Adoption of DFMA (Design for Manufacture & Assembly) Technologies in Indian Construction: Barriers, Drivers, and Workflow Implications

A Directed Research Project

by
Purvasha Shambhuwani
PCM24282

Submitted to the Office of Faculty of Technology, CEPT University
in partial fulfilment of the requirements for the degree of

MASTER OF TECHNOLOGY- CONSTRUCTION ENGINEERING & MANAGEMENT

Guide: Mr. Siddharth Panjwani
Co-guide: Dr. Amarnath CB

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ABSTRACT

The construction sector in India still primarily uses traditional methods of casting in place with reinforced cement concrete (RCC), however, this method is being challenged with regards to excessive time consumption, dependence on labor, low quality consistency, and poor coordination. As a result, Design for Manufacturing and Assembly (DfMA) has gained popularity internationally as a method of improving productivity and enhancing the performance of project deliveries through the integration of design, manufacture, and assembly. Despite the success of implementing DfMA worldwide, it is still an underutilized technique in India, especially when comparing it to other global markets.

This paper evaluates the application of DfMA technology enabled project delivery systems in India's construction sector. It focuses on organizational workflow transformation, preparation for adoption, and the impediments to adoption. The TOE (Technology-Organizational Environment) model is used to analyze the various components of DfMA implementation. To achieve both quantitative data analysis and qualitative insight collection, a mixed methodology approach was applied; i.e., a survey instrument consisting of 24 questions was administered to participants who were experienced professionals in the construction sector, and then supplemented by semi-structured interviews.

Overall results indicate that although there is some knowledge of how DfMA can be utilized technologically in India, the major obstacles to adopting DfMA include the organizational challenges associated with coordinating different stakeholders involved in projects, limited Building Information Modeling (BIM) capabilities among stakeholders, resistance to changing existing workflows, and inadequate support from senior management. Additionally, environmental constraints such as disjointed supply chain networks and limited enforcement of policies limiting large-scale deployment also contribute to DfMA adoption. The study found that there are distinct differences between typical RCC construction workflows and those utilizing DfMA-based processes in terms of early stage completion of designs, coordinated work processes during the execution phase, and manufacturing-based processes during the production phase.

A practical framework for transitioning to utilize DfMA was developed based upon the research findings. The framework outlines an organized process for determining whether an

organization is ready to adopt DfMA and assist organizations in their transition from site-based operations to manufactured construction processes.

Contributions to both theory and practice have been made by this research. This research establishes the application of DfMA within a developing market and provides actionable advice for construction organizations wishing to apply DfMA within the Indian construction sector.

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UNDERTAKING

I declare hereby that the work presented in this Directed Research Project document "Adoption of DFMA (Design for Manufacture & Assembly) Technologies in Indian Construction: Barriers, Drivers, and Workflow Implications" by me, Purvasha Shambhuwani, PCM24282 submitted towards partial fulfilment of the requirements for the award of the degree M.TECH. IN CONSTRUCTION ENGINEERING AND MANAGEMENT at the Faculty of Technology, CEPT University, Ahmedabad is an authentic record of my own work carried out during the period of Spring 2026, under the supervision of Mr. Siddharth Panjwani, Dr. Amarnath CB. Neither the data, nor any other content of this report have been copied. This work has not been previously submitted to any other institution for the award of any degree/diploma. I understand that my result and grades can be revoked if later it is found to be plagiarised or previous work resubmitted.

____

Name of student	: Purvasha Shambhuwani
Code No.:	: PCM24282
Date	: 30 Apr 2026
Place	: Ahmedabad

Disclaimer

This document describes work undertaken as part of the Master of Technology in Construction Engineering and Management program at the Faculty of Technology, CEPT University. Author is solely responsible for all views and opinions expressed therein, and do not necessarily represent those of the institute.

CERTIFICATE

Title of the DRP : Adoption of DFMA (Design for Manufacture & Assembly) Technologies in Indian Construction: Barriers, Drivers, and Workflow Implications

Name of the Student : Purvasha Shambhuwani

Code No. : PCM24282

The above titled study by the student is approved as a creditable work on the subject carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a pre-requisite for the degree of Master of Technology (Construction Engineering & Management) for which it has been submitted.

It is to be understood that by this approval, the undersigned do not endorse or approve the statements made, opinions expressed or conclusion drawn therein but approves the study only for the purpose for which it has been submitted by him/her and satisfies the requirements laid down in the academic programme.

Signature of the Guide : Siddha
Signed on 30 April 2026

Signature of the Co-guide : ………………….

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My sincere thanks go to Dr. Ganesh Devkar for his exceptional academic support and guidance throughout my postgraduate program in Construction Engineering and Management.

Lastly, I am deeply grateful to my parents and friends for their constant support, encouragement, and motivation throughout my academic journey. Their belief in me has been a source of strength and inspiration.

ABBREVIATIONS

AEC	-	Architecture, Engineering, and Construction
BIM	-	Building Information Modelling
CEPT	-	Centre for Environmental Planning and Technology
CNC	-	Computer Numerical Control
3DCP	-	3D Concrete Printing
DfMA	-	Design for Manufacture and Assembly
DRP	-	Directed Research Project
JIT	-	Just-In-Time
LGSF	-	Light Gauge Steel Frame
MD	-	Managing Director
MEP	-	Mechanical, Electrical, and Plumbing
PEB	-	Pre-Engineered Building
PM	-	Project Manager
PMAY	-	Pradhan Mantri Awas Yojana
RCC	-	Reinforced Cement Concrete
RMC	-	Ready Mix Concrete
RQ	-	Research Question
TOE	-	Technology, Organisation, Environment
UK	-	United Kingdom

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CHAPTER-1: INTRODUCTION

1.1 Background of the Study

The majority of the Indian Construction Industry still utilizes Cast In-Situ Reinforced Cement Concrete (RCC). RCC was a popular method for many years; however, it generally results in long lead times, high labor dependency, poor quality control issues, coordination problems and materials wastage. This problem increases significantly as project size and complexity increase putting added pressure on contractors to produce faster, safer and more reliable performance.(Lu et al., 2021; Roxas et al., 2023)

The increasing failure of traditional on-site construction methods has led the world wide construction sector to look at ways in which it can use manufacturing principles to improve its efficiency and delivery capabilities. The application of one such method is through Design For Manufacture And Assembly (DfMA) which seeks to integrate design decision making into the manufacturing/assembly process to enhance the final product.(Montazeri et al., 2024)

The challenges to adopting DfMA extend far beyond the technology that implements it. The development of DfMA is the result of transforming current processes used within the traditional construction workflow into aligned processes for designing, manufacturing, logistics and executing on site. As such, DfMA is a process and methodology for delivering projects as much as it is a new construction delivery process.

1.2 Introduction to Design for Manufacture and Assembly (DfMA)

DfMA is an overall design methodology that integrates manufacturing and assembly within design to help build off-site efficiently and install on site efficiently. The primary goal of DfMA is to create quality products while providing certainty regarding how those products will be delivered during the project lifecycle by moving some or all of the construction process from an uncontrolled site environment into a controlled factory setting.

DfMA may include multiple methodologies such as; precast concrete systems, modular construction, light-gauge steel framing, prefabricated service pods, hybrid precast-in situ systems, and emerging automated fabrication technologies. While each technology differs in terms of the level of prefabrication, all are aimed at reducing complexity associated with on-site activities through better design coordination and higher levels of standardization.

There have been recent studies demonstrating an interest in applying DfMA as a form of construction industrialization and/or digitalization, where it can be used in conjunction with BIM. BIM provides designers with tools to develop a coordinated design that facilitates a smooth flow of information and enables a more reliable plan among all parties involved in the manufacturing-driven delivery of a project. As a result, DfMA is ideal for use in projects that require speed, accuracy and repetition. (Montazeri et al., 2024)

Figure 1-1:Conceptual relationship between design for manufacture and design for assembly in DfMA

Source: Adapted from (Boothroyd et al., 2011)

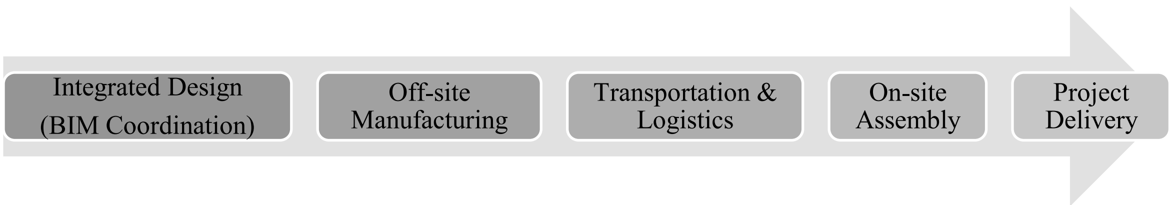

Figure 1-2:DfMA-Oriented Project Delivery Workflow

Source: Adopted from (Rankohi et al., 2023)

This workflow highlights the shift from sequential, site-driven processes to integrated, design-led and manufacturing-enabled project delivery.

1.3 Context and Need for DFMA in Indian Construction

Adoption of DfMA in India's construction industry has been slow and patchy. The primary factors behind this are that the Indian construction industry uses a 'project-by-project' method of project delivery; it is heavily reliant upon traditional methods of construction; and there is no standardization for DfMA (Design for Manufacture & Assembly) across all projects. Consequently, the need to increase productivity, quality and efficiency within the sector, has generated renewed interest in alternative approaches, including DfMA. (Widanage & Kim, 2024) DfMA has its own set of unique challenges with regards to an Indian environment's fragmented supply chain, varying capabilities from contractors, minimal ability to integrate design into projects and no established ecosystem to support off-site manufacturing. As a result, even when DfMA can be demonstrated as technologically viable, the industry frequently finds it difficult to convert that viability into regular process.

1.4 Problem Statement

While DfMA has shown a lot of global success in terms of improving the efficiency of construction projects; however it still lacks full adoption and understanding within India. To date there is little to no empirical evidence to demonstrate what changes will be required to an organisation's current workflows to support their successful transition into using DfMA. Additionally, as well as lacking such empirical evidence, there are also few if any practical frameworks or tool available to help assess the level of organisational readiness required for the use of DfMA in the Indian construction sector.

The objective of this research therefore is to identify and address both of these gaps through the examination of how the workflows of organisations need to change in order to adopt DfMA in the Indian construction context and how organisational readiness can influence this process..

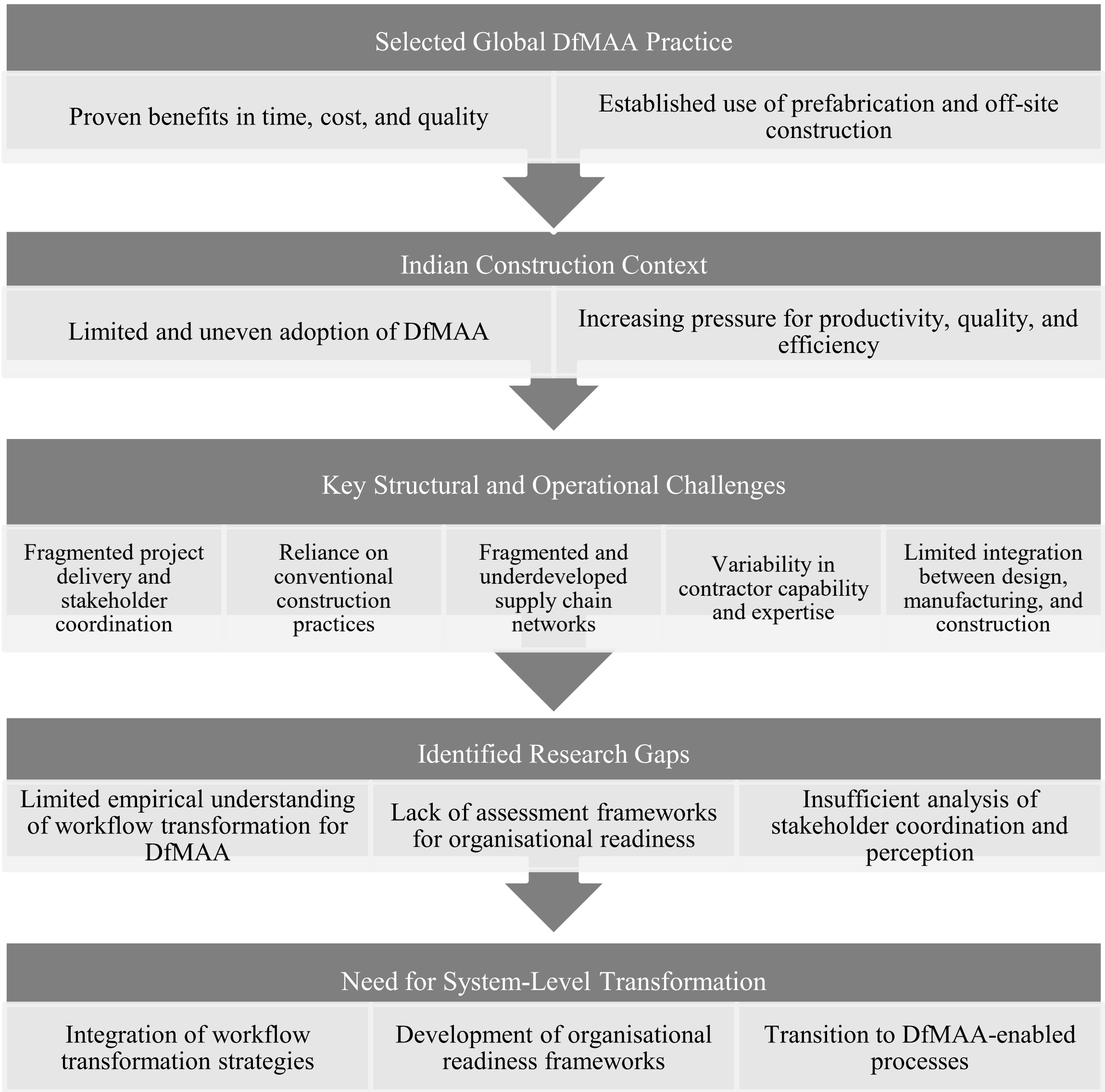

Figure 1-3:DfMA adoption in India- challenges, gaps, and transformation needs

1.5 Aim of the Study

This study aims to investigate how the use of Design for Manufacture and Assembly (DfMA) enabled project delivery systems are used on building projects delivered within India. It investigates this topic using three key areas, including workflow transformation as a result of implementing DfMA processes, assessing organisational readiness and identifying potential barriers to its adoption. A further objective of this research will be to develop a practical DfMA readiness and transition framework for use by all types of construction organisation operating within India.

1.6 Main Research Question

What ways exist to adopt Design for Manufacture and Assembly (DfMA) Enabled Project Delivery Systems for successful application by Construction Organisations within India based on the Transformation of Workflows and Readiness Development?

1.7 Objectives of the Study

To achieve the above aim, the study has the following objectives:

- Explore the limits of conventional cast-in-situ RCC construction and identify the technological, organisational and environmental factors affecting DfMA adoption within India compared to global adopters using the Technology-Organisation-Environment (TOE) model.
- Evaluate the process changes needed to transform an organisation's workflows to be able to use DfMA by comparing how projects are delivered traditionally and through the application of DfMA, particularly concerning how coordination processes, digital integration and the applications of BIM enabled practices differ.
- Develop a DfMA adoption readiness/transition framework applicable for construction firms operating in India

1.8 Research Sub Questions

The research sub-questions are grouped according to the study objectives to ensure a structured and progressive investigation

1.8.1 Research Sub-Questions for Objective 1: Context and Adoption Gap

RQ1.1

What operational and project delivery limitations are associated with conventional cast-in-situ RCC construction in the Indian context?

RQ1.2

In what project conditions does DfMA offer advantages over conventional RCC construction, and why have global adoption drivers not translated effectively into India?

RQ1.3

What technological, organisational, and environmental barriers constrain DfMA adoption in India using the TOE framework?

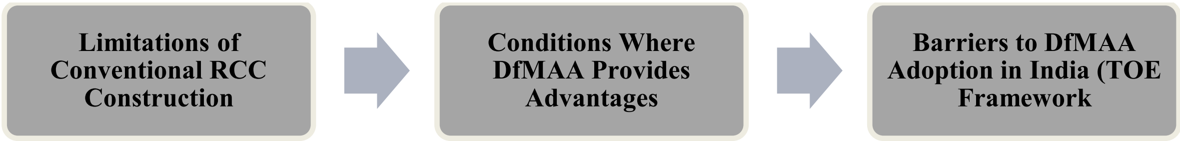

Figure 1-4:Framework linking RCC limitations, DfMA advantages, and adoption barriers in India

The framework aligns with the research questions by connecting RCC limitations, DfMA advantages, and the technological, organisational, and environmental barriers influencing its adoption in India.

