdown losses, Mean Time To Repair (MTTR), and quality defects.(Meca Vital & Camello Lima, 2020) Extending these findings to another industry, automotive case studies further affirm the evidence that implementing TPM results in marked enhancements in availability, performance efficiency, and quality rates. OEE values increase between 6% and 10% after a systematic implementation of the AM and QM pillars of TPM(Kumar Das et al., n.d.)

2.3 Impact of TPM pillars on manufacturing performance

The diverse impact of various TPM pillars is highlighted by empirical data from multiple studies. Because of operator involvement, autonomous maintenance improves basic conditions by decreasing minor stoppage and increasing fault detection speed.(Adesta et al., 2018). Unplanned downtime is decreased and scheduling efficiency is increased with plant maintenance. Quality maintenance integrates maintenance with process quality control systems to achieve zero defect pollution.(Meca Vital & Camello Lima, 2020)

Studies in the pharmaceutical and automotive industries shows that bpm adoption increases machine availability by 15 to 25%, slower corrective maintenance by over 50%, and boost OEE by roughly 20% with structured pillar implementation and ongoing monitoring.(Kumar Das et al., n.d.)

2.4 Digital TPM and Industry 4.0 integration

As industry 4.0 emerges, TPM becomes digital TPM (TPM 4.0), which integrates IoT and smart sensors with AI and TPM 4.0. This is clear from a systematic study by, which

showed how digital technology rises OEE, MTBF, and MTR and enhances condition monitoring and predictive maintenance.(Mouhib et al., 2025)

According to their research there are 4 crucial elements that must be present for TPM 4.0 to be implemented successfully:

- Workforce integration and training
- Phased deployment strategy
- Modular technology architecture
- Standardised performance metrics OEE, MTBF, MT

The research on the unified digital TPM framework is crucial, particularly for scaled applications involving SMEs and infrastructure intensive industries.(Hussien Gomaa, 2025; Mouhib et al., 2025)

2.5 Data driven and lean 4.0 based TPM frameworks

Recent literature shows how traditional total product in maintenance (TPM) will change due to data driven and digital maintenance systems in the context of industry 4.0 and lean 4.0. This paper suggests a complete data drilling framework for TPM, combining Association Rule Mining and Network Analysis to support strategic decision-making for improving Overall Equipment Effectiveness (OEE).(Lucantoni et al., 2025)

This four-layer model include data acquisition, processing, analytics, and decision support. This setup allows for real-time identification of key loss factors affecting availability, performance, and quality. The research demonstrate that advanced analytics can reveal hidden connections among production variable and TPM pillars. The results from an industrial case study showed a 14% increase in OEE and successful implementation of seven out of eight TPM pillars confirm in the effectiveness Lean 4.0-enabled TPM.

This digital shift addresses the limitation of traditional TPM, which depends on manual data collection and reactive tools like Pareto charts and Ishikawa diagram. The integration of IoT-based data acquisition systems, computerised maintenance management system (CMSS), Manufacturing Execution Systems (MES), and data warehouses allows for continuous monitoring of equipment health, failure trends, and performance, enhancing predictive and proactive maintenance capabilities. Research evidence shows that digital TPM frameworks significantly enhance the accuracy of OEE calculation and early detection of chronic losses due to speed and quality defects that the traditional maintenance dashboards generally fail to detect.

2.6 TPM implementation practices and organizational readiness

The article gives a critical classification of TPM implementation methods for large industries and SMEs and has emphasized that the success of TPM greatly realizes on

organisational maturity, skills, and management commitment (Jain et al., 2014) . An analysis of 148 studies shows that TPM boost equipment availability, cuts maintenance costs, increases operator involvement and enhance OEE. However, it also identifies challenges such as resistance to change, insufficient training, lack of standard maintenance data, and weak collaboration between production and maintenance teams.

The authors stress the importance of autonomous maintenance and planned maintenance as vital foundation in SMEs, as they empower operators and establish equipment conditions. Focused Improvement and Quality Maintenance further enhance overall equipment effectiveness by addressing losses and root causes of defects. Particularly highlights the value of integrating TPM with Reliability-Centered Maintenance (RCM) and CMMS.

This paper will further confirm these findings by synthesizing global literature on TPM's success implementation (Ngoy & Israel, n.d.). It emphasizes that TPM provides immediate benefits, such as reduction of breakdowns by 65% to 78% detect reduction by 65% to 80% and OEE improvement of 14% and 45% along with indirect benefits like enhanced safety culture, employee motivation, knowledge sharing, and better workplace organization these study reaffirms that TPM's effectiveness relies on teamwork among departments, ongoing training and strong leadership, which aligns with social-technical view of maintenance excellence.

2.7 Eight-Pillar TPM and performance outcome

The eight-pillar TPM model-Autonomous Maintenance, Focused Improvement, Planned Maintenance, Quality Maintenance, Education and Training, Office TPM, Early Equipment Management, and Safety, Health and Environment-remains central to both traditional and digital TPM systems. (Aditya Sari, 2015) Confirms this framework while executing TPM deployment in water treatment facility using Likert-scale-based on maturity assessment across all pillars.

The results indicated that implementation levels were 84.8% for Planned Maintenance, 87.5% for Quality Maintenance and 82.3% for Autonomous Maintenance. Such brought noticeable change for the better in equipment reliability, process, and customer satisfaction.

The outcome of the research reveals the importance of effective Planned Maintenance, aided by Vibration Analysis, Condition Monitoring, and Failure History, in minimizing the frequency of unplanned downtime and increasing availability. Effective Maintenance ensures no defects using Early Warning System, Poka-Yoke, and Standard Operating Procedures in the industry. The improvement teams apply problem-solving techniques and the 5S in the reduction of chronic losses in the workplace.

These results validate previous studies conducted by Jain et al. (2014) and Ngoy et al. (2021), proving that TPM's overall efficiency has extended applications beyond just equipment efficiency alone. Furthermore, these results validate that OEE stands not only for a technological purpose but also for a level of maintenance process practices.

2.8 Integration of TPM, OEE, and advanced analytics

The integration of TPM with advanced analysis and Industry 4.0 technologies is considered a breakthrough in maintenance. (Lucantoni et al., 2025) observed that, though the potential offered by these approaches, seems enormous, most traditional studies in the area revolved around TPM pillars mostly relating to availability losses, in a restrictive manner, paying less attention to losses in performance and quality. Their ARM-NA framework was, however, a deviation from the norms because it maintained a balance in eliminating and accentuating the potential for best practice.

Literature also suggests that predictive models, network-based causal mapping, and real-time dashboards can enable dynamic prioritization of TPM initiatives, aligning maintenance strategy with operational risks, costs, and sustainability goals. However, fully integrated and long-term digital TPM implementations with empirical validation remain rare, and particularly in infrastructure and construction equipment management, where issues like asset mobility, environment changes, and fragmented data systems and complexity.

2.9 Research Gap

Even though TPM and OEE have been the subject of numerous published studies the majority have installed concentrated on case studies or industries not much has been done on:

- Integration of TPM with e digital transformation models for construction projects,
- integration of TPM with digital transformation models for construction projects,
- Comparative impact analysis of the TPM pillars on OEE using systematic review methods,
- Creation of TPM implementation models that are focused on performance in an industry 4.0 setting.

These research caps highlight the significant significance of conducting a systematic literature review to examine the available data regarding the connection between TPM and OEE and consequently, to develop the conceptual framework for digital equipment management system.

A synthesis of traditional TPM-OEE literature and modern digital TPM indicates that there are numerous research gaps in a Systematic Literature Review that seeks to fail.

- While the literature review indicates a positive relationship between the three pillars of TPM and improvement in OEE, much of the literature remains industry- and case-

specific, thereby lacking broader applicability, especially in management of construction equipment.

- The literature focuses mostly on isolated TPM key pillars and OEE elements, considering mainly availability and breakdown losses, whereas there is a lack of studies that considered the whole eight pillars of TPM and three OEE limitations (availability performance and quality).
- There is no integrated, validated digital TPM framework despite the advances of Industry 4.0 and Lean 4.0 that integrate structured TPM deployment with real-time data gathering, advanced analytics, and decision-support system. Most digitalization efforts place much stronger emphasis on Predictive Maintenance or Condition Monitoring at the expense of much human-focused areas of improvement such as Autonomous Maintenance, Training Effectiveness, and Change Management.

Further, there is no standardization of performance measurement methodologies or harmonization of the formula for computation of OEE and empirical validation over a long period in many studies. These are some of the limitations to comparative studies and deployment of theory. Such knowledge gaps provide a stronger rationale for systematic synthesis of TPM-OEE literature to identify major themes, methodological trends, and success factors, and priorities for future research with implication for an integrated model of data-driven equipment management in complex project-based environments.

3.0 Research Methodology

3.1 Research design

In the current study, the design for the research is that of mixed methods, which aims to determine the effect of TPM implementation on infrastructure projects through both quantitative and qualitative analysis. Quantitative data will be collected regarding the number of running hours, unplanned downtime, number of breakdowns, repair time, and OEE values for the machinery, while Qualitative data will be gathered from expert interview with project managers, P&M in-charge, equipment operators, and maintenance crew.

3.2 Data collection

The research study collects and utilises existing equipment operation and maintenance data of ongoing infrastructure project:

- Equipment Operational Records
- Repair and Breakdown History
- Maintenance Schedule
- ERP Modules Maintenance
- Interviews with Maintenance Engineers and Site Manager

3.3 Detailed methodology to be used

- Downtime study of equipment failure
- Study on breakdown due to unavailability of consumables and spares
- Preventive maintenance plan - schedule vs actual
- Age of equipment and its impact on availability
- Study the need of skilled operator for operating critical P&M equipment
- Study of construction activity planning and scheduling on usage of machine
- Study of current process of monitoring the equipment parameter and its drawbacks

3.4 Expected contribution

- Projects can be executed at a faster pace as per project schedule by improving the availability of equipment
- Reduced labour deployment at project by enhancing P&M productivity
- Critical projects can be completed in less time with high P&M productivity using low resources like labour, equipment etc.
- Decide the frequency of preventive maintenance based on the age of equipment and/ or the repair cost.
- Reduce the cost of Maintenance/ Repair by identifying the equipment to be disposed.

4.0 Data Analysis

Operational data was analysed for machines. The OEE formula is as follows:

$$\text{OEE} = \text{Availability} \times \text{Performance Efficiency} \times \text{Quality Rate}$$

Where:

Availability measures actual operating time over planned operating time.

Performance Efficiency considers actual speed against ideal operating speed.

Quality Rate captures the ratio of acceptable output to the total outputs.

A framework for TPM has been developed based on 8 pillars of TPM

- Autonomous maintenance schedule
- Plant maintenance plan
- Focused improvement
- Quality in maintenance
- Education and Training
- Safety
- Early equipment management

Comparative analysis was performed among pre-TPM state and the state after TPM regarding:

- Reduction in the breakdown hours
- Redefined response time in maintenance
- Increase in equipment utilization
- Reduction in ideal and waiting time because of the approvals and spares
- The root cause analysis used techniques such as pareto chart and fishbone diagram to determine the key loss causing factors.
- Reduction in man hours spent preparation of schedules and plan.

5.0 Findings/ Results

Industry research suggests that TPM implementation increase equipment effectiveness and productivity. Equipment efficiency improvements, reduce breakdowns, and culture of maintenance improvements identified by studies on TPM implementation. In the context of infrastructure using TPM might bring about various advantageous results such as:

1. Reduction in equipment downtime through identifying remedies factors leading to equipment failures and performing preventive maintenance, a reduction in downtime can easily be achieved in infrastructure projects.
2. Increased resource utilization this is because of increased OEE, more time is spent on productive activity, hence effective resource utilization. This directly reduces the overall project duration.
3. Enhanced safety and quality as preventive maintenance may minimise safety risk posed by equipment failure, resulting in improved safety and quality level at the workplace.

6.0 Conclusion

Total production maintenance can be viewed as a long-term approach aimed at improving equipment performance in infrastructure projects. Since its emphasis on maintaining equipment through prevention and continuous improvement, total productive maintenance can significantly minimize downtime, maximize equipment use, and eventually optimize project performance. Although most existing research works are based on manufacturing processes the philosophy of total productive maintenance can be applied across all other infrastructure projects since it has the potential to revolutionize the management of those projects. Future research should explore the application of total productive maintenance across all types of infrastructure projects based on innovative maintenance technologies.