1.8.2 Research Sub-Questions for Objective 2: Workflow Transformation

RQ2.1

How do project workflows and key processes differ between conventional cast-in-situ RCC construction and DfMA-enabled project delivery?

RQ2.2

What organisational challenges arise when transitioning from site-centric construction to manufacturing-led DfMA delivery?

RQ2.3

How do industry stakeholders perceive DfMA implementation, and what role do digital tools such as BIM play in enabling organisational transition?

Figure 1-5:Framework illustrating workflow differences, transition challenges, and the role of perception and digital support

The framework aligns with the research objectives by connecting workflow differences, transition challenges, and the influence of stakeholder perception and digital support on DfMA adoption.

1.8.3 Research Sub-Questions for Objective 3: Framework Development

RQ3.1

What organisational capabilities and readiness factors are required for successful DfMA adoption?

RQ3.2

How can the identified barriers and workflow transformation requirements be integrated into a structured DfMA adoption readiness and transition framework?

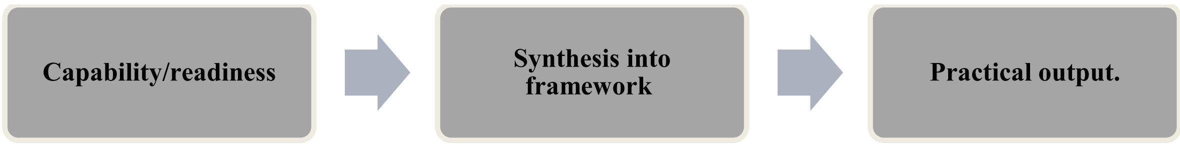

Figure 1-6:Framework illustrating the progression from global DfMA practices to challenges, research gaps, and system-level transformation

The framework aligns with the research objectives by demonstrating the progression from global DfMA practices to context-specific challenges, identified research gaps, and the resulting need for system-level transformation in the Indian construction industry.

1.9 Theoretical Framework: Technology–Organization–Environment (TOE)

To investigate the various DfMA adoption challenges that have been identified within this study, the TOE (Technology-Organization-Environment) model developed by Tornatzky and Fleisher was used as the major theoretical approach to assess DfMA adoption in India's construction sector. As presented in Figure 1.6, the TOE model describes how technology is adopted via three interconnected components: technical preparedness, organizational capability, and environmental conditions impacting the decision to implement new technologies.

In relation to the construction context, Technical aspects pertain to the existence of suitable DfMA technologies and corresponding digital infrastructure that can be used to execute DfMA, such as BIM. For this study, BIM was seen as an enabler, facilitating workflow integration, multidisciplinary collaboration and the exchange of data amongst all stakeholders in a construction project.

The Organizational aspects refer to workflow structures; coordination methods and processes; employee skills and training; senior management commitment; and ability of an organization to transform its operational processes. It should also be noted that DfMA represents a paradigm shift from conventional project delivery approaches therefore, organizational preparedness is fundamental to successfully implementing DfMA.

The Environmental aspects represent factors such as government regulation, market trends and standards; industrial culture; and supply chain networks which impact upon both the feasibility of adopting DfMA and scale at which it can be implemented. While existing literature indicates that technology based solutions and environmental awareness are increasingly being realized in the Indian context; most of the barriers to DfMA adoption in India are still primarily related to the Organization.

Therefore, this research uses the TOE model with specific focus on the organizational component to examine workflow transition from traditional cast-in-situ RCC construction to a DfMA-based delivery process. This will provide the analytical foundation for the development of a DfMA Adoption Readiness and Transition Framework for Indian Construction Organizations.(Mujahed et al., 2025)

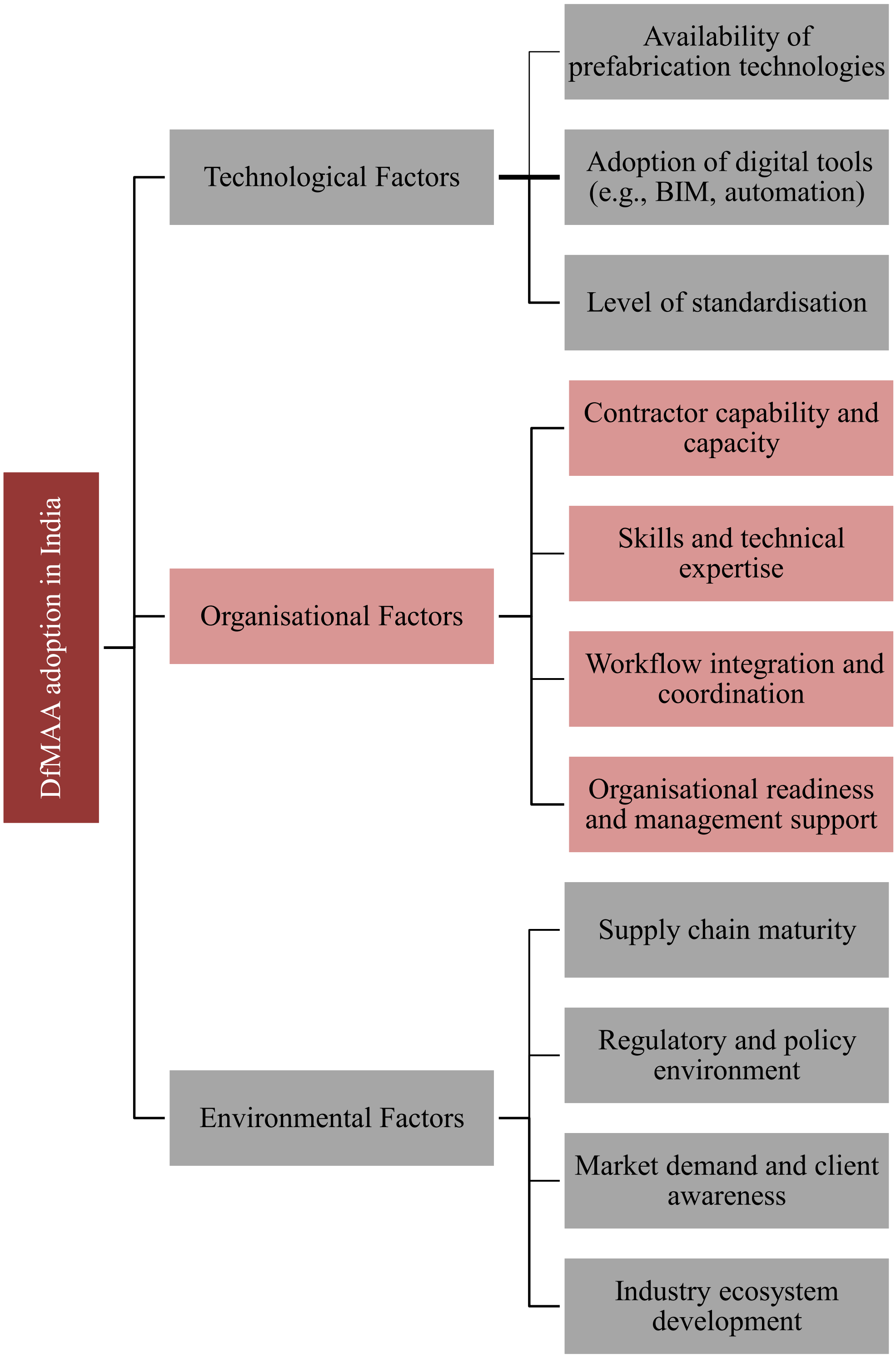

Figure 1-7: TOE framework for factors influencing DfMA adoption in India

Source: (Mujahed et al., 2025)

The TOE framework is used to categorise technological, organisational, and environmental factors influencing DfMA adoption in the Indian construction context

1.10 Overview of Research Methodology

This study is designed as an exploratory study to assess the adoption potential of Design for Manufacture and Assembly (DfMA) in the Indian Construction Industry. Data has been gathered by way of semi-structured interviews with key stakeholder groups within the construction industry who have responsibility for contracting, consultancy and project management. Interviews have been undertaken face-to-face and telephonically. Where possible, responses have been recorded during the course of the interview process by means of a structured Google Form based on the structured questionnaire that respondents were required to complete. In other cases, respondents have been asked to complete the questionnaire independently of the interview itself. This approach ensures that data is systematically recorded whilst also allowing for variation in terms of how respondents prefer to be treated in relation to the completion of the questionnaire. Secondary data sources have included relevant academic literature, industry-based reports, policy documentation relating to DfMA, off-site construction, and digital construction technologies. The primary source data has been subject to qualitative thematic analysis and descriptive interpretation. The results obtained have then been assessed using the TOE (Technology Organisation Environment) framework in order to determine which are the most significant enablers/barriers/organisational enablers that may impact upon DfMA adoption in India.

1.11 Scope of study

This study examines the adoption of Design for Manufacture and Assembly (DfMA) by the Indian Construction Industry. It will concentrate on organizational and process changes to support workflow change in terms of planning, design coordination, purchasing, integrated manufacturing, logistics, and site operations that also provide a basis for the use of Building Information Modelling (BIM), as well as its enabling characteristics of digital coordination.

Detailed structural analyses of buildings using DfMA components; complete cost/benefit modeling of DfMA components; comparative evaluation of properties of materials used in DfMA products will not be included in the study. Future studies can investigate these areas.

BIM was considered in the context of being an enabling technology in a DfMA environment and not a central focus of the investigation.

1.12 Significance of the Study

This study has contributed to knowledge and best practices in three ways. Theoretically, this is the first time the TOE (Technological, Organisational and Environmental) framework has been used to synthesize the barriers to and drivers of DfMA adoption as they relate to India. Empirically, this research provides the first comparison of conventional and DfMA work flows for practitioners and documents their digital-readiness challenges. Practically, the DfMA Adoption Readiness & Transition Framework produced from this research enables Indian construction organizations to develop and implement DfMA initiatives.

1.13 Limitations of Study

Certain limitations affect this study. Technologies related to emerging DfMA (Design for Manufacture and Assembly) technology that include 3D Concrete Printing (3DCP) have been excluded from the main empirical data collection and discussion of them has only been at a theoretical/conceptual basis in this study. The methodological approach was exploratory, and therefore included a limited number of semi-structured interviews and questionnaire responses. Interviews were conducted using video/telephone in relation to respondents who could not attend face-to-face meetings in Ahmedabad. Therefore, the results represent mainly the views of stakeholders surveyed, and do not provide statistical generalisability. Also, the study does focus on organisational workflows and preparedness rather than assesses a detail technical/performance based assessment of DfMA system.

1.14 Structure of study

The remainder of this study is organised as follows. CHAPTER-2: LITERATURE REVIEW presents the literature review, examining conventional cast-in-situ construction practices, the emergence and adoption of Design for Manufacturing and Assembly (DfMA), and innovation adoption studies structured through the Technology–Organization–Environment (TOE) framework. CHAPTER-3: RESEARCH METHODOLOGY outlines the research methodology adopted for the study, including the research design, data collection approach, and analytical framework. **Error! Reference source not found. Error! Reference source not found.** presents the data collection process and describes the information obtained through questionnaires and expert interviews. CHAPTER-5: DATA ANALYSIS provides the data analysis and discusses the results in relation to workflow transformation and organisational readiness for DfMA adoption. Finally, CHAPTER-7:Conclusion and Future Scope concludes the study by summarising key findings, outlining research contributions, and proposing future research directions related to DfMA adoption in the Indian construction industry.

CHAPTER-2: LITERATURE REVIEW

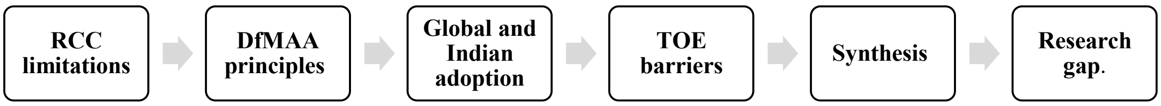

Figure 2-1: Conceptual flow of literature review for DfMA adoption

2.1 Conventional Cast-in-Situ RCC Construction in Building Projects

Cast-in-situ reinforced cement concrete (RCC) has been the dominant way to deliver a building project in India and other developing countries. This method is beneficial in that it allows for on-site adaptability and monolithic structural performance. However, all of today's studies identify site-specific inefficiency within RCC's process. Time over-runs, labor dependency, variations in quality, and materials wasted are examples of these inefficiencies that will be increasingly important as projects become more complex, urban density increases, and client delivery expectations rise. (Adhil Manoj Philip & M. Ramesh Kannan, 2021)

Cast-in-place reinforced concrete (CIP RCC) is fundamentally limited by its reliance upon sequential, site-specific operations that make it difficult to perform tasks simultaneously and have a requirement for constant coordination amongst numerous field activities. These limitations represent an increasing structural contradiction between CIP RCC and contemporary building production goals such as greater productivity and reliability. (Adhil Manoj Philip & M. Ramesh Kannan, 2021)

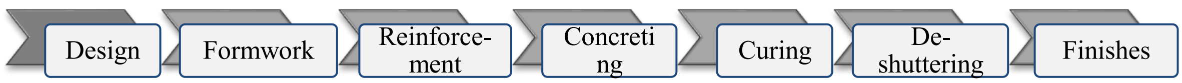

Figure 2-2: Sequential and site-centric workflow of cast-in-situ RCC construction

Source: (Adhil Manoj Philip & M. Ramesh Kannan, 2021)

2.1.1 Characteristics of Cast-in-Situ RCC Workflows

- The Cast-In-Situ RCC workflow is primarily organized with a site first logics. This logics governs how much design work can be completed prior to the field. Most of the major aspects that need to take place (i.e., concrete placement, reinforcement placement, formwork assembly, etc.) happen at the site sequentially. Thus, there are inherent characteristics associated with this method.

- Sequential site-based construction. Activities for major elements (e.g. foundations, columns, floors, finishes) are typically executed in an order that does not allow for significant levels of parallelism. The ability to execute these activities in a timely fashion requires well-coordinated scheduling of site based labor and equipment and/or formwork cycles. It has been extensively documented in constructability reviews that cast-in-situ workflows have many site specific factors..(Adhil Manoj Philip & M. Ramesh Kannan, 2021)
- High labour intensity and skill dependency are both required in high numbers on site. The number of skilled trade workers needed (carpenters for forming; steel fixers; concrete placers and finishers) is very high. If there is an issue with shortages of trained personnel or variability in skills levels this can have significant impacts on productivity and quality. Labour dependency has been identified in recent studies as one of the most common constraints to construction productivity in several developing countries, including India (Ekyalimpa et al., 2024)
- Fragmentation of coordination across disciplines. Due to the fact that most design-related decisions have been finalized or adjusted prior to actual construction (and therefore do not take place in a systematic way), ad-hoc and project-specific coordination is required for designers, contractors, and subcontractors. The fragmented nature of this process will increase the (Ekyalimpa et al., 2024)

2.1.2 Limitations of Cast-in-Situ RCC Construction

A major problem with cast-in-situ RCC construction, as discussed in recent research studies on this type of construction, has been long construction durations. The reason for the large amount of time required for each phase (i.e. erecting forms, placing reinforcing steel, pouring concrete, curing, etc.) is that these phases occur one after another and have a dependency relationship with each other; therefore, project schedules can be very responsive to changes at the jobsite..(Naathan, 2023)

Additionally, higher labor dependence can lead to both costs and productivity issues. The inability to consistently have available skilled labor will lead to variations in production volume and an increase in project risk. This can be even worse when you factor in quality variation since RCC projects rely so heavily on workmanship and site management to achieve desired levels of quality. (Ekyalimpa et al., 2024)

Another long-standing problem has been material inefficiency. Material loss during the execution phase (i.e., cutting losses, ordering extra materials than needed, rework) occurs frequently during on-site activities, which raises questions regarding sustainability and resource utilization. (Adhil Manoj Philip & M. Ramesh Kannan, 2021)

Of particular importance is that each of these problems is exacerbated by today's project environment. Larger project sizes; tighter time frames for completion; and greater expectations for quality and sustainable practices mean that traditional RCC methods of delivery are becoming less aligned with current expectations for how well a project should perform. As such, this provides an impetus for investigating other forms of project delivery. (Adhil Manoj Philip & M. Ramesh Kannan, 2021)