7.0 Recommendation

On the basis of findings in current studied and the expected findings in future studies, the following are proposed for managers in infrastructure projects:

1. Establish a Roadmap for TPM Deployment: Create a roadmap comprising assessment, TPM pilot implementation, operator training, and implementation in an organization.
2. Integration of TPM with Digital Technology: Application of the ERP system and maintenance management software for automatically gathering the equipment operating data and scheduling for maintenance task as well as tracking.
3. Invest in Training and Culture Change: Encourage our culture in which the maintenance efforts can, and most, be done together by the operators, supervisors, and maintenance personnel.
4. Monitor and Evaluate Continuously: Use OEE dashboards and performance reviews to monitor and adjust as necessary.

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CHAPTER 45

Delay Analysis of Stadium Construction Projects using RII methodology and Formulating Mitigation Strategies

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ABSTRACT

The purpose of this research paper is to analyse delay factors of stadium construction projects using the Relative Importance Index (RII) methodologies and formulate efficient mitigation strategies. Methodology: The study uses a mixed-method approach that combines both quantitative and qualitative data collection techniques. A thorough literature review identifies common causes of delay in stadium construction. Purposive sampling is employed to select professionals with relevant experience and expertise in stadium construction projects. Surveys and interviews with industry professionals collect primary data on these causes and their perceived importance. RII analyses rank and prioritize the delay factors. Based on these findings, specific strategies to reduce delays are proposed and assessed for their potential effectiveness. Limitations and Gaps: The research is limited to stadium construction projects, which may not apply to other types of construction. The study depends on expert opinions, which can introduce personal bias. Moreover, the effectiveness of the proposed strategies is theoretical and needs practical application and long-term evaluation. Future research should tackle these gaps by broadening the focus to include various construction projects, using more objective methods to measure delays, and performing long-term studies on the application of the strategies.

Keywords: Delay Analysis, Stadium Construction, RII, Mitigation Strategies.

1.0 Introduction

1.1 Background of large-scale infrastructure and stadium construction projects

Major infrastructure projects are of great significance in the development of a nation as they contribute to the growth of the economy, social and urbanization.

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Among them, stadium construction projects are the kind of infrastructure that has its own peculiar category because of the magnitude of its construction, the technical complexity, and symbolic significance. Compared to the traditional building projects, modern stadiums incorporate elevated systems of structures, special playing fields, removable seats, broadcasting, and sustainability systems, which have significantly increased their complexity (Love et al., 2022). The number of stakeholders, involved in the projects, such as government agencies, sports authorities, designers, contractors, and event operators, also increases the complexity of the projects and the need to coordinate them (Doloi et al., 2012).

1.2 Significance of stadiums projects in economic growth, urban renewal and international sporting events

The boost of economic development and regeneration of cities is usually an idea behind stadium projects. They encourage employment, tourist attraction, city branding, and ancillary business like transport and hospitality (Baade and Matheson, 2016; Fashina et al., 2021). Within the framework of international sporting events, stadiums have to meet the highest international standards and set deadlines due to which the stadium finishing can lead to losing the right to host events and can be accompanied by serious financial and reputational losses (Flyvbjerg, 2021). This means that construction is not the only important concern regarding timely delivery of stadium projects but also in a more broad economic and political viewpoint.

1.3 Research gap in studies on stadium-specific delays

Despite the vast amount of literature on construction delays on general infrastructure and building projects, few studies on delays in the context of a stadium have been gathered. The majority of available studies consider the stadium projects in the context of more comprehensive infrastructure, ignoring unique technical, managerial, and political features (Love et al., 2022). Additionally, there is a paucity of studies combining delay ranking and action-oriented mitigation models designed to address stadium construction. The limitation of this gap to generalized delay results is that it limits the extrapolation of generalized results to construction projects in stadiums, and the focus of empirical research in this area is warranted.

1.4 Intention and importance of the research

The given study is aimed at identifying, ranking, and discussing the key issues that caused the delays in the stadium construction projects in a quantitative manner. Through the RII, the paper aims at ranking the causes of delays according to their perceived importance, frequency and severity. The results should help project managers, policymakers, and

stakeholders to enhance planning, decision-making and mitigation strategies of risks. In the academic sphere, the research represents a small pool of literature on stadium-specific construction delay, whereas in practical terms, it can provide evidence-based suggestions on improving how timely and efficiently the project is delivered.

2.0 Literature Review

2.1 Concept of construction delays

Construction delay refers to the time overrun beyond the project completion date agreed upon by contracting parties. It is a persistent global issue particularly in complex and uncertain infrastructure projects (Enshassi et al., 2009). Delays not only affect schedules but also increase costs, compromise quality and create conflicts among stakeholders. Prolonged delays often damage trust and may lead to claims, disputes or project abandonment (Fashina et al., 2021).

2.2 Delay factor in large infrastructure projects

Infrastructure projects are highly prone to delays due to their large scale, long durations and involvement of multiple stakeholders. Contractor-related delays often arise from poor planning, weak site management, shortage of skilled labour and poor subcontractor coordination (Fashina et al., 2021). Financial mismanagement and lack of equipment further contribute to time overruns. External and political factors such as policy changes, regulatory constraints, economic instability and force majeure events also significantly affect project timelines particularly in government-funded projects in developing countries (Singh, 2022). Additionally, land acquisition and multi-level regulatory approvals frequently delay stadium and infrastructure projects (Enshassi et al., 2009).

2.3 Research gap

Although mass literature and surveys were carried on the causes of construction delays in infrastructure projects, the available empirical research on the cause of construction delays in stadiums is still scarce. Existing studies consider stadiums as members of larger infrastructure or public construction groups, which does not consider the unique technical, managerial, and political challenges (Love et al., 2022). More so, most of the studies define and prioritize delay factors, but few combine delay ranking with a structured mitigation planning specific to the stadium projects. A major gap in research is the absence of empirical proof of the connection between quantitative delay analysis and practical mitigation strategy. To close this gap, it is necessary to make the delay studies more relevant to practitioners working on the stadium construction project (Fashina et al., 2021; Singh, 2022).

3.0 Research Methodology

3.1 Research design

The current research will take the quantitative research design which is descriptive in nature in an effort to study delays in stadium construction projects in a scientific and objective way. Quantitative approach is also an appropriate method of conducting the construction delay studies because it makes it possible to measure, compare, and rank various delay factors, guided by numerical data provided by industry professionals (Doloi et al., 2012). The research method considered was based on a survey to get the perceptions and experiences of professionals working on the construction of stadium projects directly. The reason why survey methods are popular in construction management research is that they are efficient in capturing standardized information of a variety of stakeholders and provide an opportunity to statistically analyze complex issues surrounding a project (Doloi et al., 2012).

3.2 Questionnaire design

The questionnaire was constructed based on a thorough analysis of the peer-reviewed literature on construction delays, especially focusing on the large infrastructure and sport facilities projects. Delay factors which were found during past research have been thoroughly modified to suit the context which exists in stadium construction. The respondents were asked to rate the delay factors on a Likert scale of five points with 1 indicating very low perception and 5 very high perception. Likert scale was chosen based on the fact that it is reliable and is widely used in construction management studies to measure subjective judgments on a quantitative basis (Doloi et al., 2012). The delay factors included in the questionnaire were categorized into the following five groups to ensure structured analysis:

- Technical factors
- Management-related factors
- Design-related factors
- Logistics and procurement factors
- Other external factors, including political and regulatory influences

This categorization facilitates clearer interpretation and comparison of delay causes across different functional domains within stadium construction projects.

3.3 Sampling and data collection

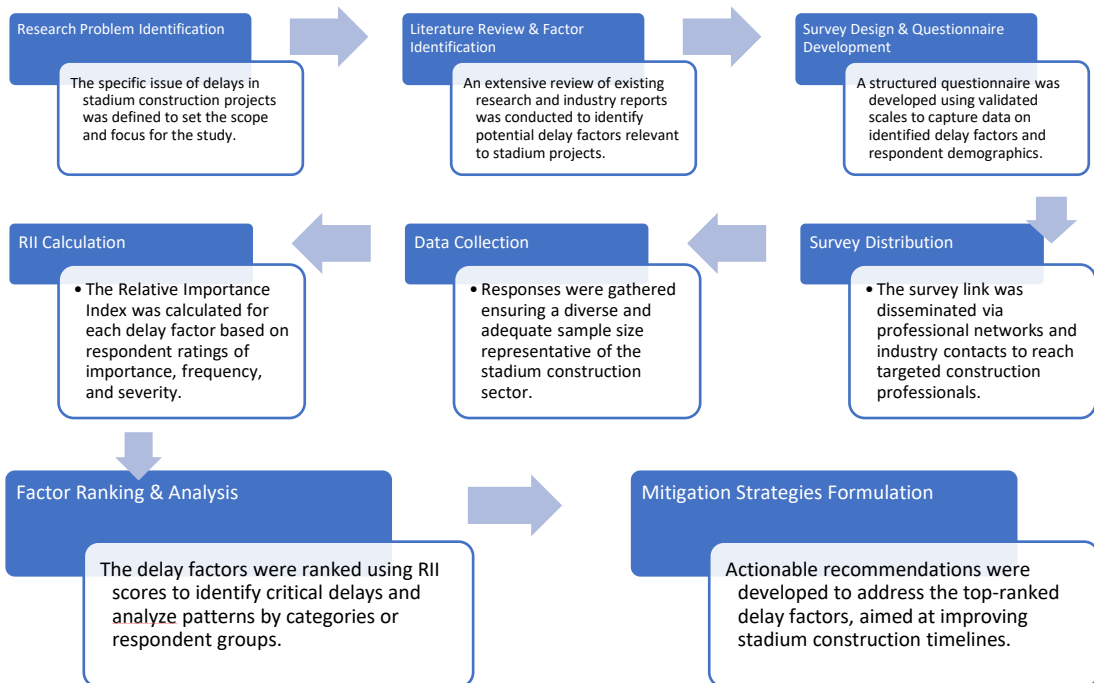
The population of the study was set to be professionals working in the area of stadium and large infrastructural projects, such as project managers, site engineers, consultants, and contractors. These respondents were chosen because they have first-hand experience with the project planning, execution and decision-making process. Purposive sampling method was

employed to make sure that the respondents involved in the study had contributed to the study through relevant experience. Purposive sampling can be employed in construction research when specialized information and industry contacts play an important role in acquiring significant and dependable information (Doloi et al., 2012). The online questionnaire was used to gather the data, thus, making it possible to distribute and collect the responses effectively due to the geographical distribution of the professionals. The final analysis was based on inclusion of complete and valid responses only to ensure the accuracy and consistency of the data.

3.4 Reliability and validity test

The internal consistency of the questionnaire was checked using Cronbach's Alpha reliability analysis. This method is commonly used in social science and construction management studies to assess whether survey items measure the same underlying concept (Walker, 2015). An alpha value of 0.70 or higher is considered acceptable, indicating good reliability. The results obtained in this study confirms that the questionnaire data are reliable and appropriate for further statistical analysis of delay factors in Stadium construction projects.

Research Methodology Flow Chart



Source: Created by authors

Table 1: Survey Profile and Data Overview

Parameter	Description
Research approach	Quantitative, descriptive
Data collection method	Structured questionnaire survey
Survey mode	Online (Google Forms)
Sampling technique	Purposive sampling
Target respondents	Project managers, site engineers, consultants, contractors
Total responses received	34
Valid responses used	34
Measurement scale	5-point Likert scale (1–Very Low to 5–Very High)
Total delay factors analyzed	19

Source: Created by authors

Explanation: This table summarizes the basic structure of the dataset used in the analysis. Responses were collected from professionals involved in stadium and large infrastructure projects ensuring domain relevance. A five-point Likert scale was used to quantify perceptions of delay causes making the data suitable for RII analysis.

Table 2: Classification of Delay Factors Used in the Questionnaire

Category	Description
Technical factors	Issues related to construction methods, skilled labor, site execution, and technical complexity
Management factors	Planning inefficiencies, coordination problems, decision-making delays, supervision issues
Design factors	Design changes, incomplete drawings, late approvals, design revisions
Logistics factors	Material procurement delays, transportation issues, imported components
External / Other factors	Political influence, funding delays, land acquisition, regulatory approvals

Source: Created by authors

Explanation: The delay factors were grouped into five categories to facilitate structured analysis and interpretation. This categorization allows comparison across functional domains and helps identify which area contributes most significantly to project delays in stadium construction.

Table 3: Reliability Analysis – Overall Questionnaire

Statistic	Value
Reliability test used	Cronbach's Alpha
Number of items	19
Cronbach's Alpha (overall)	0.953

Source: Created by authors

Explanation: Cronbach's Alpha value of 0.953 indicates excellent internal consistency among the 19 questionnaire items. This confirms that the survey instrument reliably measures delay factors and is suitable for further statistical analysis.