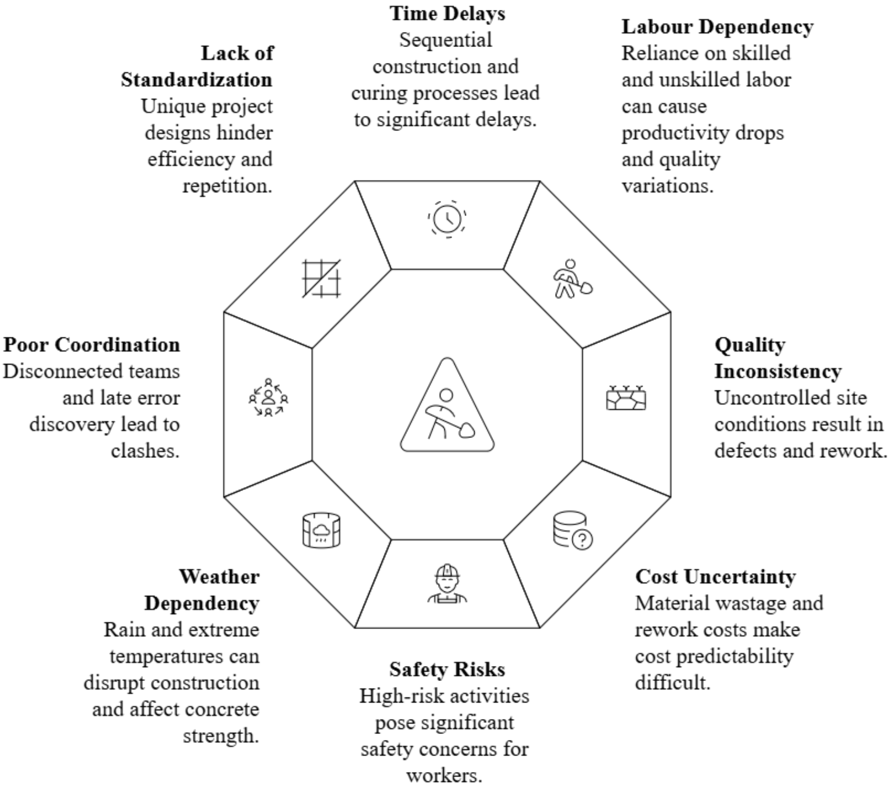

Figure 2-3: Limitations of cast-in-situ RCC construction under contemporary project demands

Source: (Ekyalimpa et al., 2024)

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Cast-in-situ RCC construction is dominant, but it is inherently site-centric and sequential, which creates predictable workflow and performance problems under modern project demands.

2.2 Design for Manufacturing and Assembly (DfMA) in Construction

2.2.1 Concept and Principles of DfMA in Construction

Design for manufacture and assembly (DfMA) is a paradigm change in construction. It is a way of designing construction projects which have been defined by how they will be

manufactured and assembled from the outset. Traditional construction has focused on delivering each building on-site as a one-off project whereas DfMA provides a platform for the development of repeatable standardized designs. (Montazeri et al., 2024)
The primary benefit of DfMA for construction is that it allows some of the most labour intensive aspects of construction work to take place in a controlled factory environment. This results in enhanced quality control, less uncertainty about what can go wrong and increased productivity.

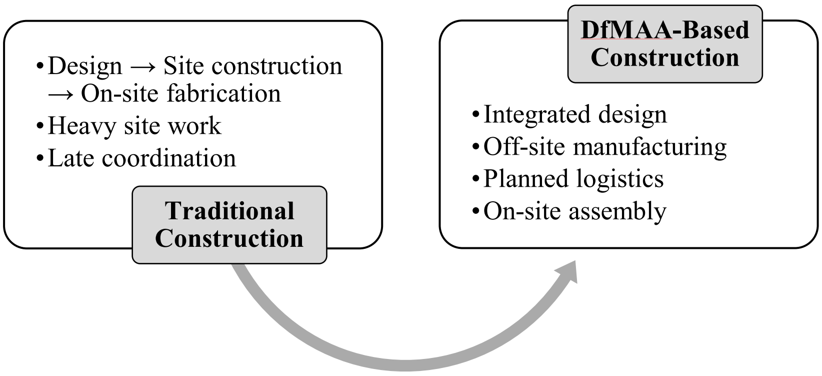

Figure 2-4: Conceptual shift from site-centric construction to design-led, manufacturing-enabled DfMA workflows

2.2.2 DfMA Systems and Applications in Building Construction

DfMA has been implemented through a number of different off-site construction methods (prefabricated components, modular building components, and volumetric units). Each method varies in terms of how much integration and off-site work is completed but each method implements similar DfMA principles to include design standardization, simplification of connections at the time of installation, and early design closure. The ability to effectively implement these technologies is dependent upon both the technological capabilities for each technology, and the maturity of the entire supporting infrastructure or ecosystem that supports them (manufacturing capacity, supply chain coordination, etc.). (Roxas et al., 2023; Tuvayanond & Prasittisopin, 2023).

Commonly Used DfMAA Technologies in India

- **Hybrid Modular Systems**
- **Precast Concrete Systems**
- **Light Gauge Steel Framing (LGSF)**
- **Modular Systems**
- **Bathroom/Kitchen Pods**
- **Structural Steel Modular Systems**
- **Pre-Engineered Buildings (PEB)**

Figure 2-5:Commonly Used DfMA Technologies in India

2.2.3 Performance Benefits and Implementation Considerations

The research has shown that DfMA can have an influence on a project's performance by reducing construction time and improving quality while reducing material waste. The primary way that DfMA is able to create these improvements is through use of controlled production facilities and the ability for both on-site and off-site activities to occur at the same time.

That being said; there are many factors that affect how well DfMA will be able to produce the expected results including: how early the decisions about the project are made; the level of cooperation among all the parties involved; and how well the logistics surrounding the project are managed. (Roxas et al., 2023; Tuvayanond & Prasittisopin, 2023).

Importantly, most empirical evidence is derived from developed construction markets, raising questions about the direct applicability of these findings to developing contexts such as India. (Roxas et al., 2023; Tuvayanond & Prasittisopin, 2023)

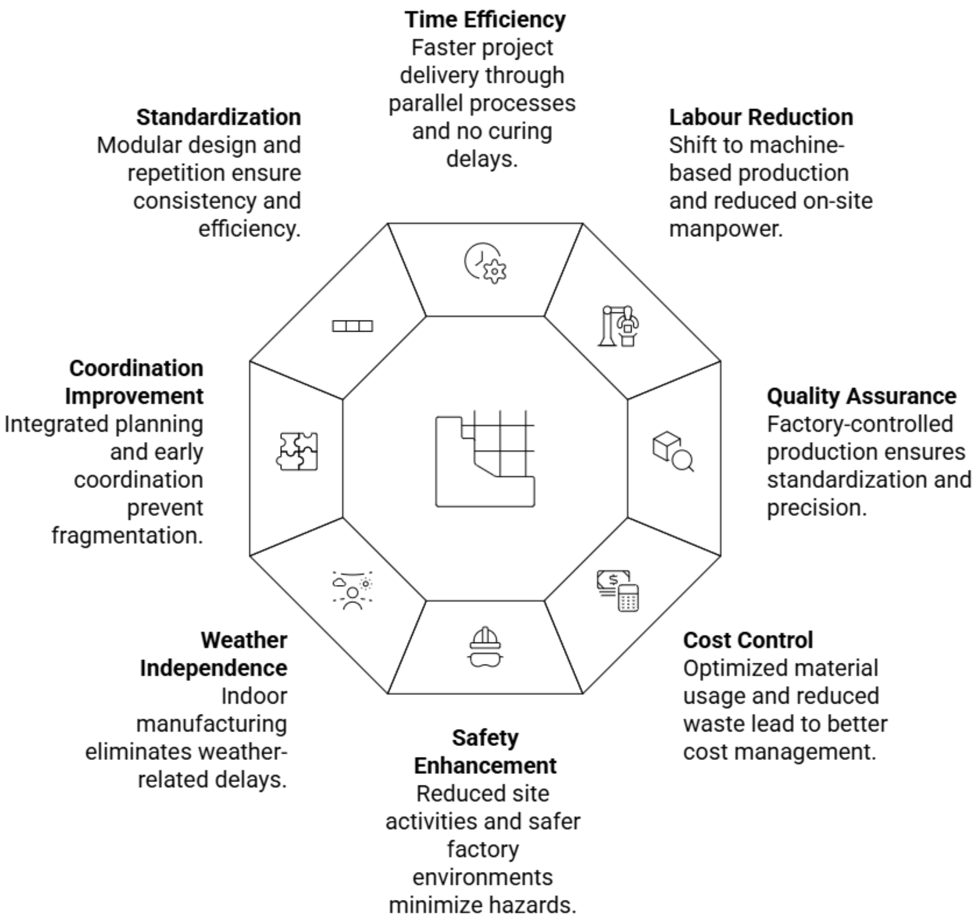

Figure 2-6:Potential of DfMA in Construction

Source: (Roxas et al., 2023)

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2.2.4 Digital Enablement of DfMA Workflows

ilding Information Modelling (BIM) is a digital approach for creating and managing an intelligent three-dimensional model of a building. The model contains both geometric and non-geometric data about how a building looks and functions. BIM provides a common digital platform for sharing data among architects, engineers, contractors, and manufacturers to enable collaboration, exchange accurate data, and inform decision-making in all phases of a project.

Within DfMA related construction processes BIM acts as a vital enabling technology which supports the design-to-manufacture process flow. In particular:

- BIM facilitates accurate coordination of designs and clash detection to prevent on-site conflicts when producing manufactured components.

- BIM can generate fabrication ready data; such as shop drawings with precision measurements, CNC cutting instructions, and assembly sequences for manufactured parts.
- BIM facilitates standardization of component manufacture via use of parametric models and rule based design methods that incorporate manufacturing constraints at the earliest stages of development.
- BIM provides integrated scheduling capabilities that link off site production schedules to on-site logistics relating to assembly operations.

Research into recent trends has shown growing emphasis toward integrating DfMA with digital technologies; including BIM transitioning from documentation tools to production management systems that connect designers' intent with factory produced products. (Widanage & Kim, 2024).

Despite there being a number of practical impediments, which include the lack of ability for different systems to be compatible with one another (between design software and manufacturing software) as well as skills shortages within the BIM-DfMA workflow, as well as differing levels of standardisation of project data between the designer and the fabricator; these are all specific to India, where BIM levels vary both by organisation and by individual project. (Widanage & Kim, 2024)

2.3 Global Adoption of Design for Manufacture and Assembly (DfMA)

While the global adoption of DfMA (Design for Manufacture and Assembly) has shown some growth; it has mostly occurred within the framework of larger-scale industrialization strategies being pursued by many developed economies experiencing growing demand for housing, growing labor shortages, increased pressure from population densities and demands to increase speed of completion of projects. The United Kingdom, Singapore, Australia and Japan are examples of several countries which have taken proactive roles in promoting DfMA through policy initiatives, government sponsored housing programs and standards that promote use of offsite fabrication processes.

Each was selected due to its high level of experience and successful implementation of DfMA. These four countries represent mature construction economies where policies supporting industrialized building methods have been created. Each country presents an unique scenario. The UK represents policy led transformation, Singapore demonstrates a very regulated environment based on mandates, Australia represents market driven responses to increasing labor costs and decreasing productivity and Japan's example represents long term integration of manufacturing into construction.

These scenarios also present documented evidence of DfMA adoption, allowing for comparison across the cases. Therefore, while this is not an exhaustive list, it is intended to be representative of different types of successful DfMA implementations, thus providing greater insight into the extent to which various factors such as policy support, labor conditions, digital capabilities, and integration of supply chains contribute to the successful implementation of DfMA. (Montazeri et al., 2024)

The studies show that the largest benefits from DfMA will be achieved when there is a strong alignment of organizational abilities, digital systems, and regulatory structures. Thus, an example would be when organizations have matured to an Integrated Project Delivery (IPD) model and high Building Information Modeling (BIM) maturity and thus can work through seamless "design to manufacturing" processes; likewise, if governments create supporting regulatory structures, they can shorten approval times for pre-fabricated systems. On the other hand, the adoption of DfMA is still at relatively low levels on a global scale even though many people are aware of the positive impacts of DfMA due to the lack of alignment of many markets in terms of their ability to support DfMA. This pattern shows that both technological feasibility and environmental conditions play a role in determining how easily an organization or industry can adopt DfMA. In those markets which are well aligned with the necessary enablers, there has been greater penetration of DfMA. Therefore, the question remains as to whether DfMA can ever be fully adopted across all industries globally regardless of what level of technology may be available to support it.

2.4 DfMA in the Indian Construction Context

The application of Design for Manufacture and Assembly (DfMA) is still at a nascent stage in the Indian construction market although there is increasing interest because of rapid urbanization and large scale demand for housing under schemes like Pradhan Mantri Awas Yojana (PMAY), and government support of prefabrication. Although some precast concrete components, and small amounts of modular building systems are being used in some individual project applications, the majority of the Indian construction industry still relies heavily upon traditional cast-in-situ reinforced cement concrete (RCC) construction methods (mordor intelligence, 2024)

The Indian construction ecosystem has a number of structural barriers that prevent manufacturing from being applied in ways that can drive Manufacturing Led Approaches. In particular, key features include a fractured supply chain system (with few specialized builders), very little standardization across projects, and an extreme reliance on labor that is available at competitive costs due to its abundance. As such, these are structural and systematic impediments to the adoption of DfMA through the current workflow optimization processes that exist today within most of the major players in this space. (mordor intelligence, 2024)

Although technology exists to facilitate the policy drivers and market pressure for DfMA, organizational preparedness as well as workflow integration continue to be inadequate. This is creating a continued gap between the awareness of the benefits of DfMA and the practical application, thus demonstrating that the barriers to adoption in India are largely based on organizational/process related issues versus the limited technological capabilities. (mordor intelligence, 2024)

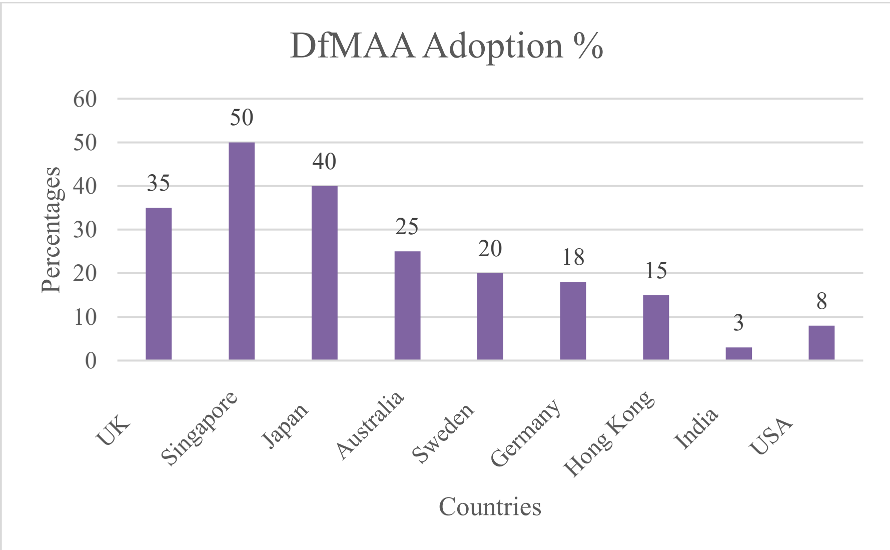

Figure 2-7: Global variation in DfMA adoption and industrialised construction adoption

Source: Literature synthesis, (Montazeri et al., 2024)

Figure 2-7: Global variation in DfMA adoption and industrialised construction adoption illustrates significant global variation in DfMA adoption rates, with policy-driven markets such as Singapore (50%) and the UK (35%) demonstrating high penetration compared to India (3%). This disparity highlights structural barriers beyond technological feasibility that constrain manufacturing-led construction in developing contexts.