Table 4: Reliability by Measurement Dimension

Dimension	Cronbach's Alpha	Interpretation
Importance	0.964	Excellent reliability
Frequency	0.952	Excellent reliability
Severity	0.953	Excellent reliability

Source: Created by authors

Explanation: Separate reliability testing for importance, frequency, and severity dimensions shows consistently high alpha values (>0.95). This demonstrates that respondents rated delay factors consistently across all three dimensions, strengthening the credibility of the RII-based ranking results.

Table 5: Descriptive Statistics Summary of Delay Factors

Statistic	Observed Range
Mean values	3.15 – 3.88
Standard deviation	~1.03 – 1.42
Number of delay factors	19
Respondents	34

Source: Created by authors

Explanation: The mean scores indicate moderate to high perceived importance of the identified delay factors. The standard deviation values suggest acceptable variability in responses, reflecting diverse professional perspectives while maintaining overall consistency.

Table 6: Data Inputs Used for RII Analysis

Data Component	Description
Importance ratings	Respondent perception of how critical a delay factor is
Frequency ratings	How often the delay factor occurs
Severity ratings	Impact of the delay factor on project schedule
Rating scale	1 (Very Low) to 5 (Very High)
Analysis method	RII

Source: Created by authors

Explanation: Each delay factor was evaluated across three dimensions—importance, frequency, and severity. These ratings formed the basis for computing RII values, allowing systematic ranking of delay causes according to their overall impact on stadium construction schedules.

Table 7: Key Qualitative Observations from Professionals

Recurrent Theme Identified
Political influence on decision-making
Delay in client approvals and absence of formal sign-offs
Frequent design revisions
Unskilled labor leading to rework
Imported materials causing procurement delays
Government funding interruptions
Land acquisition challenges
Market price fluctuations

Source: Created by authors

Explanation: In addition to quantitative ratings, respondents provided qualitative insights that helped contextualize the numerical findings. These recurring themes support the RII results and highlight real-world challenges specific to stadium construction projects, particularly in public sector and government-funded contexts.

5.0 Data Analysis and Results

5.1 RII analysis

The RII was employed to analyze and rank delay factors affecting stadium construction projects. RII is a well-established quantitative technique in construction management research, used to prioritize factors based on respondents' perceptions and to support objective decision-making (Assaf & Al-Hejji, 2006; Doloi et al., 2012).

5.1.1 RII formula and application

The Relative Importance Index is calculated using the following formula:

$$RII = \frac{\sum W}{A \times N}$$

Where:

- $\sum W$ = weight assigned to each delay factor by respondents (1–5)
- A = highest possible weight (5)
- N = total number of respondents (34)

In this experiment, the respondents ranked all of the 19 items that comprise delay factors on three scales namely-importance, frequency and severity. The RII values based on such ratings allowed the systematic ranking of delay causes based on their total effect to the project schedules. RII has wide applications in infrastructure delay studies that have been extensively validated with similar applications (Enshassi et al., 2009; Singh, 2022).

5.1.2 Ranking of delay factors

The calculated RII values displayed some observable difference amongst delay factors, meaning that there are causes that had a significant impact on project delays than the rest. The management inefficiencies, design modifications, and external factors had always reported higher RII values on the dimensions of importance, frequency, and severity. This result coincides with previous research that has highlighted the prevalence of organizational and external risks in the context of large-scale development projects of the public (Fashina et al., 2021).

5.2 Analysis of delay factors by categorical analysis

Delay factors were categorically analyzed according to their origin of function in order to make their interpretation more interpretable. It is a method of comparison of technical, managerial, design, logistics, and external areas, as suggested in earlier infrastructure research (Doloi et al., 2012).

5.2.1 Technical delays

Technical delays are mainly due to execution associated problems like design failure, insufficient technical monitoring and lack of skilled workers that result in rework. Technical factors in the current study had an average to high RII value with regard to the recurrent nature and the effect it has on the progress of construction. A large percentage of the time overruns was attributed to rework due to sub-optimal workmanship and ambiguity of drawings, which agrees with the results of Enshassi et al. (2009).

5.2.2 Management delays

In the analysis, some of the highest RII values were observed in the management related delays. Such delays were largely accredited to lack of decision-making speed, poor communication among the stakeholders, unrealistic time schedulings, and poor monitoring of the projects. Such delays are especially susceptible to stadium projects, which have several public and private participants. Other researchers have also made similar conclusions based on large infrastructure projects and managerial inefficiencies have been found to be the most common delay drivers (Doloi et al., 2012; Singh, 2022).

5.2.3 Design-related delays

The delays related to design became a critical group since design finalisation was often delayed, revisions occurred, and there were no formal design sign-offs. The types of projects subject to change of design are specifically stadium projects because of modifications in international standards, broadcasting demands, and customer expectations. Their high values of RII in terms of design delays mean that they are seriously affecting the timelines of the projects, which supports prior results in mega sporting infrastructure projects (Love et al., 2022).

5.2.4 Logistics delays

The delays related to logistics entailed mainly the procurement delays, the supply chain interruptions, and the dependency on imported materials and specialized finishes in sports. International procurement and co-ordination with foreign suppliers took considerable time that impacted on the schedules of construction. These results align with the most current research stating complexity of procurement as one of the biggest risks of specialized infrastructure projects (Fashina et al., 2021).

5.2.5 External delays

The RII values were high in relation to these external delay factors namely political influence, government funding interruption, policy change, and land acquisition issue, especially in the aspect of severity. The projects involving stadiums, which are usually funded by the government, are sensitive to the political and regulatory climate. This has been the key focus of previous studies which have highlighted the disproportional influence of external and political elements on the delivery of public infrastructure (Flyvbjerg, 2021; Singh, 2022).

6.0 Discussion

6.1 Interpretation of major findings in relation to existing literature

The analysis of the current research indicates that the delay causes related to inefficiency in management, design-related factors, and external factors proved to be the most critical in construction projects on stadiums. The large RII, which was observed in the factors like delayed decision-making, regular revisions of the design and political interference, implies that they have the overriding factor in the project schedules. These findings are not new to the existing body of construction delay research, which highlights that factors related to organizations and governance tend to dominate in large infrastructure works rather than the technical ones (Sambasivan & Soon, 2007; Enshassi et al., 2009).

In addition, the high internal consistency of the importance, frequency, and severity dimensions supports the reliability of the perceptions of the stakeholders on the causes of critical delays. The same methodological results have been reported in previous studies that apply RII-based analysis where managerial and client related factors always ranked higher than the contractor related issues (Sambasivan & Soon, 2007). This correspondence to literature supports the validity of the current results.

6.2 Comparing the delays in the construction of the stadiums with other infrastructural projects

Although delays are a common experience in infrastructure activities, the results are that the construction of stadium projects are more sensitive to design changes and the external pressures than the traditional infrastructure development, including roads, bridges and residential developments. Contrary to the linear infrastructure projects, stadiums must be adjusted to the international standards of safety, broadcasting, and experience of the spectators, which may cause the varying schedule and design changes at the final stages.

Earlier research on projects in general infrastructure projects identifies the poor performance of the contractors and shortage of the materials as the leading sources of delay (Enshassi et al., 2009). However, by contrast, the current research suggests that the changes and delays linked to stadium projects are more susceptible to its clients and the governance-related issues due to its openness and political importance. This difference highlights why there is a necessity to analyze delay in a project-specific manner and not in general terms of delay models in infrastructure (Sambasivan and Soon, 2007).

6.3 Effect of political influence and client-through transformations in the Indian case

The discussion identifies political interference and customer-oriented alterations as significant causes of delays in the building construction projects of stadiums in the Indian environment. Projects in stadiums are often publicly funded and linked with political goals, and thus they are vulnerable to the change of policies, the change of leaders, and the stop of funding sources. The professional responses that are contained in the dataset show that delays in approvals, lack of formality signing off, and change in the vision of a project is usually as a result of political and administrative nature.

These results are in line with previous studies in the developing economies that have established that political interference and bureaucratic delays are the key risks of delivering public infrastructure (Enshassi et al., 2009). The findings of Sambasivan and Soon (2007) corroborate the results of the study by Nguyen et al. (2009), which revealed that time wastages in the project due to clients are quite high especially in matters related to decision making

and scope changes. The current research expands this knowledge by showing how these aspects are magnified in stadium projects because they are of a symbolic and strategic value.

7.0 Mitigation Strategies

The mitigation solutions in this section are based on critical delay factors identified through RII analysis and supported by industry experts inputs. The strategies address technical, managerial, design and external risks specific to stadium construction.

S. No	Category	Delay Factor	Mitigation Strategy	Description	Reference
7.1	Technical	Unskilled workforce and technical errors	Skill development and training programmes	Implement systematic training focused on construction techniques, interpretation of complex drawings and adoption of innovative technologies to reduce rework and execution delays.	Fashina et al. (2021)
7.2	Technical	Poor quality control and supervision	Strengthened quality control and supervision	Deploy qualified engineers conduct regular inspections, staged quality audits and timely corrective actions to ensure compliance with specifications and avoid rework.	Singh (2022)
7.3	Management	Poor coordination and communication	Early stakeholder involvement	Engage clients, consultants, contractors and operators during early planning and design stages to align objectives, reduce disputes and improve decision-making speed.	Leslie (2007); Fashina et al. (2021)
7.4	Management	Delayed approvals and unclear authority	Unambiguous decision-making hierarchy	Establish a clear decision-making structure with defined responsibilities and centralized authority to reduce administrative bottlenecks.	Singh (2022)
7.5	Management	Unrealistic project schedules	Real-time scheduling and milestone tracking	Develop realistic timelines based on resources and planning supported by continuous schedule monitoring to detect deviations early.	Fashina et al. (2021)
7.6	Design	Design changes and late design completion	Design freeze policies	Implement formal design freeze after defined project stages to minimize scope creep, rework and coordination issues between design and construction teams.	Singh (2022)
7.7	Procurement	Delay in imported materials	Early procurement planning	Identify long-lead items early plan advance procurement and coordinate supplier agreements and customs clearance to reduce supply chain risks.	Fashina et al. (2021)

7.8	External / Policy	Regulatory approvals and policy changes	Buffer time allocation	Include buffer periods in project schedules to absorb delays caused by approvals, land acquisition and administrative uncertainties.	Singh (2022)
7.9	Financial / Contractual	Funding delays and external risks	Transparent financing and risk-sharing contracts	Ensure timely fund disbursement through clear financial mechanisms and adopt contracts that equitably distribute risks related to political, economic and force majeure events.	Fashina et al. (2021); Singh (2022)

Source: Created by authors

7.0 Conclusions

7.1 Summary of key findings

This paper reviewed the reasons behind the delays in construction projects of stadiums in an organized quantitative methodology. According to the results of the survey analysis involving the industry professionals, the analysis shows that management-related, design-related, and external factors have the greatest contribution to the project delays. Delayed decision-making, numerous design changes, political pressure, funding disruption, and acquiring specialized materials were mentioned as the high-impact delay causes regularly. Technical causes, such as unskilled labor, execution faults, also caused delays, but were usually ranked lowly with issues relating to governance and coordination.

The findings showed that there is no single cause of delays in the construction of stadium but as a result of interplay between various organizational, technical and external factors as a support to the observations made in previous construction delays studies (Sambasivan and Soon, 2007; Enshassi et al., 2009). The study will investigate how the RII works in ranking factors that contribute to delays. The use of RII was a successful and dependable approach in ranking the delay factors in construction projects of stadiums. RII allowed ranking the causes of delay systematically by calculating the perceptions of respondents on the dimensions of importance, frequency, and severity, as well as identifying the critical factors. Such a high internal consistency of a questionnaire, which has been established with the help of the values of Cronbach Alpha that are above the acceptable levels, is another argument in favor of the strength of the RII-based results. These findings are in line with the past studies that emphasize RII as a practical and well-established delay analysis tool, in research connected to construction management (Doloi et al., 2012; Singh, 2022).