DfMA adoption in India is constrained by ecosystem readiness, not just technological availability

Table 2-1:Global-India DfMA Adoption Gap Analysis (TOE Perspective)

TOE Dimension	Global Leaders (UK, Singapore, Japan)	India	Why India Lags
Technology	BIM Level 2+ (full collaboration) (BIM UK) Automated DfMA design tools	BIM Level 1 only (basic 3D drawings) Manual coordination	Cannot freeze design early for factory production
Organisation	Designers + fabricators work together from Day 1 DfMA training programs (Montazeri et al., 2024)	Architects, engineers, contractors work separately Only know RCC methods	No team readiness for factory-based construction
Environment	Government requires 30-50% DfMA in public projects, Factory ecosystems available	Only small PMAY pilot projects Daily labour ₹800/day	Traditional methods cheaper and easier

Source:**(BIM UK; Design for Manufacturing and Assembly (DfMA), 2026; Montazeri et al., 2024)**

Table 2-1:Global-India DfMA Adoption Gap Analysis (TOE Perspective) shows India's DfMA adoption lags due to technological immaturity (BIM Level 1 vs global Level 2+), organisational silos, and economic conditions favouring conventional RCC construction (₹800/day labour).

2.5 Barriers and Drivers Influencing DfMA Adoption

This chapter builds upon the technology – organisation – environment (TOE) framework established in CHAPTER-1, combining previously established literature to identify all drivers and barriers of adopting DfMA, organised into the three categories: Technological, Organisational and Environmental. Although DfMA has significant opportunities to improve construction productivity, quality and predictability, there is a lack of global uniformity in its adoption. More recently research has indicated that successful implementation will require technological readiness and organisational capability to be aligned with an appropriate set of external environmental factors. (Montazeri et al., 2024; Roxas et al., 2023)

2.5.1 Technological Factors

The literature identifies a number of key technology drivers that are expected to lead to increased take-up of Design for Manufacture and Assembly (DfMA). Off-site building systems — such as modular construction, prefabricated components and volumetric modules — have been shown to deliver real benefits including improved accuracy in terms of dimension; lower on-site workforce requirements; faster assembly times; better quality control; through the use of standardised designs and manufacturing planning at an early stage. (Tuvayanond & Prasittisopin, 2023)

Digital technology; in particular, BIM and Parametric Design Workflows are a vital means of enabling the translation of design output to manufacture ready output, the generation of Clash Free Shop Drawings and minimizing re-work during the construction phase. Technology based restrictions are majorly limiting its use. Early Design Freeze, Tight Dimensional Tolerancing and Precise Data Exchange between Design and Production Systems is in direct conflict with the traditional iterative process of designing. Furthermore, Inconsistencies in BIM Maturity amongst Project Stakeholders combined with the lack of interoperability between Architectural Design Software and Manufacturing Control Systems are creating ongoing Implementation Challenges. (Widanage & Kim, 2024)

Physical constraints-including transportation logistics, crane capacity, and restricted site access-further limit the feasibility of large, prefabricated components, particularly in dense urban environments(Montazeri et al., 2024; Widanage & Kim, 2024)

2.5.2 Organisational Factors

Organisational Readiness is the single largest factor to a company's success when adopting Design for Manufacture and Assembly (DfMA). The strongest support from Senior Management allows companies to make decisions at an earlier stage than they normally would and provide necessary resources as well as coordinate across different functional groups which are all key to delivering projects using Manufacturing processes. Companies that have previously used Off-Site Construction also show greater organisational readiness due to their own organisation now understanding the complexity of coordinating the various functions involved throughout each phase of the Design, Production and Site Execution. (Montazeri et al., 2024; Roxas et al., 2023)

Organisational maturity is a major factor contributing to the successful application of BIM and DfMA. The close working relationship between designers and fabricators and their ability to plan work together at an early stage ensures that the manufacturing process does not need to accommodate changes made late into the design process. In addition, both the designer and the manufacturer are able to synchronise their schedules so as to ensure that components can be assembled on-site as efficiently as possible. (Widanage & Kim, 2024).

In contrast, organisational barriers are present in almost every context. Organisations continue to resist change from traditional cast-in-situ processes mainly due to the lack of understanding about DfMA and the fact that they do not have sufficient specialized training to allow them to move away from these traditional processes. (Alhawamdeh & Lee, 2024; Roxas et al., 2023)

2.5.3 Environmental Factors

The right environment can be a major driver of the adoption of new technologies. For example, government policy to support the use of prefabricated modules, standardized building designs and fast track housing delivery creates an "enabling" framework for innovation. Similarly, the increasing demand by clients for faster construction projects will encourage the manufacturing sector to provide more efficient solutions; such as providing manufactured components to site. Procurement systems that reward suppliers who adopt off-site solutions will further drive this process throughout the entire industry. (Montazeri et al., 2024)

However, despite these potential drivers there are many environmental factors which could act against DfMA in developing countries. These include lack of standards and regulation, no common format for the design of pre-fabricated elements or modular units and the general lack of clarity on what is acceptable from a regulatory perspective. This level of confusion adds to the perceived risk for investors and may discourage companies from investing in the ability to manufacture modules/elements using DfMA methods. (Montazeri et al., 2024)

Additionally, other than regulatory issues, there are also significant commercial challenges for DfMA within each country. For example, fragmented supply chain networks (with limited numbers of specialized manufacturers) combined with inconsistent client requirements for off-site solutions reduce opportunities for large-scale production and therefore limit cost savings through economies of scale. Clients' purchasing decisions often focus solely on the initial purchase price rather than the overall life cycle cost advantage provided by DfMA; which limits clients' willingness to invest at the beginning of a project to enable the necessary early coordination and investment into factories. (Alhawamdeh & Lee, 2024)

Table 2-2: Barriers and Drivers Influencing DfMA Adoption (TOE Framework)

TOE Dimension	Key Drivers (Enablers)	Primary Barriers (Constraints)
Technological	- Off-site systems (modular,	- Early design freeze conflicts with

TOE Dimension	Key Drivers (Enablers)	Primary Barriers (Constraints)
	precast, volumetric) improve quality & speed - BIM enables clash-free manufacturing data - Parametric design supports standardisation	iterative practices - BIM-manufacturing software interoperability gaps - Transport/crane limitations for large modules
Organisational	- Top management commitment to DfMA transition - BIM-proficient workforce & DfMA training - Early architect-fabricator collaboration	- Cultural resistance to abandoning RCC methods - Lack of manufacturing-led workflow experience - Siloed design/procurement/construction teams
Environmental	- Government prefabrication mandates & incentives - Market demand for accelerated delivery - Lifecycle-cost-based procurement policies	- No codified DfMA regulations/approvals - Fragmented supply chain (few factories) - Client preference for lowest upfront capital cost

Source: (Alhawamdeh & Lee, 2024; Montazeri et al., 2024; Roxas et al., 2023; Widanage & Kim, 2024)

Table 2-2: Barriers and Drivers Influencing DfMA Adoption (TOE Framework) reveals organisational readiness as the predominant DfMA adoption constraint, requiring workflow transformation beyond technological solutions alone

2.6 Thematic Synthesis of DfMA Adoption Literature

Building on Sections 2.1 - 2.5, this section synthesises recurring patterns across DfMA research to identify why adoption remains uneven despite demonstrated technical benefits. Rather than restating individual findings, the synthesis consolidates insights into five dominant themes that reveal both established knowledge and critical research gaps.

2.6.1 Workflow Transformation from Site-Centric to Manufacturing-Led Construction

A major concern in all DfMA papers has been the need for a transition from traditional, on-site, sequential processes for cast-in-situ works (Section 2.1), to more integrated and manufacturer-driven delivery systems. DfMA will move 40-70% of construction activities into the control of the factory environment. This requires that the majority of the design process be completed prior to manufacture, that each stage of the production process is planned with precision and that the integration and coordination between each stage of design, manufacture, distribution and site execution are tightly controlled. (Lu et al., 2021; Roxas et al., 2023)

All stages of a project are impacted by this transformation. Planning is now done with design certainty instead of details that will be progressively developed. Procurement has transitioned from materials to factory capacity. Logistics have changed and now require just-in time delivery. Site work has been compressed into an extremely rapid assembly process. In RCC (Reinforced Concrete Construction) late design changes were often tolerated but they are clearly unacceptable in factory produced buildings. The literature documents this "workflow discontinuity" as the largest single obstacle to implementing DfMA and therefore supports comparing the differences between traditional vs. DfMA delivery methods.

2.6.2 Organisational Readiness and Capability for DfMA Adoption

Organizational readiness is the biggest barrier to implementing DfMA in many parts of the world, based on results from a survey of industry experts, as shown in Table 2 2: Barriers and Drivers Influencing DfMA Adoption (TOE Framework). The fact that an organization has technical capability will not be enough for it to implement DfMA successfully. To have success with DfMA, organizations need to develop their capacity in several areas including how to make sure designers and fabricators are committed to working together, what skills designers and fabricators need to have in order to collaborate effectively and how to establish collaborative designer-fabricator relationships.(Lu et al., 2021; Roxas et al., 2023)

The way leaders support organizational efforts related to DfMA can determine whether or not the right decision are made at the beginning of a project and if resources are moved appropriately into manufacturing-oriented process. Organizations with BIM-qualified staff and previous experience with off-site construction are able to manage the level of coordination needed by both design and fabrication teams in order to deliver products through a factory-based delivery method. (Babanagar & Giriraju, 2024)

2.6.3 Digital Enablement and Information Integration

The use of BIM to enable DfMA is a crucial enabling technology that allows for the creation of a single source of truth for information about building projects (in particular regarding clash free coordination; production ready data creation and the alignment of design and construction processes). Advanced forms of application within BIM (i.e., parametric modeling; rule based design and digital twins), allow designers to check for constraints in their designs during the design phase and produce an automated production sequence. (Abrishami & Martín-Durán, 2021)

However, as noted above the realization of the potential benefits from these technologies requires organizational maturity beyond just having access to them. The technological capability to utilize these tools will be limited by both the ability of various stakeholders to understand how to properly utilize them and interoperability issues related to the integration of Architectural BIM platforms with Manufacturing Execution Systems.(Qi & Costin, 2023)

2.6.4 Policy, Market, and Supply-Chain Influences

Environmental factors have a large influence on how quickly construction companies adopt the use of DfMA. The UK and Singapore are examples of countries that require all building projects to be completed using off-site construction methods. These mandates provide strong incentives to build faster. In addition, companies can be rewarded financially by clients who purchase buildings built with off-site construction processes. On the other hand, developing countries lack consistent rules and regulations; the fragmentation of the supply chain also makes it difficult for new technologies to become part of standard practice; and many clients choose the option of paying the least amount of money as possible to meet their needs.. (Lu et al., 2021; Roxas et al., 2023)

The impact of India's specific circumstances exacerbate the above limitations. As an example, Pilot Projects for PMAY represent less than one percent of India's total housing needs. Furthermore, speciality Factories are a rarity in India. In addition to this, daily wages at Rs. 800 make onsite manufacturing of building components economically viable as compared with potential productivity losses from offsite manufacturing (Section 2.4). Figure 2 7 shows that there is considerable variation globally among both the adoption of DfMA and industrialised construction; therefore, it can be concluded that although India has some degree of adoption of DfMA with respect to other countries, its level of DfMA penetration is approximately three percent whereas many leading nations have adopted levels of 25 – 50 percent. (Babanagar & Giriraju, 2024)

2.6.5 Adoption Challenges in Developing Construction Contexts

Global DfMA literature is primarily based on experiences from developed markets (mature industrial base, labor shortages, government support) that are inherently conducive to remote fabrication (off-site). The direct application of a DfMA system to developing countries will be difficult because of differences in the cost of labor, degree of organizational development, and regulatory framework. (Lu et al., 2021; Roxas et al., 2023)

The results of India-specific studies have shown chronic organizational impediments that exist even though the technology for DfMA is feasible. Specifically, limited knowledge about DfMA among Indian organizations, an entrenched culture of RCC use by most engineers and contractors, and a general practice of freezing designs too early to be compatible with DfMA. These study results indicate there is a need to conduct empirical studies into how workflows can be transformed through DfMA, as well as how organizational readiness assessments can be conducted using frameworks that consider the unique realities of emerging economies. (Babanagar & Giriraju, 2024)

2.6.6 Research Implications

The results from this thematic synthesis show that to successfully adopt DfMA, all four levels of a manufacturing organisations systems (i.e. Workflow Transformation, Organisational Readiness, Digital Capability and Environmental Conditions) need to be aligned in order for a successful DfMA process to occur; it cannot simply be driven by the introduction of individual technologies. Interest globally has been shown in DfMA however there is still very little evidence available on how it can be adopted successfully within developing countries such as India. The combination of long-standing RCC-based workflows and organisational structures that exist today along with an economy that supports wages of no greater than approximately ₹800 per day, present many different barriers that are absent in developed economies.

Table 2-3:Detailed Alignment of Literature Review with Research Components

Research Aim	Main RQ	Sub-RQ	Objective	Literature Coverage (Chapter 2)	Expected Output
Examine DfMA adoption in India through workflow transformation, readiness, and barriers + develop practical framework	How can DfMA-enabled project delivery be effectively adopted in Indian construction through organisational workflow transformation and readiness development?		Obj 1: RCC limitations + TOE barriers	2.1 (RCC workflows), 2.3-2.4(global/India adoption), 2.5 (TOE framework)	RCC limitations + India-specific DfMA barriers identified
		RQ1.1: RCC operational	2.1.2 (site-centric issues, labour	Indian RCC constraints mapped	

Research Aim	Main RQ	Sub-RQ	Objective	Literature Coverage (Chapter 2)	Expected Output
		limitations in India	dependency)		
		RQ1.2: DfMA advantages + global-India adoption gap	2.3 (Singapore/UK drivers), 2.4 (PMAY <1% penetration)	Global benchmarks vs India reality	
		RQ1.3: TOE barriers in India	2.5.1-2.5.3 (T-O-E), Table 2-3 (org=45%)	Barriers prioritised by TOE framework	
			Obj 2: Workflow transformation + coordination/digital	2.2 (DfMA systems), 2.6.1 (workflow shift), 2.6.3 (BIM)	RCC → DfMA workflow differences
		RQ2.1: Workflow/process differences RCC & DfMA	2.6.1 (40-70% factory shift, early freeze)	Complete workflow transformation map Site workflow	
		RQ2.2: Organisational transition challenges	2.6.2 (leadership, skills, silos)	Site-centric → manufacturing challenges	
		RQ2.3: Stakeholder perceptions + BIM role	2.6.3 (BIM Level 1 vs 2+), 2.2.4 (digital enablement)	Digital/perception barriers confirmed	

Research Aim	Main RQ	Sub-RQ	Objective	Literature Coverage (Chapter 2)	Expected Output
			Obj 3: DfMA readiness/transition framework	2.6.2-2.6.5 (readiness gaps, India context)	Practical Indian DfMA framework
		RQ3.1: Required organisational capabilities	2.6.2 (leadership, cross-functional skills)	Readiness factors established	
		RQ3.2: Integrate barriers + transformation into framework	2.6.5-2.6.6 (developing market gaps, framework absence)	Structured transition roadmap	

Table 2-3 demonstrates how CHAPTER-2: systematically covers every research question through targeted literature review sections. However, it simultaneously reveals three critical gaps that existing research leaves unanswered - gaps this study directly addresses:

Gap 1: India-Specific RCC-DfMA Workflow Comparison (RQ2.1)

No study systematically maps workflow differences between conventional RCC construction and DfMA delivery in the Indian context, despite workflow transformation being identified as the primary adoption challenge (Section 2.6.1).

Gap 2: Organisational Readiness Assessment Framework (RQ3.1-3.2)

While organisational factors dominate barriers (Table 2-2: Barriers and Drivers Influencing DfMA Adoption (TOE Framework): 45%), no validated readiness assessment framework exists for developing market contractors transitioning to manufacturing-led workflows.

Gap 3: Practical Transition Roadmap (RQ3.2)

Literature lacks actionable implementation guidance tailored to ₹800/day labour economies, where cheap on-site labour eliminates traditional DfMA economic incentives (Figure 2-7: Global variation in DfMA adoption and industrialised construction adoption).

Key Chapter 2 Findings Explaining These Gaps:

- **Workflow discontinuity** prevents late design changes common in RCC (Section 2.6.1)
- **Organisational unreadiness** (45% barrier weight,Table 2-2: Barriers and Drivers Influencing DfMA Adoption (TOE Framework)) blocks technical solutions
- **Digital immaturity** (India BIM Level 1 vs global Level 2+, Table 2-1:Global-India DfMA Adoption Gap Analysis (TOE Perspective)) undermines coordination
- **Economic disincentives** (3% vs 47% penetration, Figure 2-7: Global variation in DfMA adoption and industrialised construction adoption) suppress adoption

These gaps provide the direct foundation for Section 2.7 conceptual framework and Chapter 3 methodology, where TOE variables (Table 2-4: The 7 Things India Needs for DfMA Success) become empirical measures and workflow analysis guides data collection protocols.