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CHAPTER 46

Instrumentation for Horizontal and Vertical Level Monitoring using Laser and Sensor Technology in Formwork Applications

*Bhagyesh Milind Kulkarni**

ABSTRACT

Formwork is an important but temporary structural component in the construction of reinforced concrete and it can easily be out of alignment, deformed or unstable while wet concrete is being placed on top of it. Real-time displacement monitoring ensures safety, accuracy, and design quality compliance. Conventional inspection methods may overlook sudden deformations in complex formwork systems. The objective of this study is to review limitations of existing formwork monitoring techniques and to evaluate application of real-time solution using sensor-based technologies integrated within a Ubiquitous Sensor Network (USN) and Internet of Things (IoT) framework. Ultrasonic sensors and inclinometers can be used to assess the alignment and stability of vertical support members and wireless displacement sensors to monitor horizontal movements. Additionally, Fibre Bragg Grating (FBG) sensors inscribed in optical fibres using ultraviolet laser technology capture high-resolution strain responses related to formwork misalignment. Sensor data can be transmitted through a ZigBee-based wireless network to a centralized monitoring platform for real-time evaluation and alerts. This study shows improved early detection of misalignment, enhancing safety and decision-making. The study recommends implementing such systems for complex and high-rise formwork applications following suitability assessment.

Keywords: Concrete Formwork, Alignment Monitoring, FBG Sensors, IoT-Based Monitoring, Construction Safety.

1.0 Introduction

Concrete formwork is an essential temporary construction that is utilized to determine the shape of permanent buildings and offer a requisite area of construction work. Despite the temporary character of such systems, they are often exposed to extreme concentrated loads, seismic conditions, geological instability, and unfriendly weather. Structural potential.

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Failure - support buckling, slab breakage or complete collapse is dangerous to Such failures can happen suddenly and within several seconds, and because they are related to site safety and project schedules. Through the ages, contractors have adapted to traditional ways of monitoring such as plumb. manual optical instruments like levels and total stations, lines and weighted strings.

Nonetheless, these methods are becoming ineffective when it comes to the large-scale projects today because of. dense scaffolding and slow manual reporting which cannot cause optical blind spots. predict sudden failures. This leads to a severe requirement of constant, real-time monitoring. to make horizontal and vertical formwork alignment fall within allowable ranges. when concrete is being laid and cured. The basic input of this paper is the synthesis and systematic assessment. a combined framework of horizontal and vertical level monitoring with the help of. laser- and sensor- based technologies.

As compared to the conventional studies which look at isolated. sensors, this review provides a single solution that involves a combination of ultrasonic sensors to measure the vertical sag. detection, horizontal stability, and high-technology fibre-optic sensing inclinometers. in a Ubiquitous Sensor Network (USN) and Internet of Things (IoT) design. One of the main developments that were discussed is the use of laser-based Fibre Bragg Grating (FBG). sensors, inscribed with the help of the UV laser technology, which is a high-resolution digital. formwork structures are named nervous system. These sensors are absolute, electromagnetic. It can be multiplexed along a and it can be measured in terms of interference-immune strain and temperature. single fibre.

Moreover, the Distributed Fibre Optic Sensing (DFOS) is Rayleigh based. backscattering permits strain profiling (millimetre scale) to be done in a quasi-continuous mode and permits early. identification of localized stress concentration and micro-cracks that cannot be detected by point sensors. The paper identifies the use of ZigBee-based low to facilitate the implementation of the project in the field. power, multi-hop wireless communication to ensure data transmission over large distances. more than 80 m on construction sites that have too much congestion. In general, this review indicates that there are ways the horizontal and vertical level monitoring using both laser and sensor technologies. converts traditional type of formwork into intelligent formwork that is self-monitoring, that is, smart structures. significantly increasing the early detecting failures and safety during construction.

1.1 Practical significance and contribution to accident prevention

This technological-oriented review has a special practical importance in the context of. high-rise buildings and geometrically complicated systems of formwork, where the aftermath of the consequences of Failure of formwork are extreme and devastating.

Formwork is exposed to in such projects. long cumulative loads, re-use, prolonged construction periods and complicated load. ways, and so traditional visual inspections could not be used to guarantee safety. Through critical assessment and incorporation of a high level of sensor- and laser-based surveillance. this review proves continuous, real-time instrumentation to be directly dependent on technologies. aids in accident prevention. Ultrasonic sensors, inclinometers, and technologies like these are useful. wireless displacement sensors, and fibre-optic sensing systems allow to detect early on. signs of critical failure such as excessive sagging of the supports, tilting, local overstressing, and concealed slab distress.

These are early-warning signs that are necessary in. high-rise buildings, where access to formwork is frequently limited by manual means, and failures are possible. spread fast on various levels. The application of these sensing technologies in Ubiquitous Sensor Network (USN) and IoT architecture enables automatic alarming and distance monitoring, which minimizes the use of. biased interpretation and lateness. This applies particularly to complicated formwork. systems of climbing, enormous slabs, and massive scaffold patterns, where there are optical blind spots and human error at a high-risk level[2], [3]. Finally, this review indicates that there has been the adoption of technology driven formwork. monitoring moves the safety management approach beyond an inspection-based approach that is reactive. active, evidence-based approach to accident prevention, which is of significant use to worker. high-rise and complex construction safety, continuity of the project, and reduction of risks. environments.[4]

2.0 Literature Review

The literature review below is a synopsis of existing studies on instrumentation in. observing temporary buildings, paying attention to sensor networks integration, Internet of things (IoT) infrastructures, and laser-fibre optic infrastructures.

2.1 Challenges in conventional formwork monitoring

Concrete formwork is a temporary structure that is crucial as it provides the permanent structure. constructions, and often it is exposed to localized stresses and subterranean instability. Studies have shown that about 29.63 per cent construction accidents entail the collapse. of scaffold shoring systems[5]. The conventional safety surveillance uses manual data collection. with optical instruments, such as levels[5] and total stations. Literature however identifies. major shortcomings of these approaches: they are impeded by blind spots where structural. blocking the optical path are components, and the manual reporting intervals are generally too slow to. sense the sudden failures that typify formwork collapse[5].

2.2 Instrumentation for displacement and stability

In order to deal with these gaps, researchers have offered automated systems with different characteristics.

Sensory devices:

- Vertical Sagging: The amount of sagging or is determined using ultrasonic sensors. deflection millimetre-scale precision formwork[6], [7].
- Horizontal Stability: Horizontal inclinometers are used to measure the inclination of the pipe supports, which is a severe measure of structural stability[6], [7].
- Structural Load and Strain: The weight of concrete batches is monitored by load cells, and strain gauges are used to measure the internal stress of the structural body of the formwork[6], [7].
- Settlement: Wireless displacement sensors have been used in order to gather real time data. on slab settlement[5].

2.3 IoT and Wireless Sensor Networks (USN)

The theme of integrating these sensors into a Ubiquitous sensor Network (USN) is important. recent literature[6], [7]. These systems normally use ZigBee standard which is an open standard. operating system that supports wireless personal area networks (WPAN) that is capable of. sending low amounts of data with low power consumption[5], [7]. Multi-hop wireless These are networks that are used to increase the transmission range of information that can be sent across distance. workplaces to a central location office[6]. Sophisticated structures have embraced surveillance. cloud computing and a mobile client that allows the managers to be informed of real-time alerts and automated alarms when concrete is laid.

2.4 Laser-Processed Fibre Bragg Gratings (FBG)

A complex development in the monitoring of the structure is the application of Fibre Bragg Gratings. The phase structures are imprinted into the core of optical fibres with UV lasers in (FBG) phase structures[8]. FBGs have specific benefits in the construction industry:

- Intrinsic Properties: These are resistant to electromagnetic interference (EMI), lightweight, and also can be multiplexed to form a quasi-distributed sensor network along. a single fibre[9].
- Thermal Stability: At the lower temperatures that are standard operating temperatures of FBGs, regenerated FBGs can be used. It can be fibre Bragg gratings, created by thermal treatment of a seed grating. resist severe temperatures to 1,295degC[10].
- Sensing Mechanism: FBGs detect the strain by detecting the movement of the Bragg. wavelength: but it is mentioned in the literature that they are temperature sensitive as well as sensitive to. strain, necessitating thermal compensation methods to be measured accurately[11].

- **Embedding Challenges:** It has been noted that studies of embedding FBGs in composite materials emphasize that spectral distortion or split of peaks may be due to non-uniform strain fields, implicating that the sensors need to be placed facing the same direction as the neighbors. reinforcement to sustain single peaked spectrum[12].

2.5 Data evaluation and processing

DFOS systems have high sensitivity and sampling rates. produce huge amounts of data that are usually full of anomalies and noise[13]. Recent Software solutions, including the FOS Evaluator, focus on the significance of developments. post-processing techniques. Locally weighted scatterplot (LOWESS) is a method. Smoothing), moving averages and Bessel filters are reported to be necessary to clean raw. strain outliers that are unreasonable to plot out and mechanical properties in advance are. calculated[14], [15].

3.0 Methodology

3.1 Nature and scope of the review

This study assumes a technology-oriented, state of art review methodology that is geared towards. critically examining the improved instrumentation systems in level horizontal and vertical. monitoring concrete formworks. The review is specifically aimed at temporary. structural systems used in the course of concrete placement and early curing stages, where the lowest level of risk of sudden failure. The scope has been narrowed down intentionally to technologies that facilitate. real time or near real time monitoring, automated alarming and data-based safety. management. It is emphasized on high-rise building apps, long-span slabs and applications. scaffolding systems, which are geometrically complex, in which traditional inspection methods are used. inadequate. Instead, the review does not seek to substitute code-based design methods but rather. assesses the effects of the operational safety augmentation of emerging sensing and laser technologies. traditional practices.

3.2 Review type and research design

The research is qualitative and technology-based narrative review, instead of a statistical meta-analysis. Such strategy is chosen because of a heterogeneous nature of the. available literature, to which laboratory experiments, field trials, pilot implementations, etc. belong. and full-scale construction case studies. The review design will be designed in a manner that it follows the development. of surveillance strategies--between discrete physical sensors and integrated laser-based and IoT. enabled systems- emphasizing technological maturity, practical feasibility, and safety. relevance. The methodology gives more priority to

studies which show measurable performance. accuracy, reliability, response time and alarm effectiveness under real are some of the indicators. construction conditions.

3.3 Literature identification strategy

The strategy is to determine the literature on the topic, focusing primarily on the advantages and disadvantages of employing virtualization technology in accounting. Relevant literature was found by extensive searches of the existing scientific. civil engineering, structural health monitoring databases and technical repositories. construction safety, optics sensing, and safety. Search strings and keywords were developed with the aim of. monitoring of form work capture, scaffold stability, ultrasonic sensing, optical fibre monitoring, fibre optic monitoring, Fibre Bragg Gratings, Distributed Fibre. Ubiquitous Sensor Networks, IoT-based construction monitoring, and Optic Sensing. Lists of the most significant papers had also been analyzed to find more seminal works and influential case study This may not necessarily be found in a database search.

3.4 Literature selection and screening process

The selection was based on multi-stage screening strategy. In the first stage, titles and abstracts were read and those studies which were not related to construction-stage monitoring were discarded. temporary structures. During the second phase, the full-text screening was undertaken in order to retain studies. that gave technical descriptions, calibration procedures, quantitative results, or recorded field implementations. Research studies that concentrate only on long term structural. Relevance of health monitoring to formwork behaviour was eliminated. Preference was presented to peer-reviewed journal articles, experimental-validated conference papers, and technical reports that are authoritative. This step allowed making sure that the reviewed literature was direct. facilitates the aims of monitoring performance assessment and prevention of accidents. potential.

3.5 Technology classification framework

The reviewed technologies will be analysed based on the dual-layer classification structure to systematically analyse them. was adopted. The initial layer groupings technologies using monitoring function, such as vertical level monitoring, horizontal stability monitoring, local strain sensing, and distributed structural profiling. The second level puts technologies under different categories based on them. sensing mechanism, e.g. acoustic (ultrasonic sensors), inertial (inclinometers), electromechanical (wireless displacement sensors), and optical/laser-based sensors (FBG and DFOS). This systematic framework makes sense of comparison between fundamentally. various technologies as they complement each other in integrated. monitoring systems.

3.6 Evaluation parameters and assessment criteria

All the technologies were tested based on the same and clearly outlined performance parameters. These were the accuracy of measurements, spatial resolution, temporal responsiveness, sturdiness in austere site conditions, prone to noises and interference, convenientness, maintenance, and installation requirements. Further attention was paid to safety. oriented measures like the ability to detect failures early, alarm triggering limits, system consistency, and alignment with construction safety standards. For fibre-optic systems, appraisal also took into account strain sensitivity, thermal stability, multiplexing capacity and. long-term signal integrity. The criteria of assessment was chosen to represent practical. deployment issues that are witnessed in active construction sites.