2.7 Research Positioning and Conceptual Framework

Building directly on the three critical research gaps identified in Section 2.6.6, this section operationalises the TOE framework to position the study and guide empirical investigation. It identifies key variables (Section 2.7.1), presents the conceptual research model (Section 2.8), and articulates contributions to knowledge.

2.7.1 Identification of Key Variables for DfMA Adoption Framework

Section 2.6 synthesis identified seven critical TOE variables that explain India's 3% DfMA penetration (Figure 2-7: Global variation in DfMA adoption and industrialised construction adoption). Table Table 2-4: The 7 Things India Needs for DfMA Success translates these into practical measurements for **Error! Reference source not found.** surveys.

Table 2-4: The 7 Things India Needs for DfMA Success

What India LACKS	What DfMA Requires	Measurement	Reference
2D drawings + late changes	BIM models factories use directly	BIM Level score	(Widanage & Kim, 2024)
Unique designs per project	Standardised repeating components	% modular design	(Roxas et al., 2023)
Design team works alone	Architects + Factory + Site coordinate	Coordination meetings	(Roxas et al., 2023)
"We'll figure it out" bosses	MD commits budget + timeline	Leadership commitment	(Montazeri et al., 2024)
RCC formwork experts	BIM + factory production training	Staff training hours	(Widanage & Kim, 2024)
No prefab policy push	Govt fast-tracks prefab approvals	Policy awareness	(Lu et al., 2021a)
Factories 500km away	Local suppliers + JIT logistics	Supplier distance	(Roxas et al., 2023)

These variables directly address **Section 2.6.6** gaps: RQ2.1 (Coordination + Standardisation), RQ3.1 (Leadership + Skills + BIM), RQ3.2 (integrated TOE framework).

2.8 Conceptual Framework for DfMA Adoption Research

2.8.1 Framework Development

It can be clearly seen from the literature review provided in sections 2.1 to 2.6, that design for manufacture and assembly (DfMA) in construction is a multifaceted phenomenon and that its use will depend upon technology, organisation and environmental factors. While previous research has used the Technology-organisation-environment (TOE) model to identify how each factor influences the adoption of DfMA, this research extends our knowledge of DfMA by also identifying workflow transformation and organisational readiness as key mediating processes influencing DfMA adoption.

Literature also demonstrates that adopting DfMA is not simply about introducing new technologies but represents a significant paradigmatic change away from traditional site based, sequential reinforced concrete construction (RCC) workflows to manufacturing led project delivery methods that are designed to integrate all project stakeholders.

Therefore, this research conceptualizes DfMA as an outcome resulting from the interaction of TOE factors, with both workflow transformation and organisational readiness acting as intervening variables.

2.8.2 Key Constructs of the Framework

(A) Technological Factors

Technological readiness plays a critical enabling role in DfMA adoption. Key variables include:

- Building Information Modelling (BIM) maturity
- Interoperability between design and manufacturing systems
- Standardisation and modular design capability
- Availability of off-site construction technologies
- Logistics and transportation constraints

These factors determine the feasibility of translating design intent into manufacturable and assembly-ready components.

(B) Organisational Factors

Organisational readiness is identified as the most critical determinant of DfMA adoption. Key variables include:

- Top management commitment
- Workforce skills in BIM and DfMA
- Early collaboration between designers, contractors, and fabricators
- Prior experience in off-site construction
- Resistance to change from traditional RCC practices
- Fragmented organisational structures

Literature consistently identifies organisational barriers as dominant constraints, particularly in developing construction contexts.

(C) Environmental Factors

External conditions significantly influence adoption decisions. These include:

- Government policies and prefabrication mandates
- Supply chain maturity and availability of manufacturing facilities
- Labour market conditions (cost and availability)
- Client procurement practices
- Market demand for faster project delivery

In the Indian context, low labour costs and fragmented supply chains act as major constraints to DfMA implementation.

(D) Mediating Variables

- **1. Organisational Readiness**

Organisational readiness represents the ability of firms to transition towards manufacturing-led construction through capability development, leadership alignment, and process integration.

- **2. Workflow Transformation**

Workflow transformation refers to the shift from:

- Sequential, site-based RCC construction to
- Parallel, design-led, manufacturing-enabled DfMA workflows

This transformation requires early design freeze, integrated planning, and coordination across design, manufacturing, and site execution phases.

(E) Dependent Variable

- DfMA Adoption in Construction Projects

(F) Outcome Variable

- Project performance improvements in terms of:
    - Time reduction

- Quality enhancement
- Material efficiency
- Reduced rework

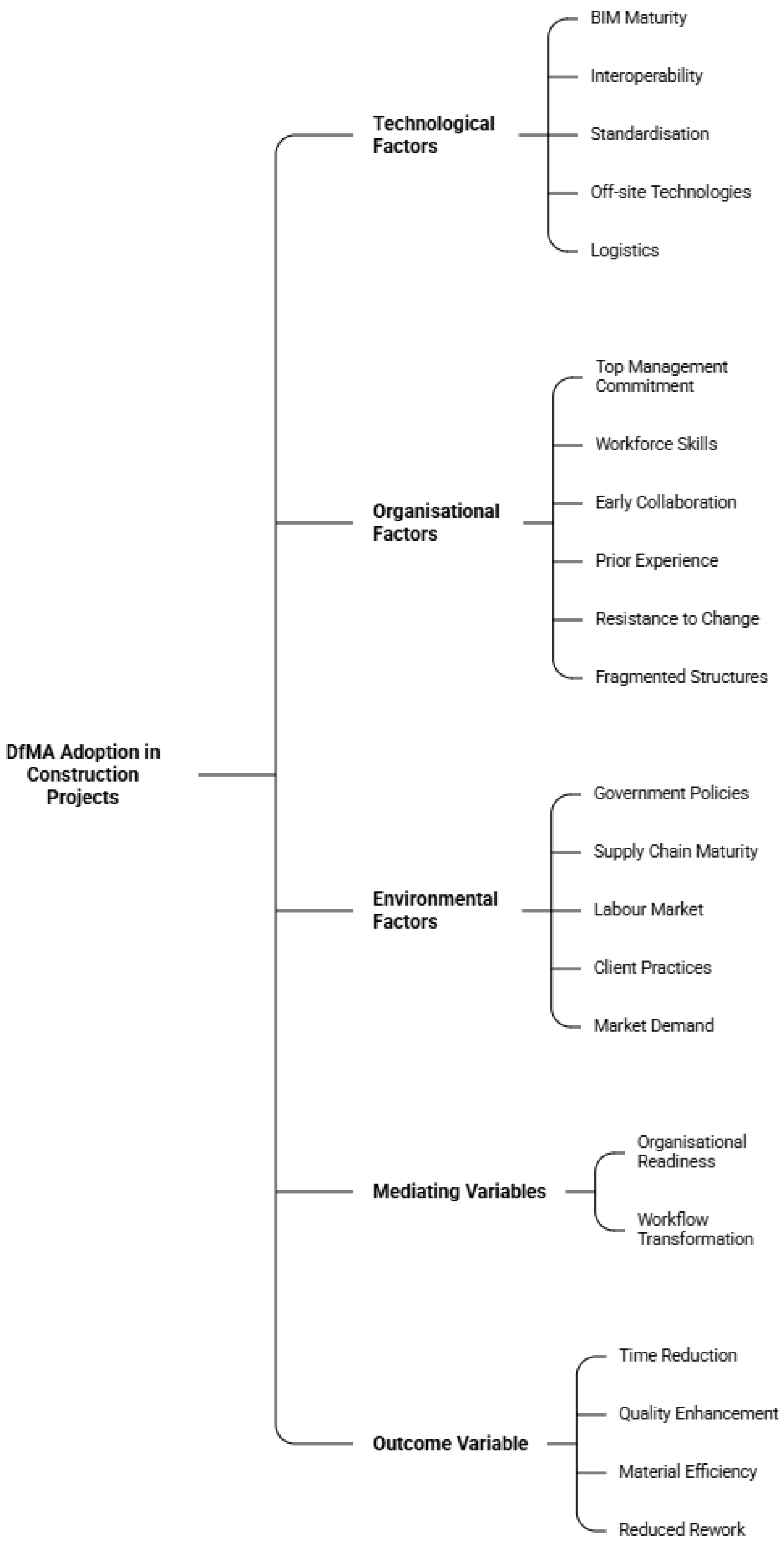

Figure 2-8: Conceptual framework for DfMA adoption in India

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CHAPTER-3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the methodology used in this research study. The conceptual framework shown in Figure 27: Global Variation in DfMA Adoption and Industrialized Construction Adoption was used as an operationalisation of the framework that addresses the following three research questions:

- RQ2.1: What are the differences between RCC (Reinforced Cement Concrete) and DfMA (Design For Manufacture And Assembly) construction workflows in India?
- RQ3.1: What are the influencing factors on the industry's ability to adopt DfMA?
- RQ3.2: How can we develop a practical transition framework?

This study follows a sequential mixed-methods design.

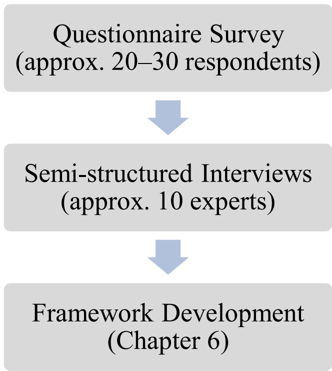


Figure 3-1: Mixed-method approach

The questionnaire provided quantitative insights, while interviews offered deeper understanding. Both were integrated to develop the final framework.

3.2 Research Philosophy

This study used an interpretive philosophical paradigm because the decision to adopt DfMA is based on how different stakeholders perceive it and their organizational behaviors. Different stakeholders have varying perspectives regarding DfMA; for example:

- Architects see the completion of early designs as limiting.
- Contractors are labor-orientated in terms of method.
- Decision makers view high capital expenditure at the outset as a risk.

Therefore, it is crucial to understand these perceptions. The methodology of this study was mixed-methods:

- Quantifying the perceptions via survey data
- Explaining the reasons behind those perceptions through interviews

3.3 Research Design

An exploratory mixed-methods design was adopted due to the limited adoption of DfMA in India and the lack of empirical workflow-based studies.
The research process was structured as follows:

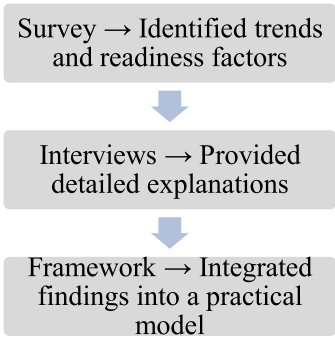


Figure 3-2: Research design process

A mixed-methods approach was adopted to ensure both breadth and depth of analysis. Quantitative data from the questionnaire enabled identification of trends and patterns, while qualitative insights from interviews provided contextual understanding and explanation of underlying factors influencing DfMA adoption.

3.4 Research Approach

The study followed an abductive approach, involving continuous interaction between theory and data.

- Concepts from CHAPTER-2: guided the survey design
- Data collected from the field was analysed
- Findings were used to refine the theoretical framework

This ensured that the final framework was both theoretically grounded and practically relevant.

3.5 Data Sources

Primary Data

- **Questionnaire Survey:**
  Responses were collected from construction professionals
- **Interviews:**

Semi-structured interviews were conducted through face-to-face and telephonic modes

Secondary Data

Secondary data was collected from:

- Existing research studies
- Literature reviewed in CHAPTER-2:

3.6 Research Instruments

3.6.1 Questionnaire Design

The questionnaire was structured into six sections to address different aspects of the research.

Table 3-1: Structure of questionnaire

Section	Focus Area	Purpose
A	Respondent profile	Background information
B	RCC practices	Identification of current issues
C	Workflow transformation	Understanding process differences
D	Organisational readiness	Skills, leadership, coordination
E	Technology and policy	BIM usage and policy support
F	Framework validation	Feedback and suggestions

3.6.2 Question Types

The questionnaire included:

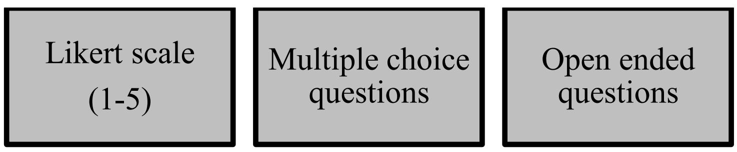


Figure 3-3: Type of questions

3.6.3 TOE Framework Linkage

Dimensions in the questionnaire included:

- Technology: Use of Building Information Modelling (BIM)
- Organisation: Skills, coordination and leadership
- Environment: Support from policy and the general state of the industry

TOE is an appropriate framework to assess the adoption of DfMA through its assessment of technology, organisation and environment. As such it can be used to investigate the need for DfMA as well as the ability to adopt the process with respect to each individual's technical capacity and their ability to transform the organisation that they work in, and the ability to do so against a backdrop of what is happening in the industry.

3.6.4 Interview Method

Semi-structured interviews was conducted to gain deeper insights.
Each interview lasted approximately 45 minutes and covered:

1. Existing RCC workflow
2. Perceptions of DfMA
3. Key challenges identified in the survey
4. Industry readiness gaps
5. Feedback on the proposed framework

3.6.5 Sampling Strategy

A purposive sampling method was used to select participants with relevant experience.

Table 3-2: Sample size of questionnaire survey

Role	Expected Survey Responses	Expected Interviews
Contractors	~10–15	~5–8
Architects	~5–10	~3–6
PM/BIM professionals	~5–10	~3–6

Geographical Scope

- Ahmedabad (face-to-face)
- Other cities in India and abroad (telephonic)
- The sample size, although limited, is considered appropriate for an exploratory study focusing on perception-based analysis. The inclusion of experienced professionals and the integration of qualitative interviews ensure depth and validity of insights despite the small sample size.

3.7 Data Analysis

3.7.1 Quantitative Analysis

Likert scale responses were analyzed using mean score analysis to quantify respondent perceptions. Each response was assigned a numerical value ranging from one (lowest level) to five (highest level of agreement or frequency).

The average scores were determined by the weighted average method based on the frequency of the respective responses and thus allowed for comparison across different variables as well as identification of important factors influencing adoption of DfMA.

Mean scores were also evaluated by predetermined ranges for classification of their degree of importance.

Survey data was analysed using:

- Mean score analysis
- Ranking of factors
- Frequency distribution

Table 3-3: Range for data interpretation

Mean Range	Interpretation
1.0 – 2.0	Low
2.1 – 3.0	Moderate
3.1 – 4.0	High
4.1 – 5.0	Very High

Each research question was addressed using specific data sources and analysis methods, and the findings were systematically integrated to develop the final DfMA transition framework.

3.7.2 Qualitative Analysis

Qualitative data was analysed using thematic analysis, involving:

1. Familiarisation with data
2. Coding
3. Theme development
4. Review of themes
5. Definition of themes
6. Reporting

Both predefined and emerging themes will be considered.

Table 3-4: Qualitative analysis - methods and outcomes

RQ	Data Source	Analysis Method	Expected Output
RQ2.1	Sections B & C + Interviews	Thematic + Mean analysis	Workflow comparison
RQ3.1	Sections D & E	Mean + Ranking	Readiness factors
RQ3.2	Section F + Interviews	Combined analysis	Final framework

3.8 Quality Assurance

To obtain an accurate (reliable) and valid result:

- A pretest (pilot-test) was made
- Content validity was obtained to match CHAPTER-2: LITERATURE REVIEW.
- Triangulation was used as a means for verifying information from several different data-sources.

By combining all three forms of triangulated data—questionnaire responses; interview insights; and literature findings—this will enhance the reliablity of the findings in that they were validated across multiple levels of perspective..

3.9 Ethical Considerations

- Informed consent was obtained from all participants
- Confidentiality was maintained
- Data was stored securely
- Research bias was minimised

3.10 Limitations

- The study was limited to Ahmedabad or else it was telephonic
- Sample size was limited
- Findings was based on participant perceptions
- Advanced technologies such as 3D printing were not included

3.11 Chapter Summary

This chapter outlined the methodology adopted for the study, including research design, data collection methods, and analysis techniques.
The next chapter will present the data collected**.**

CHAPTER-4: DATA COLLECTION

4.1 Introduction

The focus of this chapter is on presenting the data collection methodology used for the study on the use of Design for Manufacture and Assembly (DfMA) in India's construction sector. The aim of collecting data was to collect empirical evidence that would enable an analysis of workflow changes, organizational preparedness and barriers to adoption, which are consistent with the aims of the research project as well as the Technology – Organization – Environment (TOE) model.