3.7 Data extraction method

Data mining was directed to both quantitative and qualitative data that have been reported in the. selected studies. Quantitative data consisted of values of linearity of calibration and accuracy limits. acceptance of deflection and tilt, spatial resolution, and system reliability. percentages. Qualitative data involved sensor location plans descriptions, networking design, installation issues, and reported safety measures. Case experiments on slab failure detection, scaffold instability, or emergency evacuation. special consideration was paid to those, which directly show how effective is in real life. the technologies.

3.8 Data synthesis and comparative analysis

The information was extracted as opposed to statistical aggregation of numerical data. created based on a comparative and thematic analysis approach. Technologies were when compared across and within category of classification to determine performance trends, strengths, and limitations. Combination of various types of sensors were examined. to determine the effect of redundancy and cross-validation on reliability. The synthesis highlights how sensor and laser-based system of monitoring is superior to traditional inspection procedures. with regard to coverage, responsiveness, and objectivity.

3.9 Methodological support for findings and conclusions

The results and conclusions of this review are based on the adopted methodology. providing the evaluation of all the technologies reviewed, through a standardized and open evaluation. framework. The principles of sensing are connected to the system architecture and the safety results by means of the system. methodology shows how developed instrumentation can facilitate prioritized risk. management in formwork operations. The logical generalization is justified by the conclusion that technology-based surveillance alters the formwork safety to a more reactive and inspection-based safety. transform into an

ongoing, data-centered accident prevention plan, which is especially needed in high rise and complicated construction settings.

3.10 Technology-focused review

According to the methodology embraced, the paper falls under technology-focused review. that offers an analytical and comprehensive study of instrumentation technologies of. The monitoring of concrete formwork at horizontal and vertical levels. The study does not are intended to present a new sensing device or experimental prototype, but are intended to consolidate, assesses, and contrasts current sensor and laser technologies of monitoring reported in. field trials, experimental studies.

The review is organized in the basic sensing guiding principle measurement. mechanisms, accuracy among them, installation habits, and functionality constraints of frequently. used instrumentation, such as ultrasonic sensors, inclinometers, wireless displacement. sensors, Fibre Bragg Grating (FBG) sensors and Distributed Fibre Optic Sensing (DFOS). A special focus is put on the integration of these technologies into Ubiquitous. Sensor Network (USN) and Internet of Things (IoT) designs in order to allow real-time information. in active construction, acquisition, wireless communication, and automated safety alarming. environments.

This is in contrast to the traditional literature reviews which provide an overview of the outcome at an abstract level. paper is concerned with such technological performance measures as the precision of measurement, linearity, resolution spatial, thermal tolerance, data reliability, and network scalability. The methodology also analyzes practical implementation factors, such as sensor positioning, calibration, alarm threshold definition, data filtering and environmental protection based on. structural limits. In this regard, this review contribution is that it provides a technology-focused synthesis. and integration system that facilitates informed choice, comparison and execution. of sensing technologies and laser technologies of intelligent transformation of traditional formwork, self-monitoring structures.

4.0 Results

The real-world application and total review of advanced instrumentation of Application of horizontal and vertical level monitoring It is evident in formwork applications. enhancements of structural safety, measurement precision, and real-time fault detection. Findings of experimental trials, field deployments and reported case studies. continuously verify the practicability and dependability of Ubiquitous Sensor Network (USN) and Monitoring systems based on Internet of Things (IoT) in proactive construction sites. Performance and monitoring efficiency of the system in question.

4.1 System performance and monitoring efficiency

Quantitative performance measurements show that integrated sensor networks are able to attain an. reliability of overall operation of 98.4, which is able to pass the high standards of construction site. monitoring. Multi-hop multi-hop wireless networks were provided by ZigBee based on data that was not interrupted. transmission longer than 24 hours long, including crucial stages between concrete pouring. to initial curing. Even though individual USN nodes normally offer a range of communication of. equivalent distance, multi-hop routing was effective at distances of approximately 25 m. to more than 80 m giving smooth connectivity between distributed formwork zones and centralized overseeing locations.

4.2 Precision in vertical and horizontal level monitoring

The combination with high-resolution monitoring of the structural movement was attained. of ultrasonic sensors, inclinometers and displacement sensors. Adjusted ultrasonic sensors. measured vertical deflection at ± 1 mm accuracy and kept deviations within tolerance. within the 10 mm safety limits stipulated in codes of construction. Field measurements showed constant mean deflection values with the highest deviations of 5.6 mm. Horizontal. inclinometer based stability measurements showed good sensitivity, which was able to detect tilt. The range of variations of 0.43deg to 0.50deg, enough to detect instability at an early stage. prior to collapse.

4.3 Real-time failure detection and alarming

One of the most important results of automated monitoring systems is that they are able to identify lurking or abrupt. Invisible failures that cannot be seen by a human eye. On a scaffold of 9.0 m height recorded. IoT-based system, it was observed that slab settlement was increasing rapidly and more than the. 10 mm alarm level, which will sound an instant wireless alarm and evacuation. Later research established the slab fracturing and leakage of concrete. Tiered alarm systems--programmed to 60, 80 and 100 percent allowable limits--permitted gradual and timely intervention.

4.4 Performance of laser-based sensing technologies

The sensors were of excellent linearity which was Fibre Bragg Grating (FBG) sensors based on laser ($R^2 = 0.9999$). when inverted alongside the reinforcement to give a higher resolution strain monitoring with a sensitivity of about 1.2 pm/ue at 1550 nm. Although angled or cross-ply These results enabled spectral anomalies by configurations, and best-practice was brought to light. installation strategies. FBGs that were regenerated worked at extreme temperatures. to 1,295degC, which illustrates that it is fire-safe monitored.

Distributed Fibre Optic Sensing (DFOS) systems had a millimetre level spatial resolution (as fine as 6 mm), enabling the early identification of micro-cracks and localized redistribution of stress along reinforcement members. On the whole, the findings can confirm the hypothesis that sensor- and laser-based instrumentation should be integrated into a. USN framework is an efficient way of converting traditional formwork into an intelligent self-observing one. structure.

4.5 Research Gaps

4.5.1 Cost effectiveness and practical implementation

Although proven in technical performance, there is lack of literature on cost-benefit analysis, easy to use. Installation, maintenance, and viable adoption structures of large-scale clients. application in normal construction works.

4.5.2 Temperature effects in FBG sensors

It is challenging to separate the strain measurements and temperature effects in FBG sensors. real site conditions.

4.5.3 High cost and limited practical use

Sensor and interrogation systems are very expensive which restricts their application in normal construction projects.

5.0 Conclusion

Finally, the research synthesised on this review supports the fact that the transition between holistic instrumentation of manual data collection to automated data collection is of great benefit. accuracy and security of horizontal and vertical level monitoring in concrete formwork. The traditional type of monitoring with optical devices, including total stations and levels, is. more and more regarded to be inadequate because of fundamental blind spots and reporting periods that are slow enough not to sense the sudden structural failures that occur when scaffolds collapse. The deployment of Ubiquitous Sensor Network (USN) and Internet of Things (IoT). platforms has been very effective in real time structural health monitoring.

The implementation of Ubiquitous Sensor Networks (USN) and Internet of Things (IoT) platforms has proven highly effective for real-time structural health monitoring. Key sensory findings include:

- Vertical Level Monitoring: Separated ultrasonic and wireless displacement. sensors give centimetre resolution to sagging, deflection and slab. settlement, with the malfunctions, broken, being detected instantly. slabs--which none can see with their eyes.
- Horizontal Stability: Inclinometers have been able to optimally monitor the tilting of the vertical support. pipes, which is a very important early-warning environment of structural instability in advance. collapse occurs.
- Laser-Based Technologies: Fibre Bragg Gratings (FBG), which are written into optical fibres. with UV lasers, is equivalent to a high-resolution digital nervous system that is immune to. electromagnetic interference. Besides, regenerated FBGs have shown. thermal stability an unprecedented level of, can operate at extreme temperatures up to. 1295 °C, which is important in fire-safety inspection in civil buildings.

These sensors are integrated into multi-hop wireless networks that are based on the ZigBee. standard has conquered the range disadvantages of the construction sites through transmission. the surveillance area to 80 m and above. Based on quantitative performance measurements, it is revealed that. these automated systems are able to sustain operational requirements at a reliability of 98.4%.

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CHAPTER 47

An Automated GIS and Image-based Inspection System for Pre commissioning Assessment of High-tension Transmission Tower

Sakshi Khadke and Pradeep Paul**

ABSTRACT

Transmission towers are an essential component in the power transmission setup, which needs comprehensive inspection before being used. Traditional inspection processes tend to be physically intensive, time-consuming, and pose serious risk to the lives of personnel conducting the inspection, especially in terrains that are difficult to traverse. This paper aims to provide an automated inspection system for pre commissioning tasks involving high tension transmission towers, combining the usage of GIS and image analysis techniques. High resolution images captured through Unmanned Aerial Vehicles and satellite imagery would be used for analyzing and identifying transmission towers and their structural integrity through missing object detection techniques. All inspection results are georeferenced and managed within the GIS environment for exact spatial visualization, efficient data management, and systematic analysis. The study introduces innovative system that reduces the time of inspection in contrast with conventional approaches while improving the accuracy and consistency of observation. The framework improves safety operation by minimizing direct human involvement in hazardous inspection activities and provides a sound, data-driven basis for inspection documentation, quality verification, and maintenance planning before the handover of the project.

Keywords: Automated tower inspection, Pre-commissioning evaluation, GIS-based assessment.

1.0 Introduction

High tension transmission towers are a very important part of power transmission network which is responsible for transferring electricity over long distances. With a very rapid expansion in power infrastructure factors such as increasing energy demand, number, height and structural complexity of the transmission towers have increased significantly.

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Ensuring the structural integrity, proper assembly and assembly of these towers before commissioning is therefore critical. Factors such as operational safety, system reliability, and life span of the towers may not be as promised. Even minor construction defects such as missing members, improper bolt connections or misalignments can lead to very serious operational failures, increased maintenance costs and safety hazards after commissioning.

Pre commissioning inspection is a very major step in the transmission projects to ensure proper quality assurance. Traditionally this process relies mainly on manual inspection which is carried out by trained personnel who must climb the full length of the towers to carry out the inspection process which involves measurement checks and other major checks. These inspections are effective to some extent, but they are very much time consuming, labour intensive, and are subjected to human errors. Other than this the inspectors are exposed to high level of safety risks due to working at heights, harsh weather conditions. These disadvantages make the conventional method of inspection inefficient and very unsuitable for large-scale transmission projects.

Recent usage of unmanned ariel vehicle (UAV) technology and remote sensing have opened new possibilities for safer and faster inspection. These unmanned ariel vehicles are equipped with high resolution cameras which capture detailed visual photographs of the tower components from multiple angles. This feature of UAVs allows inspection of inaccessible and hazardous areas while reducing the inspection time and safety hazards. This has also gained attention as an alternative to manual climbing, especially for large transmission towers. Many UAVs still depend on manual inspection of captured images which limit their effectiveness.

Developments in computer vision and image processing have enabled automated detection, classification and assessment of structural elements by digital images. Some techniques such as auto detection, feature extraction and anomaly identification can be used to identify errors. This can have an improved consistency over human visual judgement. When the UAVs are used in the acquired image, the raw data can be transformed into actionable inspection data. The absence in combination between automated image analysis and structured spatial management systems narrows the practical usability of these methods in large infrastructure projects.

Geographical information system (GIS) provides a platform for managing, visualizing and analyzing spatial referenced data. GIS enables precise mapping of locations of the tower, storage of inspection attributes and visualization of defects along transmission corridors. When this information is combined with the UAV images and automated image analysis output, GIS will be serving as a centralized inspection system that supports systematic documentation, verification of quality and helps in decision making. Most

existing studies focus mainly on post commissioning maintenance monitoring but ignore construction stage quality assessment.

This study proposes an integrated UAV and GIS based automated inspection framework for pre commissioning assessment of high-tension transmission towers. This study combines high resolution UAV imaging and GIS based spatial data to improve inspection accuracy, enhance safety and reduce inspection time. This ensures data driven quality assurance in power transmission construction projects

2.0 Literature Review

Inspection of high-tension transmission tower is a critical activity for ensuring the safety, reliability longevity of power transmission infrastructure. Conventional inspection methods rely hyper on manual visual assessment, tower climbing and helicopter aided surveys add time consuming costly and associated with significant safety risk. These limitations have driven extensive research into automated inspection techniques based on unmanned aerial vehicles (UAVs), computer vision deep learning geographic information system (GIS).

2.1 UAV-based inspection of transmission towers and power line

Current studies clearly illustrate a change in interest from traditional manual inspection towards inspection assisted by UAV technology for power transmission inspection. The experimental study verifies that safe access of UAV platform to tower structure and power transmission corridors which could be difficult and dangerous for manual inspection. Visual based system using images taken by UAVs have been broadly used in locating transmission towers, power lines, as well as their structural components.

Computer vision-based approaches to tower identification have proven effective in separating lattice structure from their environment based on principle of features extraction and machine learning classification algorithms. Computer vision-assisted inspection system makes it possible to automate the identification of geometric shapes and structural elements of towers with minimal manual visual inspections.(Chen et al., 2024; Jiang & Jiang, 2019; Li et al., 2023)

2.2 Damage and defect detection in structural automatically using UAVs

Various works and detect the structural damage of transmission towers automatically by using UAV acquired images. Deep learning based methods specifically convolution neural networks, has been conducted in detecting damaged or missing components such as bolts, joins and steel members. These ways provide an enhanced level

of detection accuracy and consistency over those obtained using conventional image processing techniques on images with both varying illumination and backgrounds

They have been used in steel transmission towers for the detection of surface defects like corrosion and cracking among others. This method is based on enhancing images, finding boundaries and recognising patterns in images collected by high-resolution UAV camera to perform defect feature extraction. Such kinds of automated defect detection system are gaining attention due to their reliability and repeatability of inspection results in comparison with subjective results from manual inspections.(Chen et al., 2024; Santos et al., 2022)

2.3 GIS-based visualization and inspection data asset management

Applications of geographic information system is a common means of managing and visualising inspection data of power transmission infrastructures. For GIS-based inspection system enables a spatial organisation of transmission assets, integration of inspection results, and visualisation of structural conditions at the network scale. Further enhancements in inspection analysis are possible using three-dimensional GIS environment to enable spatial visualisation of towers, corridors and defect locations.

This system-based access management framework locates the effectiveness of combining inspection attributes with spatial database to enable planning and maintenance activity and also monitoring infrastructures. The case studies on power utilities reveal that the traceability documentation and long-term asset management have been involved advanced by GIS platforms as the inspection records and spatial analytics are given under one platform. Such system provides an important building block to combine the result stemming from automated inspection into operational workflows.(Jiang & Jiang, 2019; Li et al., 2023)

2.4 3D modelling and photogrammetric reconstructions of transmission towers

3D reconstruction techniques of UAV photogrammetry have been considered for the detailed structure condition assessment of transmission towers. Photogrammetric modelling can accurately reconstruct the geometry of any tower, as there are no limitations to the evaluation of alignment deformation and completeness integrity of all the constituent parts without physical contact. Ground reality documentation and visualisation where possible using UAV based 3D reconstruction methods. It has produced high quality models suitable for offsite inspection and engineering studies.

Oblique photogrammetry and multi-view imaging techniques further enhance the accuracy of construction by capturing tower components for multiple viewpoints these approaches provide comprehensive spatial information that supports accurate measurement

and structural verification, which is particularly valuable during pre-commissioning assessment stages.(Jiang & Jiang, 2019)

2.5 Remote sensing and GIS for transmission corridor monitoring

Various remote sensing methods along with the use of GIS has been adopted on a last scale for monitoring transmission corridors. Satellite images and analysis done using GIS are helpful for identifying environment related risk and infrastructure conditions over large geographic areas. The reviews and the lined that while applications of GIS and remote sensing tools are fruitful for monitoring on large scale, they do not have the necessary spatial resolution required for the structural analysis of individual towers.

Satellite monitoring system works best when coupled with high resolution UAV images which help in creating multi-scale inspection system. GIS is essentially the platform which integrates satellite monitoring system, UAV images and inspection results together in a common spatial database for carrying out infrastructure monitoring.(Jiang & Jiang, 2019; Li et al., 2023)

2.6 UAV based visual inspection of transmission infrastructure

UAV based inspection has been more of a practical alternative to traditional inspection approaches due to its ability to capture high resolution imagery of transmission towers and power line corridors while minimising human exposure to hazardous environments. Studies on UAV based inspection consistently highlight advantages such as improved accessibility, reduced operational cost and enhanced inspection frequency. And automated power line inspection using UAV imagery has proved that aerial platforms are particularly effective for monitoring surprisingly distributed infrastructure over large geographic areas.(Zhang et al., 2017)

Early UV inspection research focused on detecting power lines and surrounding obstacles using photogrammetric and stereo vision techniques automated extraction of power line geometry and spatial position from UAV images has been shown to achieve accuracy comparable to manual stereo measurements enabling obstacles detection within transmission corridors. (Zhang et al., 2017) However, these approaches primarily address corridor monitoring and vegetation clearance rather than structural assessment of towers.

2.7 Automated damage and defect detection using UAV images

With advance access in computer vision and planning research has increasingly focused on automated detection of structural damage in transmission towers using UAV imagery. Deep learning-based methods have been applied to identify corrosion, missing paint, surface degradation on steel tower components. These studies emphasises that

automation significantly reduces the effort needed for manual imagery inspection while improving consistency and repeatability of damaged assessment.

A key challenge identified in UAV based damage detection is the scarcity of labelled training data as damaged components are relatively rare and difficult to capture. Researchers have addressed this issue through data augmentation technique and Taylor neural network architectures to improve robustness under limited data conditions. Experimental evaluation demonstrate that deep neural networks can successfully localised and segment damage regions on tower surface even under wearing illumination and background complexity.(Barreiro et al., 2021)

In addition to surface damage automated inspection system have been developed to identify quality or missing components such as insulators, bolts and vibration dampers. Real time come onboard detection system using deep learning models have shown the feasibility of performing component and fault detection directly on UAV platforms enabling near real time inspection results and reducing post processing requirements.

2.8 Transmission tower recognition and image-based identification

Accurate identification of transmission towers within large UAV image data set is prerequisite for automated inspection workflows. Machine learning and deep learning techniques have been employed to rapidly recognise transmission towers from aerial imagery, even in complex backgrounds. Fast image recognition models based on Convolutional neural networks and big data frameworks have demonstrated significant improvement in processing efficiency enabling large scale inspection of transmission networks.(Hu et al., 2018)

This recognition systems are particularly important for reducing manual intervention in inspection pipelines. By automatically distinguishing towers from background features such system allows inspection algorithms to focus on relevant regions of interest, improving overall efficiency and scalability.

2.9 GS based visualisation and spatial management of inspection data

While UAV and vision-based techniques provide detailed inspection data, Effective management and interpretation of inspection results requires spatial integration. GIS-based system has been widely used to manage, visualise, and analyse transmission infrastructure data. GIS enables georeferencing of inspection findings spatial querying of tower attributes and visualisation of inspection outcomes at network scale.

GIS based approaches have been shown to improve inspection demonstration and asset management by providing a structured spatial database or transmission network. Spatial analysis techniques allow inspectors and Decision makers to identify locations

specific issues and prioritise maintenance activities more effectively. Studies unified decision support environment. (Zipf et al., 2019)

However, many GIS applications focus on planning and routing of transmission lines rather than integrating automated inspection intelligence. This highlights the need for tighter integration between image-based inspection outputs and GIS based asset management system.

2.10 Integration of UV inspection and GR system

Recent reviews studies emphasises that the full potential of UAV based inspection can only be realised through integration with advanced data management and analysis platforms. Combining UAVs imagery b learning based inspection, and its GIS visualisation enables comprehensive monitoring for transmission infrastructure. Review literature highlights that you a v equipped with optical thermal and LIDAR sensors provide complementary information for structural assessment, but also notes Challenges related to data processing sensor integration and regulatory constraints.(Ince, 2024)

Despite technology advancement most existing studies focus on operational monitoring and maintenance rather than pre commissioning inspection period furthermore, inspection system is often developed as standalone solutions, either emphasising image analysis or spatial visualisation without end-to-end integration.

2.11 Limitations of existing approaches

While UAV imaging computer vision analysis, geographic information system analysis and 3D modelling have each contributed individually to the advancement of transmission infrastructure analysis, nearly all these previous works have been related to operation and maintenance analysis. Most of these are designed as standalone application that do not have linkage from analysis to management of geographic infection process.

Moreover, the new techniques for defect point detection and tower identification remain well developed in literature relatively few papers deal with verification of construction completeness and documentation of systematic inspection results prior to handover project. The attention given to integrating automated image analysis results for inspection in GIS-based quality assurance system clearly identifies a gap in the field of literature.(Chen et al., 2024; Jiang & Jiang, 2019; Li et al., 2023)

2.12 Research gap identification

Based on literature reviewed, it is evident that significant advancement has been achieved in the individual domains of UAV based image acquisition automated analysis GIS based spatial management for power transmission infrastructure inspection. UAV

platforms equipped with high resolution sensors have been widely adopted to reduce human exposure 2 hazardous inspection and environments computer inspections and deep learning techniques have demonstrated strong capabilities in detecting defects and Differences in transmission towers. Similarly, GIS based systems have been effectively used for spatial visualization asset inventory management and large-scale infrastructure monitoring despite these advancements existing inspection solutions largely operate in isolation focusing either on UAV based image analysis or GIS based spatial management Kumar rather than offering a unified framework that integrates automated structural assessment With spatial you driven inspection management. Most studies emphasis operational maintenance task such as damage detection, vegetation monitoring or transmission corridor safety with limited attention to specific requirement of pre commissioning stage.

Pre commissioning inspection demands a distinct inspection objective the primary focus is on verifying construction completeness structural conformity and the correct installation of critical tower components prior to energisation or project handover. Existing UAV based inspection frameworks rarely address these requirements, as they are predominantly designed for fault detection in commissioned systems. As a result, systematic verification of missing or improperly elected members, which is crucial for pre commissioning quality assurance, remains insufficiently addressed in current research.

Furthermore, while automated image-based inspection techniques generate valuable analytical outputs these results are often stored as stand-alone image level findings or textual reports. The lack of direct integration of automated inspection outputs into GIS environments restricts Patel dress ability, tower wise inspection tracking, and comprehensive documents. GIS platforms, in turn, or commonly used as passive repositories rather than active systems that incorporate automated inspection intelligence.

Therefore, a clear research gap exists in development of an integrated inspection framework that combines UAV based automated image analysis with GIS based spatial visualisation and data management specifically tailored for pre commissioning inspection of high-tension transmission towers. Addressing this gap is essential to enhance the efficiency, accuracy and reliability of inspection process prior to commissioning, and forms the central motivation of the present study.

3.0 Research Methodology

The proposed paper uses a combined image identification technique that uses UAVs and GIS based inspection method for pre commissioning inspection of high tensioned transmission towers. The high-resolution images are captured using Unmanned Aerial Vehicles (UAVs), which guarantee a very minimal risk of exposure to people in

dangerous site conditions during inspection. The flight of UAVs is planned such that there is a very accurate coverage of important areas like cross arms, bracing and tower legs.

These captured images are then processed for the detection of any flaws in transmission tower and evaluation of the presence and completeness of the critical structure features with the help of computer vision algorithms. This approach focuses on the identification of missing or improperly erected members as well as structural purity, which are important in for pre-commissioning assessment.

All inspection results are geo referenced and all results are merged in Geographic Information System (GIS) environment. This helps to spatially organize the location of transmission towers, display inspection results, and organize inspection results. Finally, geo referenced inspection maps and detailed inspection records are produced.

4.0 Analysis of Data

Using UAV-acquired imagery and spatial data obtained during the pre-commissioning phase of high-tension transmission towers, the data analysis process, the efficacy of the suggested automated GIS and image-based inspection framework. Automated computer vision techniques are used to analyse image data obtained from UAV platforms in order to identify transmission towers and evaluate the presence, alignment and completeness of critical structures. In order to verify construction quality before commissioning, the analysis focus on finding missing members, incorrect installation, and obvious surface irregularities

The accuracy of spatial data, consistency of the geo-referenced process, and completeness of the records of the GIS analysis environment. Tower-to-tower comparison of the inspection, spatial distribution of problems found an organisational structuring of the inspection data can be achieved as a result of analysis by the GIS environment. Regarding the length of inspection, consistency of the observation, level of human interaction and quality of documentation, the qualitative assessment of the automated inspection outputs and the conventional manual inspection is accomplished. The assessment is aimed at determining the level at which the automated system can address the aforementioned challenges for their literature review.

5.0 Result

The results of analysis show that the proposed framework of UAV/GIS Integrated inspection in collaboration with a UAV/GIS system has a more efficient approach to pre commissioning inspection compared to traditional technique used in inspection by human

observation. The image analysis based automated system allows for the systematic detection of transmission tower structures identification independent of the experience of a human inspection expert. The system also identifies any deficiency in installed equipment and detects in structure setup.