The data collection method employed was a mix-methodology approach consisting of questionnaire surveying and semi-structured interviewing. A mix-methodology was chosen because it allows for quantifying trends in addition to providing in-depth insight into how DfMA can be implemented in practice.

4.2 Data collection approach

Data were collected using a mixed-methods (both primary and secondary) approach.

Primary Data:

- Survey questionnaire distributed among construction industry professional respondents
- Semi-structured interview with a selection of these respondents

Secondary Data:

- Literature review of academic studies on DfMA
- Reports from relevant industry sectors
- Government policy reports related to DfMA and in the construction sector.

Both primary and secondary data were integrated into this study to achieve triangulation which added credibility to the conclusions that are drawn from the research results. The two approaches to collecting data were used together because, while there are quantifiable aspects of DfMA adoption by the construction sector, there are also many qualitative, perception-based dimensions associated with the stakeholders involved. Therefore, a mixed-methods approach provided the best way to explore all of those.

4.3 Questionnaire Survey

4.3.1 Design of Questionnaire

The Questionnaire was developed using findings from the Literature Review (CHAPTER-2:) identified Gaps in Research and TOE Framework Dimensions (Technology, Organisation, Environment).

Therefore it was structured to provide direct answers to the Research Questions: **RQ2.1**: What are the differences between RCC and DfMA Workflows? **RQ3.1**: How ready is an organisation to adopt DfMA? **RQ3.2**: How can I develop an Adoption Framework for DfMA? Thus each question contributes significantly to the Analytical Objectives of this Study.

4.3.2 Structure of Questionnaire

The questionnaire was organised into six sections to capture different dimensions of the research:

Table 4-1: Structure of questionnaire

Section	Focus Area	Purpose
A	Respondent Profile	Background and experience
B	RCC Practices	Identification of current workflow issues
C	Workflow Transformation	Comparison of RCC and DfMA processes
D	Organisational Readiness	Skills, coordination, and leadership
E	Digital & Policy Factors	BIM usage and environmental conditions
F	Framework Validation	Feedback on proposed adoption framework

This structured approach ensured systematic data collection aligned with the TOE framework.

4.3.3 Types of Questions

The questionnaires contained all four types of questions; Likert scale to measure the perception and strength of an individual's answers and multiple choice to gather factual and categorical data. Open ended questions were also used to get qualitative feedback from practitioners and to get their personal views.

4.3.4 Pilot Testing

The pilot test of the questionnaire was carried out using a limited number of industry professionals before it was fully rolled-out. The pilot test aimed at:

- Validating that each question is clear
- Validating how relevant the questionnaire is to the current practice in the industry
- Validating whether there are any ambiguous terms or redundancy within the questionnaire. Minor adjustments were made based upon the feedback from respondents so as to make the questionnaire more readable and structured.

The design of the questionnaire allowed for direct input into all of the research questions, since it captured data regarding RCC workflow issues (RQ2.1), an organisation's and a digital environment's state of readiness (RQ3.1) and respondent's comments on potential developments to the framework (RQ3.2

4.4 Sampling and Respondent Profile

4.4.1 Sampling Strategy

A purposeful sampling strategy was used to ensure respondents had appropriate knowledge and/or practical experience with respect to the processes associated with construction work flows; and where possible, some form of exposure to prefabrication or DfMA related practices. This method was suitable due to the study's exploratory nature and the need for information from informed professionals as opposed to a randomly selected population.

4.4.2 Sample Size

The results of this study are based on 24 complete and validated responses. A total of 24 valid respondents provided answers. Although this is a small sample size (and therefore likely to be subject to sampling error), it was felt to be sufficient for all three of the above purposes.

This was because;

a) The nature of an exploratory research design often relies upon a small number of subjects.

b) Perception-based studies can also rely upon small numbers of participants as they tend to focus on specific aspects of perception.

c) Semi-structured interviews can provide additional supplementary qualitative evidence that supports the quantitative findings.

Structured semi-structured interviews were chosen to enable the researcher to explore each respondent's perceptions with some degree of freedom whilst still ensuring consistency in terms of key discussion points. This methodology allowed for the collection of rich descriptive data relating to the current workflows practiced within the organisations studied, the various types of organisational issues experienced by those organisations and potential barriers to technology adoption that may have been difficult to identify using questionnaire methodologies.

4.4.3 Respondent Characteristics

- **Professional Roles**

The respondents' roles included all aspects of the construction life cycle such as:

- Architects and designers
- Construction contractors & project managers
- Professionals who use BIM (Building Information Modeling)
- Site engineers and site supervisors

This was important to ensure that there are various opinions and viewpoints through all of the three main stages of Design, Coordination and Execution.

- **Years of Experience**

Experience varied among participants as they ranged from early career people to those with over ten years of experience. This variety will allow for a combination of Operational views and Strategic views.

- **Project Types**

The respondent's involvement in construction projects varied by type, including:

- Residential
- Commercial
- Infrastructure
- Industrial

This is to ensure that no one Project Type is being addressed exclusively.

4.5 Data Collection Process

The questionnaire was distributed through an online platform (Google form).
Respondents were informed about:

- The purpose of the research
- Voluntary participation
- Confidentiality of responses

Also, in order to encourage a high rate of responses and consistent completion of each survey, the time required to complete it was estimated at no longer than 5-7 minutes.

4.6 Semi-Structured Interviews

In addition to the information collected from the surveys; semi structured interviews were conducted with selected participants.

4.6.1 Purpose of Interviews

- Validate/expand on survey results
- Identify the realities of how people work (workflow)
- Identify real-world, practical issues related to adopting DfMA

4.6.2 Interview Format

- Length: approximately 30-45 min.
- Type: either in person or over telephone
- Questions will be flexible to accommodate respondents' levels of expertise

4.6.3 Key Discussion Areas

- Workflow for RCC Construction
- Respondents' Perceptions of Implementing DfMA
- Readiness of Organization & Barriers
- Use of BIM/Digital Tools

Interviews added a qualitative component that assisted in providing context for the quantitative survey data. Integrating both types of data provided a means to triangulate findings. Trends identified by quantitative methods were verified and additional insight was provided through qualitative information. In addition, combining these two types of data enhanced the validity and depth of the analysis.

4.7 Data Preparation

The data that had been gathered was systemically formatted so it could be analyzed. The questionnaire responses were compiled then coded. The likert scale responses were converted into a numeric value (1-5), for quantitative analysis. Then frequency distributions, and mean scores were calculated to observe trends. The open ended responses, along with the transcript of interviews, were coded and categorized based on common themes, which will allow for qualitative analysis.

Therefore, this systematic approach to preparing the data helped ensure consistency in all subsequent analysis.

4.8 Reliability and Validity

To establish that the data collected in this study are valid (i.e., represent what they appear to be), a number of methods can be used.

In order for the data collected in the study to be considered valid, content validity is required. The researcher established content validity by linking the research questions or objectives to information found in literature reviews.

Additionally, reliability of the response process was also supported in the study. Reliability refers to consistency of results across time and/or people. In this study, reliability was supported through the use of a consistent Likert scale and through pilot testing.

4.9 Ethical Considerations

- This study followed typical ethics guidelines of conducting research (See Section 2):
- All participants gave informed consent
- Participants chose whether or not to participate
- Anonymity of respondents and confidentiality were ensured by the researcher
- Research data were only used for educational purposes

4.10 Summary

The current chapter has provided an overview of the methodologies that were used to collect data for the study. Specifically, this includes the structure of the questionnaire, how the sample was selected, characteristics of respondents and details about the interviews. A total of 24 responses were received from industry personnel representing many different job titles and many different types of projects.

Combining both quantitative data through surveys and qualitative data from interviews will provide a solid base for assessing the transformation of workflows as well as how prepared organisations are for DfMA and what barriers there are to adoption. The detailed assessment of these data is discussed in the next Chapter.

There are some limits to collecting data. The number of participants in the sample is limited, therefore it may not be representative of all stakeholders involved in the Indian construction sector. In addition, participant responses are based on their own perception; therefore, responses can be biased due to subjectivity. However, using multiple perspectives of stakeholders and combining them with qualitative methods enhances the validity of results.

CHAPTER-5: DATA ANALYSIS

5.1 Introduction

This chapter presents the analysis and interpretation of data collected through a structured questionnaire survey and semi-structured interviews conducted among construction professionals. A total of 24 valid responses were obtained, representing stakeholders across design, execution, and coordination roles.

The analysis aims to:

- Examine inefficiencies in conventional RCC construction
- Compare RCC and DfMA workflows
- Assess organisational, technological, and environmental readiness
- Identify key barriers to DfMA adoption

The findings are structured to address:

- RQ2.1: Workflow transformation (RCC vs DfMA)
- RQ3.1: Industry readiness
- RQ3.2: Framework development

5.2 Respondent Profile Analysis

5.2.1 Role in Construction Industry

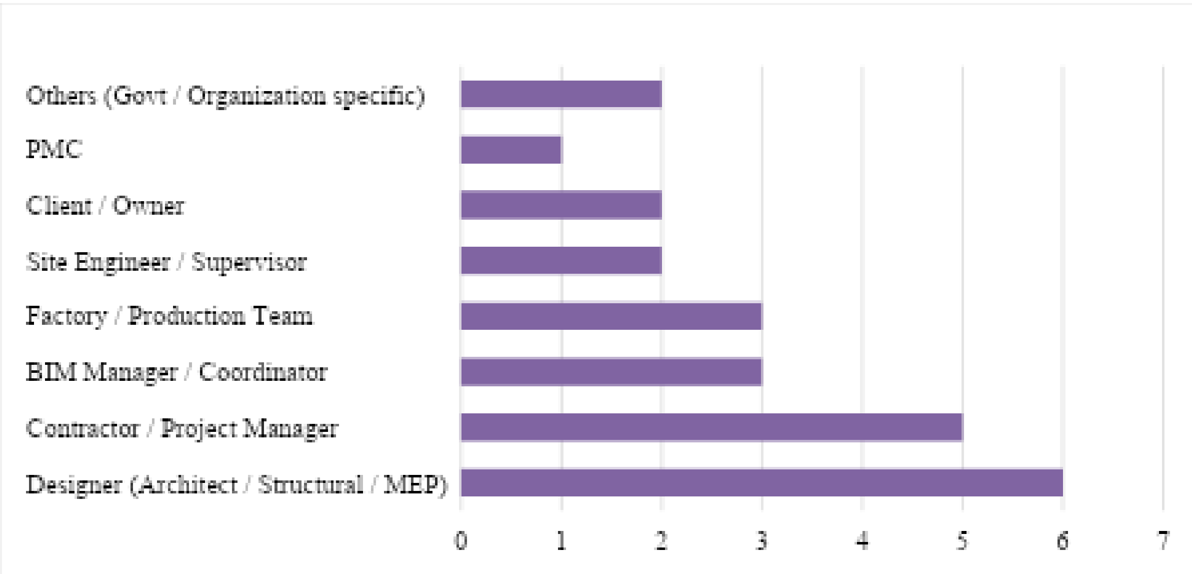


Figure 5-1: Role in Construction Industry

Inference:

The respondent distribution indicates strong representation from designers (25%) and contractors/project managers (20.8%), followed by BIM professionals and prefabrication-related roles.

The dataset is well-balanced across design and execution stages, ensuring that insights reflect critical phases where coordination failures and workflow inefficiencies occur.

5.2.2 Type of Projects

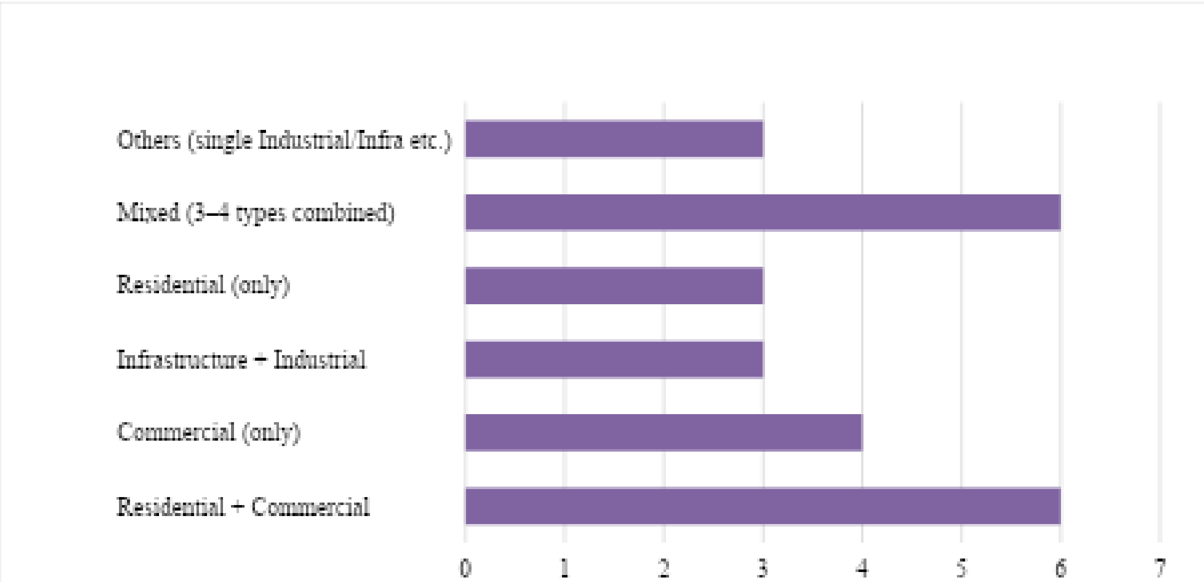


Figure 5-2:Type of Projects

- Commercial (66.7%) – highest
- Residential (58.3%) – significant
- Industrial (37.5%) – moderate
- Infrastructure (29.2%) – lowest

Inference:

The data is heavily skewed towards building sector projects, particularly commercial developments, where tight schedules, stakeholder complexity, and contractual risks are high. Infrastructure-related delay factors (e.g., land acquisition, policy issues) are less represented.

5.2.3 Project Stage Involvement

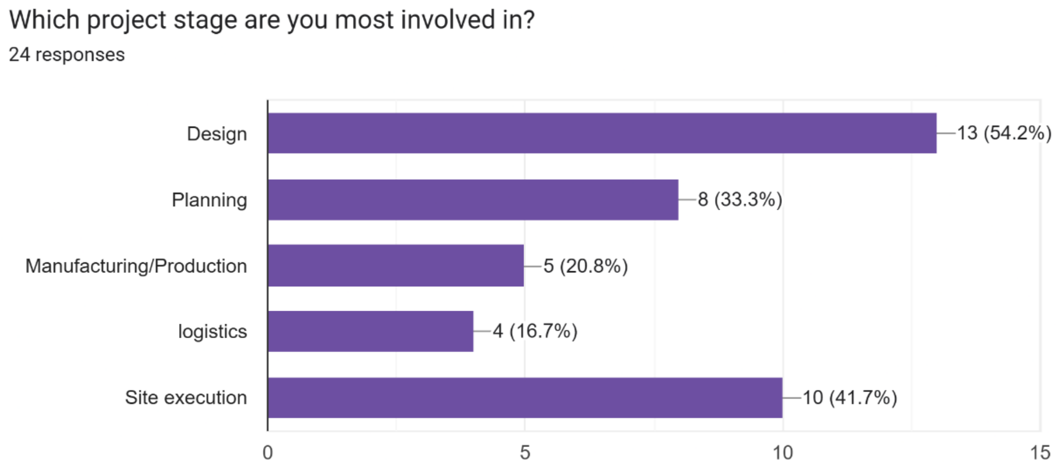


Figure 5-3: Project Stage Involvement

- Design (54.2%) – dominant
- Site execution (41.7%)
- Planning (33.3%)
- Manufacturing (20.8%) and Logistics (16.7%) – lower

Inference:

The responses are concentrated in early-stage (design) and execution phases, which are the most critical for delay generation and dispute escalation. However, DfMA-related supply chain insights are comparatively limited.

5.2.4 Awareness of DfMA

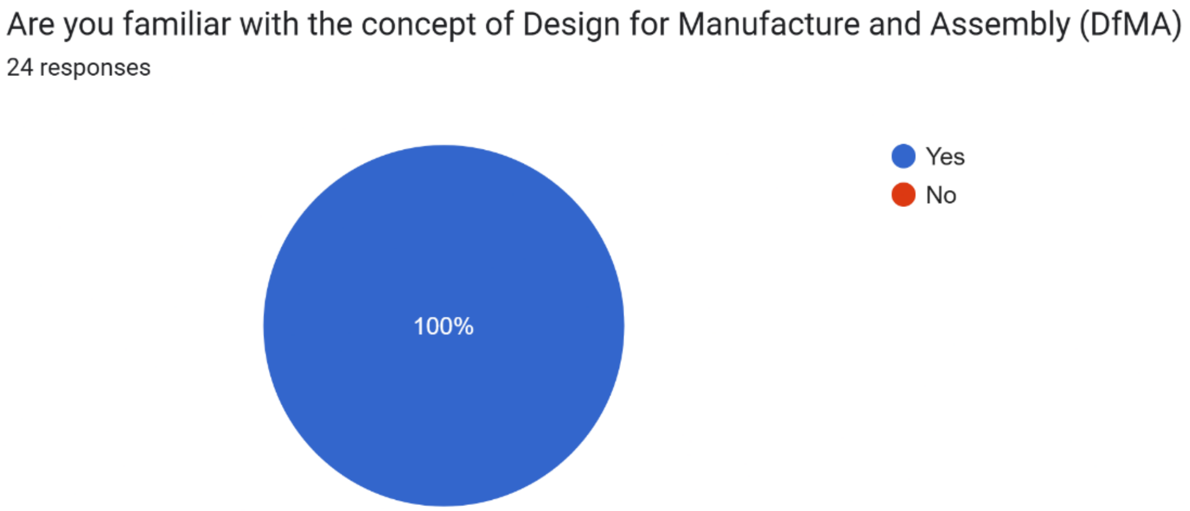


Figure 5-4:Awareness of DfMA

- Awareness of DfMA: 100%
- Mixed experience in prefabrication

Inference:

This indicates a high level of industry awareness, making the dataset reliable for evaluating practical challenges and adoption readiness, rather than basic understanding.

5.2.5 Experience in Prefabrication

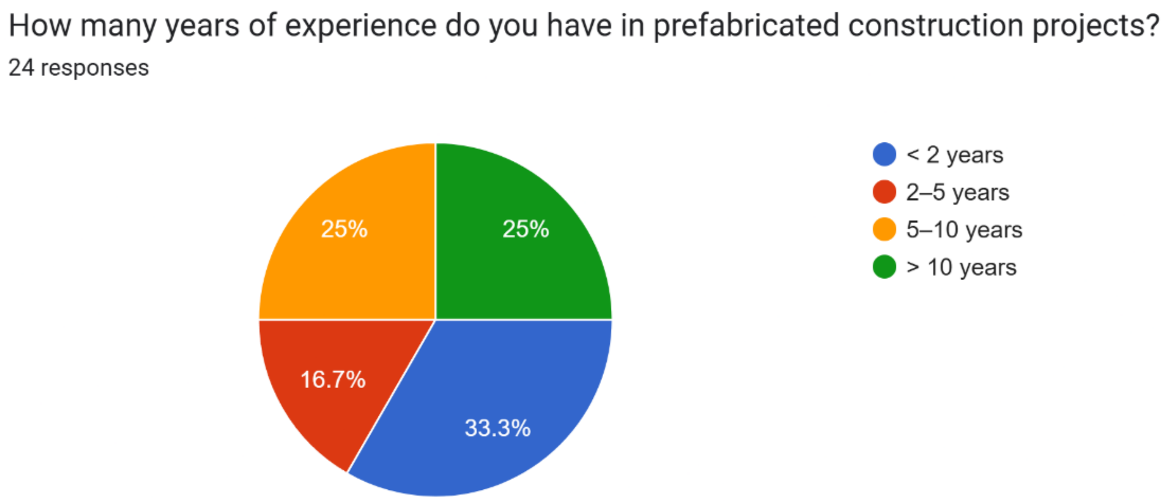


Figure 5-5:Experience in Prefabrication

- Mixed distribution across experience levels
- Majority fall within <5 years and 5–10 years

Inference:

The dataset includes both emerging and moderately experienced professionals, providing a balanced perspective between theoretical awareness and practical exposure.

5.2.6 Prefabrication Systems Used

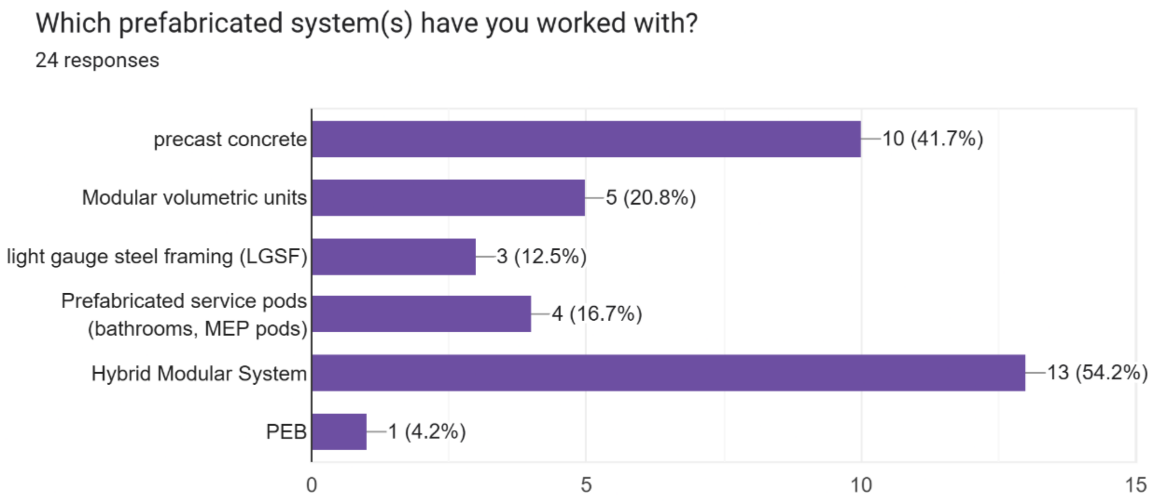


Figure 5-6:Prefabrication systems Used

- Hybrid Modular Systems (54.2%) – highest
- Precast concrete (41.7%)
- Lower use of LGSF, MEP modules, and PEB

Inference:

The dominance of hybrid and precast systems suggests that DfMA adoption in India is still evolving, with preference for partially industrialized approaches rather than fully modular systems.

5.3 RCC Construction Challenges and Delay Analysis

5.3.1 Frequency of Delays in RCC vs DfMA

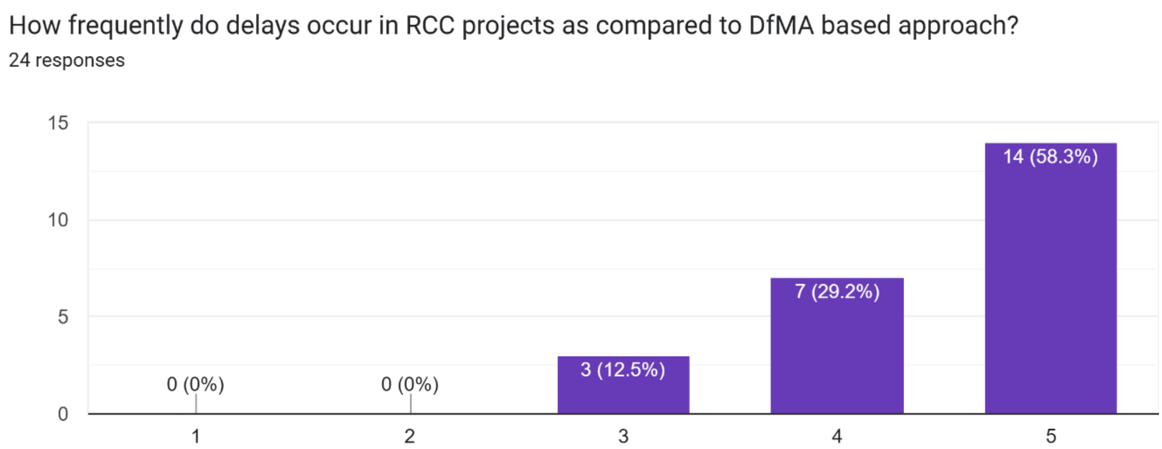


Figure 5-7:Frequency of Delays in RCC vs DfMA

Inference: Mean score = **4.46 (Very High)**

Delays in RCC construction are perceived to be highly frequent. This indicates systemic inefficiencies in traditional workflows and reinforces the need for alternative delivery approaches such as DfMA.

5.3.2 Frequency of Design Changes

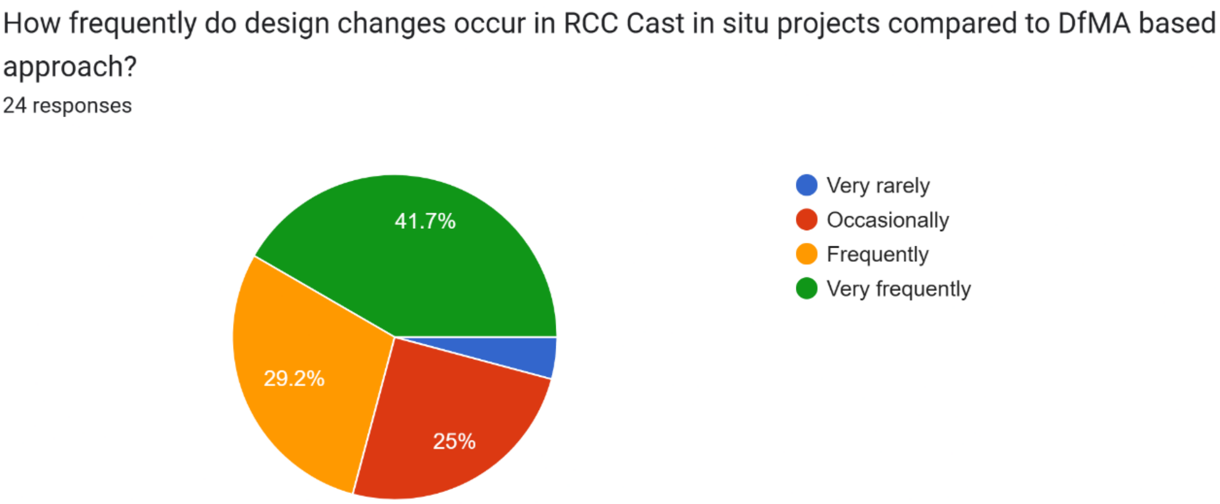


Figure 5-8:Frequency of Design Changes

- Very frequent: 41.7%
- Frequent: 29.2%

Inference:

Estimated mean score ≈ 4.1 (High)

Design changes are very common in RCC projects, indicating lack of early design finalization, which is a major cause of delays and disputes.

5.3.3 Stage of Design Changes

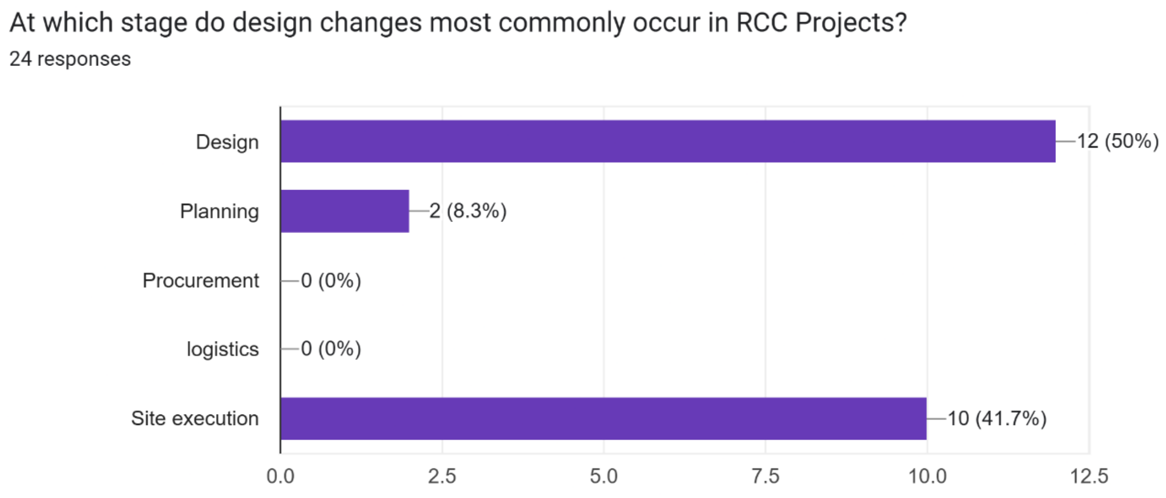


Figure 5-9:Stages of Design Changes

Inference:

- Design stage: 50%
- Execution stage: 41.7%

A significant portion of changes still occur during execution, leading to rework, cost overruns, and contractual conflicts.

5.3.4 Key Challenges in RCC Projects

Factor	% Responses	Rank
Late design changes	87.5%	1
Rework	75%	2
Poor coordination	70.8%	3
Material delays	37.5%	4

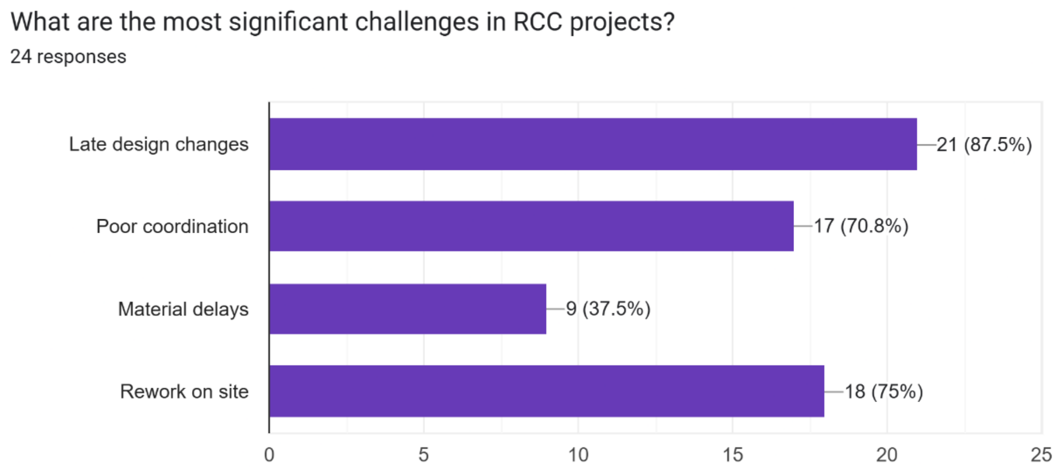


Figure 5-10:Key Challenges in RCC Project

Inference: The ranking indicates that coordination failure and late design decisions are the most critical issues in RCC construction. These factors directly affect project timelines and efficiency.

5.3.5 Qualitative Responses (Major Issues)

From open-ended responses:

Briefly describe one major issue you have faced in RCC projects compared to DfMA Based construction approach?

23 responses

- Lack of coordination
- Delayed approvals
- Rework due to late changes
- Communication gaps

Inference: There is a consistent pattern of systemic inefficiencies, especially:

- Poor stakeholder integration
- Late decision-making
- Fragmented workflows

5.4 DfMA Workflow and Benefits

5.4.1 Importance of Early Design Finalization

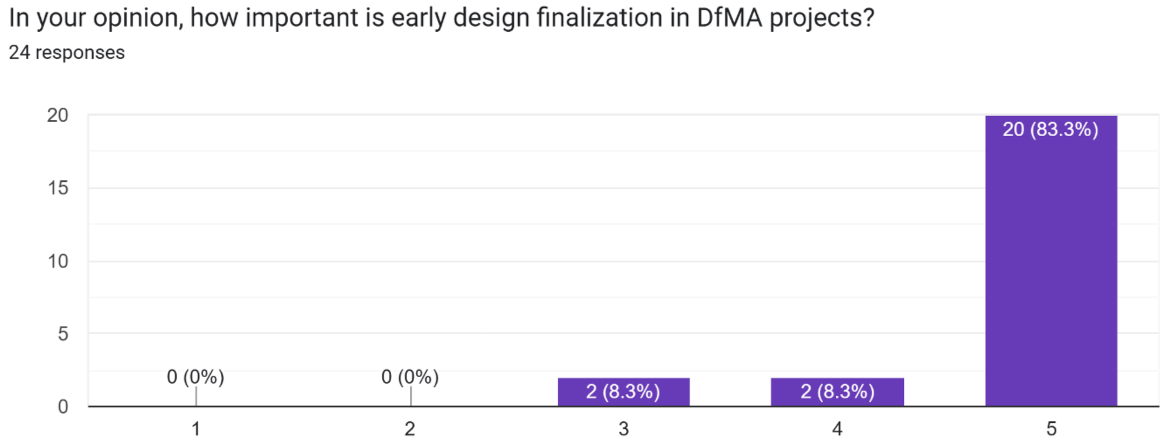


Figure 5-11:Importance of early design finalization

- Mean score (approx.) = 4.3 (Very High)
- 83.3% rated it very high

Inference: Early design finalisation is identified as a critical requirement for DfMA, highlighting a fundamental shift from RCC practices.