Integration of inspection results in GIS environment enhance the traceability and organisation of inspection results in GIS environment. Tower-specific inspection results are now visualised and retrieved effectively, and it helps in better identification of location-related issues in transmission corridor. Against conventional inspection process, the purposed method shows a significant reduction in the time required for inspection, consistency of results and safety, as it reduces the need to climb towers manually. The results are in line with the trend shown in the literature survey conducted.

6.0 Conclusion

This study demonstrates that the integration of UAV based images analysis with GIS spatial management provides a suitable and effective approach for the pre commissioning inspection of high-tension transmission towers. Based on existing literature that primarily focuses on UAV assisted inspection for operational maintenance and fault detection this work extends the application of computer added inspection system to pre commissioning stage, where construction completeness and structural conformity for critical importance.

The reviewed literature establishes the individual effectiveness of UAV platform for high resolution data acquisition and automated image-based assessment as well as the utility of GIS for spatial visualization and infrastructure data management. By combining these technologies into single inspection framework, the proposed approach addresses the limitations of fragmented inspection workflow identified in previous studies. The framework enables systematic verification of critical structural components, geo reference documentation of inspection outcomes and improved traceability go of inspection findings prior to commissioning.

The implications of this research extend to the broader energy transmission sectors, as improved pre commissioning inspection has the potential to enhance construction quality reduce commissioning delays and lower the likelihood of post commissioning maintenance interventions. By shifting the rule of automated inspection systems from predominantly maintenance-oriented applications to pre commissioning quality assurance, this study provides a foundation for more reliable efficient and data driven inspection practices in future energy transmission projects.

7.0 Recommendations

Consequently, the findings such as that all power transmission utilities and infrastructure developers should adopt UAVs and GIS-based automated inspection system as part of standard pre-commissioning procedure. Future research could be directed to integrating advanced deep learning models further improvement of component-level detection accuracy, integrating thermal or LiDAR data to enable multi-sensor inspection and framework validation across diverse terrain and tower configurations. Additionally extending the system to support post-commissioning monitoring and predictive maintenance will further enhance its practical value and operational impact

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CHAPTER 48

Evaluation of Silver Sand as Backfill Material for Reinforced Earth Walls in Highway Projects as per MORTH (5th Revision, 2013) and IRC: SP:102–2015

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ABSTRACT

RE walls have become an integral component of modern highway engineering due to their malleability, economy, and improved performance characteristics under differential settlement conditions compared to conventional rigid retaining structures. The performance characteristics of RE walls are significantly affected by the engineering properties of the backfill material used. The MoRTH Specifications for Road and Bridge Works, 5th Revision, 2013, and IRC: SP:102-2015 specify granular free-draining non-plastic soils with adequate shear strength as reinforced soil backfill material. In Guwahati, Assam, the cost of construction is appreciably higher since the crushed aggregate backfill material is transported from a long distance away with limited availability in the region. Silver sand, on the other hand, is abundantly available from the river deposits of the region and can thus be considered as a viable alternative material; however, most of the existing literature or codal specifications have not comprehensively ascertained the suitability of the same. The silver sand is experimentally assessed in the current study through laboratory and field tests, such as grain size analysis, Modified Proctor compaction test, liquid limit test, plastic limit test, California Bearing Ratio (CBR) test, and field dry density test. The obtained results have been compared systematically with the results of the other two types of backfill materials, i.e., clay soil, as per the requirements of MoRTH Clause 3105 and IRC: SP:102-2015 for the construction of Reinforced Earth Walls. The technical feasibility, along with the cost-effectiveness, of using silver sand as backfill material for the Reinforced Soil Structure, in the rainy climatic zone of Assam, has been established.

Keywords: Reinforced Earth walls, Silver sand backfill, MoRTH and IRC:SP:102–2015.

1.0 Introduction

Reinforced Earth (RE) walls are widely used in highway projects due to their efficiency in terms of structure, construction time, and economy in different soil conditions.

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However, when compared to conventional reinforced cement concrete (RCC) retaining walls, in the case of RE structures, the soil-reinforcement interaction plays an important part; therefore, the selection of an appropriate backfill material becomes an essential input in the design. Inappropriate properties of the backfill material can lead to increased lateral earth pressures.

The MoRTH Specifications (5th Revision, 2013) and IRC: SP:102-2015 provide particular recommendations for reinforced soil structures, specifying that a well-graded, non-plastic, free-draining, granular soil should be used. The specifications for soil were again largely for crushed aggregates or generic sand, without any specific emphasis on other regional types of sand, such as silver sand. The silver sand has generally been assumed to have uniform gradation, high permeability, be non-plastic, but doubts have been raised regarding compaction, density, or strength compared to normal sand.

The silver sand is available in a large quantity at a river site near Guwahati, whereas the aggregate materials that are crushed are often available from a substantial distance away. Thus, a scientific analysis is required to determine suitability with respect to other materials like clay soils that can act as a potential alternative for reinforced earth walls.

2.0 Backfill Requirements as per Codal Provisions

2.1 MORTH Specifications (5th Revision,2013)

As stated in MoRTH Clause 3105, the backfilling in the reinforced soil should be granular, non-plastic, free-draining material that can be compacted. The most important criteria are as follows:

- Maximum fines content does not exceed 15 percent
- Plasticity Index (PI) no more than
- Sufficient shear strength and bearing capacity
- Permeability is high to prevent the accumulation of pore water pressure

These criteria are aimed at ensuring a positive interaction between the soil and the reinforcement, as well as the stability and functionality of the reinforced earth structure.

2.2 IRC: SP:102–2015

IRC: SP:102–2015 provides guidelines for design and construction, stating that the internal stability (rupture and pullout of reinforcement, as well as external stability (sliding, overturning, and bearing capacity)) should be verified. The characteristics of the Backfill material influence:

- Active Earth pressure coefficient
- Reinforcement length and spacing

- Factors of safety against pullout and sliding

There is an implicit assumption that well-graded granular soils are used. In this manner, the relevance of evaluating alternative available local material, such as silver sand, is determined.

Table 1: Codal Requirements

Property	MoRTH	IRC: SP:102–2015	Importance
Fines content	$\leq 15\%$	Low fines preferred	Prevent pore pressure
Plasticity Index	≤ 6 (preferably non-plastic)	Non-plastic	Avoid shrinkage
Permeability	High	High	Drainage behind wall
Shear strength	Adequate	Mandatory	Internal stability
Gradation	Granular	Well-graded preferred	Reinforcement interaction

Source: Created by authors

3.0 Review of Previous Studies

3.1 Experimental study on waste foundry sand as partial replacement of retaining wall backfill

This study was designed to explore the possibility of using a waste foundry sand, which is an industrial by-product in the metal casting process as a partial replacement of natural sand in retaining walls. Considering the fact that the demand of natural sand is high because of the unavailability of natural sand resources, the authors had tried to explore a sustainable alternative of natural sand without compromising the performance of the retaining walls. To achieve the above objective, small-scaled models of retaining wall were collected and tested in a controlled laboratory environment. The waste foundry sand was increasingly substituting the natural sand in varying ratios. Lateral earth pressure, horizontal movement of the wall, and interaction between backfill and geogrid were some of the key elements that were measured continuously during the experiment.

The experimental results were very clear that, when it was confirmed that waste foundry sand was added, the effect was the decrease in the lateral earth pressure on the wall. Further, the lateral movement of the retaining wall proved to be less than that of walls with traditional soils, which is an indication of enhanced stability. It is worth noting that the backfill was highly drained and with enough shear strength just like clean sand. This study is quite applicable in terms of the application of silver sand. Since silver sand is also a clean uniformly graded and high silica content sand, the good performance of waste foundry sand

further supports the argument that sand materials make a good retaining wall backfill. In that way, one can say that silver sand is technically qualified in the purpose.

3.2 Performance analysis of geosynthetic reinforced earth wall

The research will also examine the reinforcement behaviour of reinforced earth walls with sand backfill material when reinforced with geosynthetic material. The main aim was to determine the efficiency of sand to geosynthetic reinforcement load transfer and the influence on the stability of the wall. In this research, the earth wall was designed as reinforced to be used with sand as the backfill, and geogrids separated at a given vertical distance.

A combination of analytical calculations, laboratory tests, and finite element modeling was used in the analysis of the performance of the wall. This facilitated a close comparison of the theoretical and experimental outcomes. The findings revealed that the sand backfill substance can be used in enabling the transfer of loads between the soil and the geosynthetic reinforcement and this leads to the large decrease in the deformation of the wall. Geogrid inclusion enhanced the overall stability of the wall through limiting the lateral movement.

Further, the well-graded sand was observed to interact with geogrids in a better manner due to the improved interlocking and resistance of friction. This can be directly applied to silver sand. Silver sand has good interactions with the soil and geosynthetic reinforcements and this is essential requirement of the reinforcement of the earth walls with soil because it is selected as clean and well graded sand.

3.3 Earth pressures on retaining walls backfilled with sand admixed with building-derived materials

The present study investigates the influences of lateral earth pressure distribution in case of retaining walls filled with sand, which do contain construction waste materials or the building wastes materials. The primary objective of the study was to establish whether there are other materials that can be as efficient as sand backfill. In order to attain this research, laboratory models of retaining walls were constructed and earth pressure sensors were installed on the depths of the retaining wall.

The research was done using various combinations of sand and compared with the findings of pure sand backfill. The findings demonstrated that sand in the purest form led to smaller and predictive lateral earth pressure. Nevertheless, the earth pressure was erratic when sand was mixed with construction wastes.

This study emphasized the reasons why clean sand is the conventional material to be used to backfill retaining walls due to the predictability of its behavior. This study agrees wholeheartedly with the use of silver sand since it demonstrates that high quality and clean

sand is most predictive with regards to the earth pressure response, which is essential in the keeping wall design.

3.4 Retaining wall model test with waste foundry sand mixture backfill

The retaining wall model test involving waste foundry sand mixture backfill was done using backfill of size 10 cm. The paper is among the pioneer experimental efforts to determine the feasibility of industrial sand used as a retaining wall backfill material.

This research was aimed at studying the mechanical characteristics of waste foundry sand as a backfill material behind retaining structures. The laboratory constructed physical models of retaining walls and waste foundry sand mixtures were applied as the backfill material. The researchers monitored the lateral earth pressure development, as well as, the horizontal wall displacement as the loading conditions were varied when the experiments were being carried out.

The study results indicated that the waste foundry sand mixtures resulted in low lateral earth pressures as compared to the conventional soils that are cohesive. The backfill and free-draining material ensured that the pressure of the pore water was not accumulated. The sand mixture had also a greater frictional resistance, which resulted in more stable walls.

This study proposes that silver sand may be effective and thus as effective as the use of waste foundry sand as a retaining wall backfill material since it is cleaner and of better grade.

3.5 Seismic resilience of retaining walls backfilled with sand–tire chip mixtures

The paper explores the seismic behavior of retaining walls using sand based backfills. The lateral forces on retaining walls may increase significantly during seismic loading and as such, the backfill properties have to be observed during seismic loading.

The authors conducted retaining wall model shaking table tests. A flexible and energy-dissipative system was created using sand combined with tire chips to create the backfill. The wall displacement, acceleration, and earth pressure were measured during the process of simulation of seismic loading.

The results indicated that the use of sand heavy backfills has the potential to minimize the seismic earth pressure and the displacement of walls significantly. The loose characteristics of the backfill were beneficial in seismic energy dissipation and the sand provided major contribution in the strength and drainage qualities.

Silver sand is best suited to the use in dynamic and seismic conditions as it does not have any grain size variations and is highly permeable to create less excess pore pressure and to drain rapidly during shaking.

3.6 Geosynthetic-reinforced soil walls with sustainable backfills

This paper will make a comparison between the conventional sand backfill and alternative sustainable and recycled materials in geosynthetic-reinforced soil walls. It was done to analyze the ability of other materials to substitute sand without affecting the performance of the wall. Numerical analysis was conducted as well as laboratory testing. The traditional backfill material that was used to make a comparison was sand and the performance of the walls that were constructed using recycled materials was compared with it. The findings revealed that sand backfill had the least wall deformation and the most reinforcement performance. Clean sand was easier to mobilize the pull forces in the geogrids and also possessed better drainage properties.

The other materials had to be of the same kind as sand as far as shear strength and permeability were concerned. As it has been confirmed in this paper, the best material used to backfill a RE wall is sand, and silver sand is the most obvious.

3.7 Effect of backfill sand density on dynamic response of MSE walls

The effect of the density of sand backfill on the behavior of mechanically stabilized earth (MSE) walls especially under dynamic load such as vibration of traffic and earthquake movement is the primary focus of the research. The model of MSE walls of different relative densities of sand backfill was undertaken through numerical analysis. The analysis was based on the factors such as displacement of walls and strain of reinforcements. It was observed in the research that the effect of a dense sand backfill is quite concrete as it minimizes the displacement and strain of reinforcement in walls. But the sand was compacted too little, which resulted in an over deformation. Compaction property of silver sand is better that enables it to achieve high relative density in the field. This sand can therefore be used in reinforced retaining structures where deformations are of paramount importance.

3.8 Evaluation of mechanically stabilized earth retaining walls – a review

The given paper provides the in-depth review of the research work performed over the years concerning the mechanically stabilized earth (MSE) and reinforced earth (RE) retaining walls. The review points out the significance of clean granular backfill having small proportions of fines. It also shows that poor-quality of backfill material is among the primary contributors to high earth pressure, drainage and premature wall breakage. This paper provides strong theoretical support of using clean sand as a backfill material, which also supports the use of silver sand as a backfill material of reinforced earth walls.

3.9 Suitability of silver sand as backfill material

The characteristics of silver sand are:

- High silica content
- Uniform grain size distribution
- Low plasticity
- High permeability
- Good compaction properties

The above characteristics match well with the IRC: SP:102-2015 and MoRTH requirements for reinforced earth wall backfill material. When compacted, silver sand has the potential to attain high relative density, thus increasing its shear strength and reducing deformations.

From the literature reviewed, it can be concluded that silver sand has the potential to:

- Resist lateral earth pressure
- Improve soil-reinforcement interaction
- Drain effectively
- Ensure long-term durability of retaining and RE walls

4.0 Experimental Investigation on Silver Sand

Moreover, in this research, silver sand is subjected to various lab and field tests as per IS code guidelines to check its effectiveness as a backfill material for reinforced earth walls. The results are then compared with that of Conventional sand and other materials.

4.1 Grain size analysis

The grain size analysis is carried out as per IS 2720 (Part 4), which helps to check the particle size distribution. Silver sand is found to be poorly graded sand (SP) as per the Indian Standard Soil Classification System, while for clay soil, there is a high percentage of fines. The low percentage of fines in silver sand is desirable for drainage, with less possibility of pore water pressure development in rear walls with RP waterproof structures.

4.2 Atterberg limits (liquid limit and plastic limit)

Liquid limit and plastic limit tests are carried out as per IS 2720 (Part 5). Silver sand is non-plastic and has a plastic index of almost zero, while Conventional sand is highly plastic. The non-plastic nature of silver sand satisfies MoRTH standards and does not have volume change and shrinkage problems.

4.3 Modified proctor compaction test

Modified Proctor compaction curve tests as per IS 2720 (Part 8) are carried out to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). It is

observed that the MDD of silver sand is less compared to the crushed aggregates, but it can achieve a good density with the help of optimized moisture content. The OMC and compaction efficiency of Conventional sand are high.

4.4 California Bearing Ratio (CBR) test

The CBR test is carried out as per IS 2720 (Part 16) to determine the strength and bearing capacity of silver sand. The CBR value of silver sand is much higher compared to the CBR value of clay soil, which shows that silver sand has better bearing capacity properties for the distribution of loads

4.5 Field dry density test

The field dry density is determined by the normal field method like the sand replacement method as per IS 2720 (Part 28). The result shows that it is possible for silver sand to achieve the required percentage of MDD in the field, whereas Conventional sand is sometimes faced with difficulties in achieving equal compaction due to its vulnerability to moisture.

Table 2: Comparison of Engineering Properties of Silver Sand and Clay Soil

Property	Silver Sand	Clay Soil
Grain size	Uniform sand (SP)	Fine-grained
Plasticity	Non-plastic	Highly plastic
Permeability	High	Very low
Compaction	Easy	Moisture-sensitive
CBR (%)	High	Low

Source: Created by authors

5.0 Comparative Performance with Conventional Sand and Other Materials

After a comparative study it has been noted that the performance of silver sand is far much superior to that of Conventional sand in terms of drainage and compaction properties, plasticity as well as strength. The permeability of a silver sand material is high in this case due to the lower fineness and non-plastic nature hence good drainage property and no pore water pressure at the back of the wall. Conventional sand, on the other hand, is not so permeable and is very plastic making it trap moisture and weaken.

Based on the compaction perspective, silver sand allows equal density, and less sensitivity to the change of moisture content, but in comparison to clay soil, there ought to be the right moisture content, and numerous issues could occur in terms of density. Silver sand

shear strength and California bearing ratio were also discovered to be superior to clay soil, which implies superior interaction and load transfer. Though crushed aggregates are more dense and stronger, The silver sand has been determined to be a better replacement that is less expensive and acceptable, when the sources of the natural aggregates are justifiable and unlike the conventional aggregates, the source of the silver sand is available in the region.

Table 3: Comparative Performance of Backfill Materials

Parameter	Silver Sand	Clay Soil	Crushed Aggregate
Availability	Local	Local	Distant source
Cost	Low	Low	High
Drainage	Excellent	Poor	Excellent
Plasticity	Nil	High	Nil
Suitability for RE walls	High	Poor	Very high

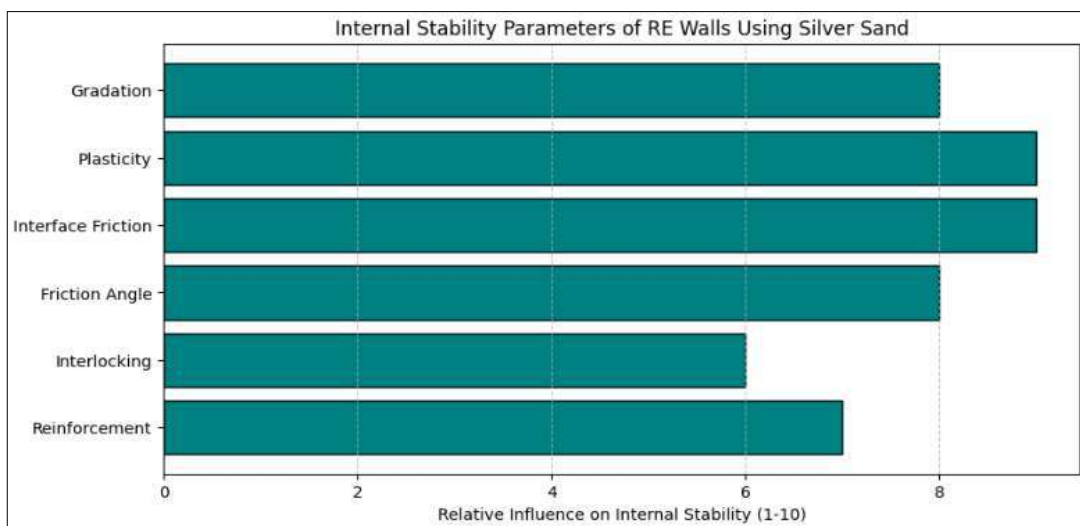
Source: Created by authors

6.0 Stability Considerations for Re Walls using Silver Sand

6.1 Internal stability

The reinforced earth wall stability relies on the soil-reinforcement interaction as the main factor of internal stability to determine the pull-out and direct pull resistance.

Figure 1: Internal Stability Parameters – Influence of Silver Sand Properties



Source: Created by authors

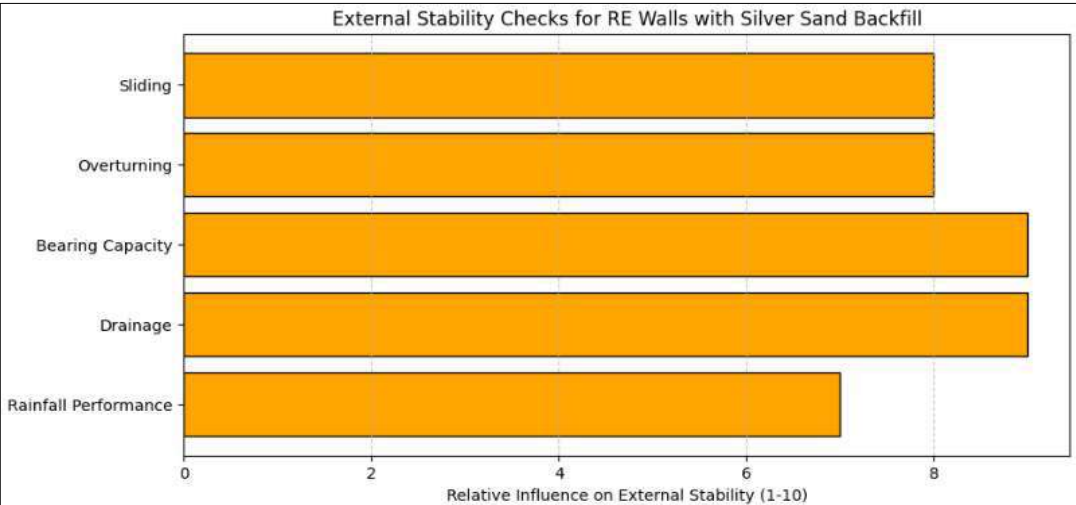
The low fines and the non-plasticity of silver sand applied in this research study enhance increased soil-reinforcement interface friction. Based on laboratory analysis, the outcome of grain size examination and shear strength parameter examination tests done on silver sand show that the stability of pull-out is satisfactory by means of friction. Friction angle values, which are applied in the calculation of pull-out, are obtained directly through the laboratory testing as required in IRC: SP:102-2015.

Nonetheless, the same graded quality of silver sand, as determined by the analysis of the grain size, requires the additional precaution to be taken during the design. The reason is that, the uniformly graded sands will, generally, be less interlocked than the well-graded sands, which will, perhaps, affect the interaction parameters of the reinforcement and the soil. In this case, the research methodology follows the analysis checks with the most limited design parameters, reinforcers spacing maximum, and length.

6.2 External stability

The overall behavior of the mass of reinforced soil against the slides, overturning, and bearing weight failure are basically connected with the verification of external stability of reinforced earth walls. The input parameters of the external stability analysis of this investigation are the calculated density and strength parameters through Modified Proctor compaction, CBR and field dry density tests. The fact that the unit weight of silver sand was rather lower than the crushed aggregate, led to lower unit pressure laterals in earth, which is beneficial to the overall stability.

Figure 1: External Stability Parameters – Influence of Silver Sand Properties



Source: Created by authors

An analytical evaluation provided in compliance with IRC: SP:102-2015 shows that the reinforced earth walls with silver sand backfill are related to the appropriate factors of safety against sliding, overturning, and bearing capacity failure provided that the appropriate design aspects are considered. The incredibly high permeability of silver sand as the evaluation of the gradation and plasticity values further enhance the exterior stability by eliminating the accumulation of pore water pressure in the background of the wall. The method therefore forms a direct relationship between the experimental research and analytical evaluation of external stability.

7.0 Research Gap and Need for Study

Though Indian conditions have ensured an ample supply of local silver sand, there is a lack of sufficient regime-specific experimental work available in literature to determine its effectiveness as a reinforced earthing wall backfill material. The existing codal provisions such as MoRTH (5th Revision, 2013) and IRC: SP:102-2015 are prepared taking into consideration the traditional granular materials and do not have a separate section describing the uniformly graded river sands. In fact, the overall lab and field test analysis of silver sand as a material for reinforced earthing is still inadequate. The comparison of its effectiveness as a different material type, such as clay and other commonly available backfilling materials, is even rarer, especially in a high rainfall region such as Assam. This is because the absence of established experimental results makes it difficult to make a safe choice of selection. This issue is addressed in this study and the effectiveness is determined through a lab analysis process of grain size, compaction, plasticity, strength, and field densities of silver sand and a comparison analysis of the results with Conventional sand and other materials.

8.0 Conclusion

The experimental and comparative study reveals that silver sand does not possess plasticity, compaction properties are satisfactory, CBR values are good to be used for the reinforcement earth wall backfill, and drainage properties are good.

Silver sand is much better than Conventional sand in reinforcement earth wall backfill and is nearer to the MoRTH and IRC: SP:102-2015 specifications for plasticity and permeability. Although the aggregates may cause strength to be crushed at high singular values, silver sand has proved to be an economical and readily available alternative. It can therefore be efficiently used as a reinforced earth wall backfill material.

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