5.4.2 Coordination Level in DfMA

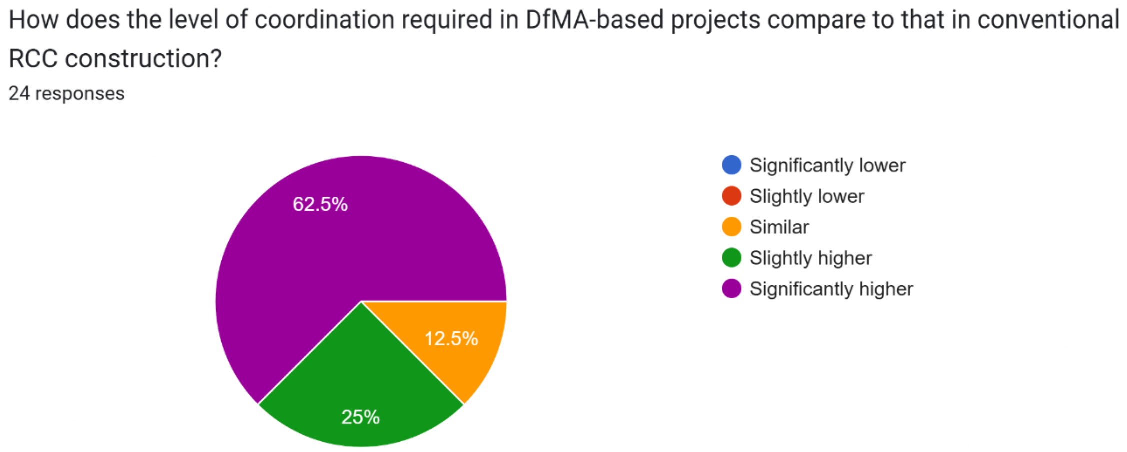


Figure 5-12: Coordination Level in DfMA

Inference:

Mean score (approx.) = 4.2–4.5 (High to Very High)

DfMA requires significantly higher levels of coordination across stakeholders, particularly between design, manufacturing, and execution teams.

5.4.3 Most Critical Stage in DfMA

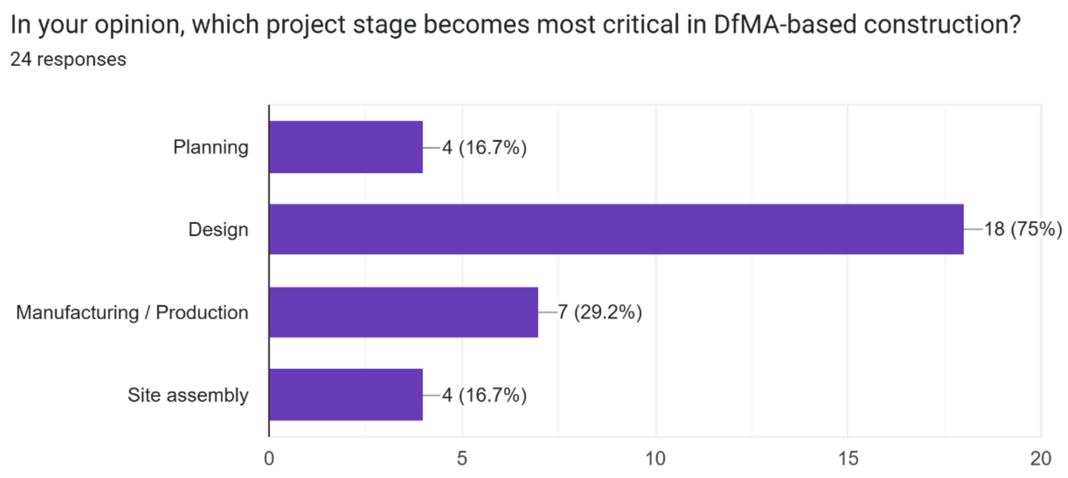


Figure 5-13:Most Critical Stage in DfMA

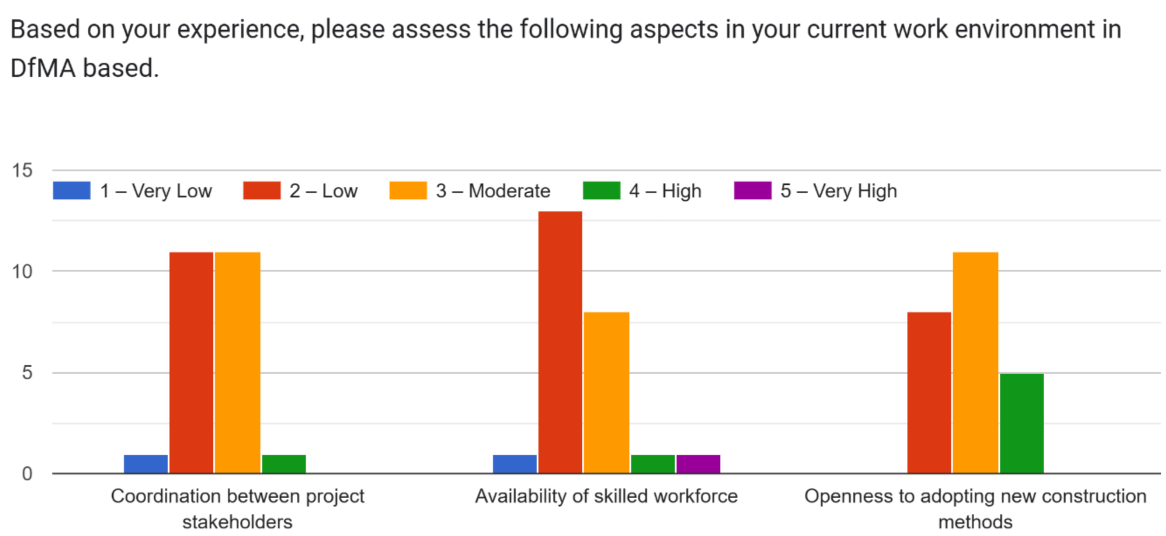
- Design stage identified as most critical
- Design stage (75%)

Inference:

DfMA shifts project risk to the design phase, making it the most critical stage for decision-making and planning.

5.5 Organizational Readiness

5.5.1 Coordination and Workflow Structure



- Mean score (based on coordination issues) ≈ 4.0+ (High)
- Qualitative ranking: High
- Mean perception: Moderate to High gap

Inference:

- Poor coordination indicates significant organisational limitations, which indicate that currently used workflows do not support the needs of DfMA.
- There is strong industry-wide alignment to traditional RCC processes, which provides an obstacle for transitioning to different types of work flows, specifically DfMA.
- Limited experience in using BIM and manufacturing based building processes limit the ability to successfully apply DfMA.

5.5.2 Key Organizational Factors

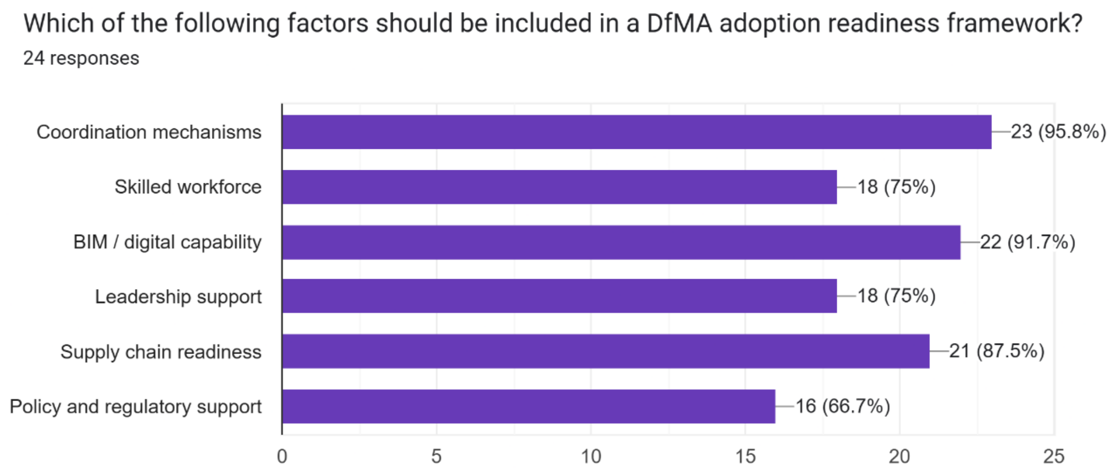


Figure 5-14:Key organizational factors

- Coordination mechanisms (95.8%)
- BIM/digital capability (91.7%)
- Supply chain readiness (87.5%)
- Skilled workforce & leadership (75%)

Inference: DfMA adoption depends heavily on:

- Digital integration (BIM)
- Coordination frameworks

- Supply chain maturity

5.6 Digital Readiness

5.6.1 BIM Usage

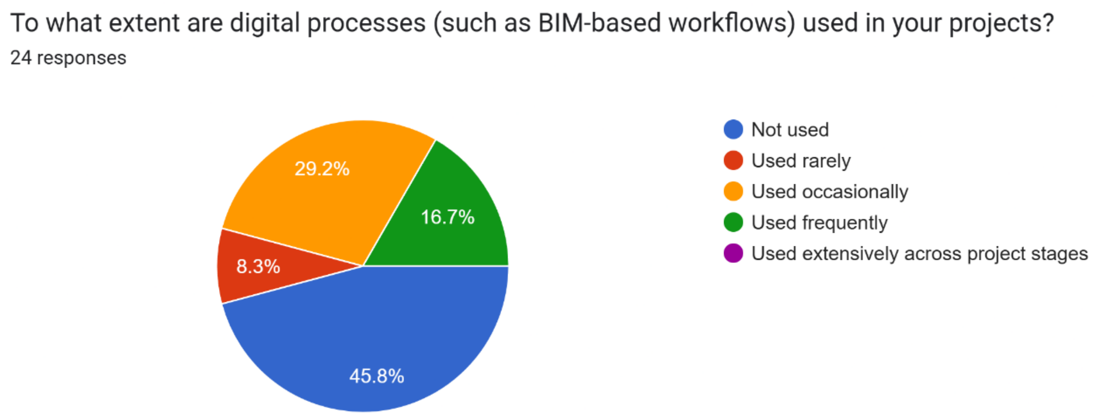


Figure 5-15:BIM Usage

Inference:

Mean score ≈ 3.0–3.5 (Moderate)

Digital adoption exists but is not fully optimized across project lifecycle stages.

5.6.2 Importance of BIM

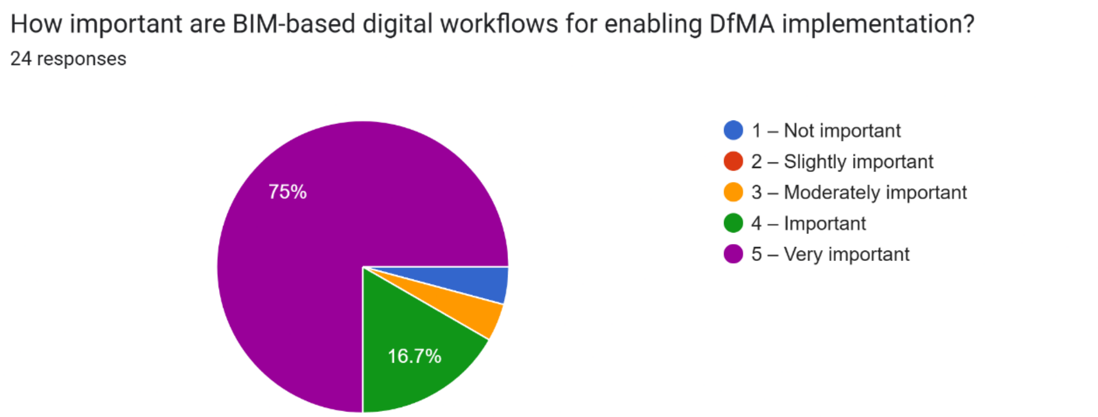


Figure 5-16:Importance of BIM

- 75% rated BIM as very important

Inference: There is strong recognition of BIM as an enabler for DfMA, even if implementation is still developing.

5.6.3 Policy Support

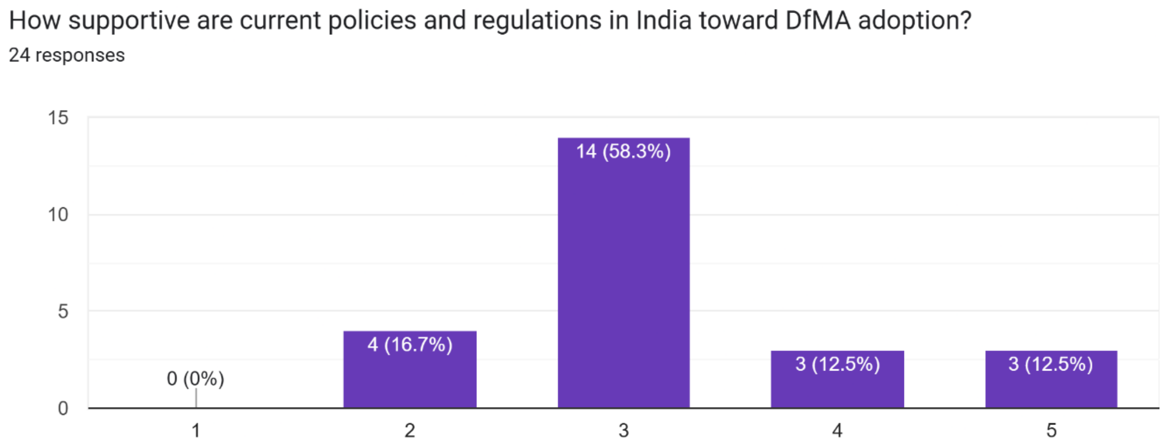


Figure 5-17:Policy Support

Inference:

Mean perception - Low to Moderate

Regulatory frameworks exist but are not strong enough to drive large-scale adoption.

5.6.4 Readiness Level in India

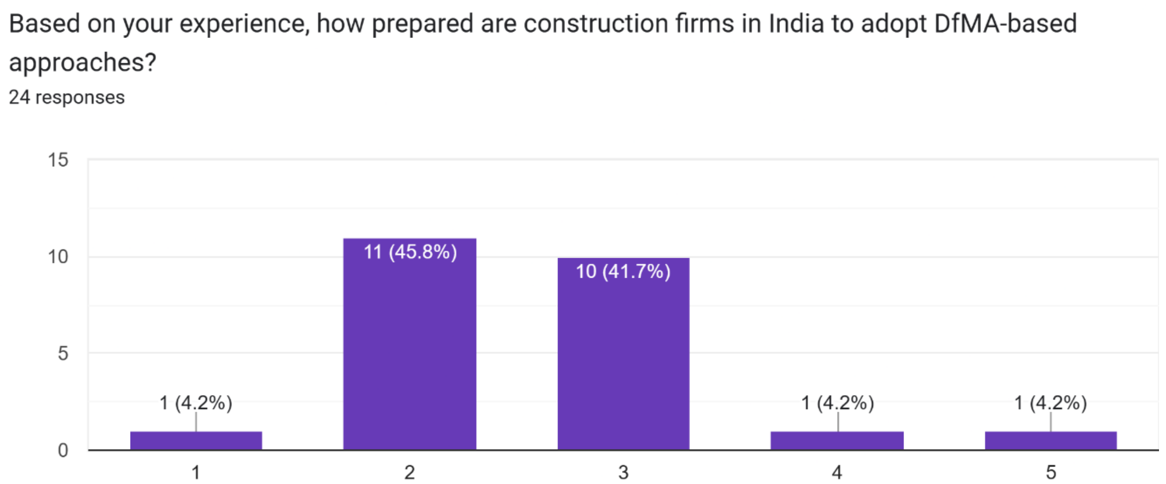


Figure 5-18:Readiness level in India

Inference: The Indian construction industry is in a transitional phase, with partial readiness but lacking full-scale adoption capability.

5.7 Framework Validation

5.7.1 Need for Structured Framework

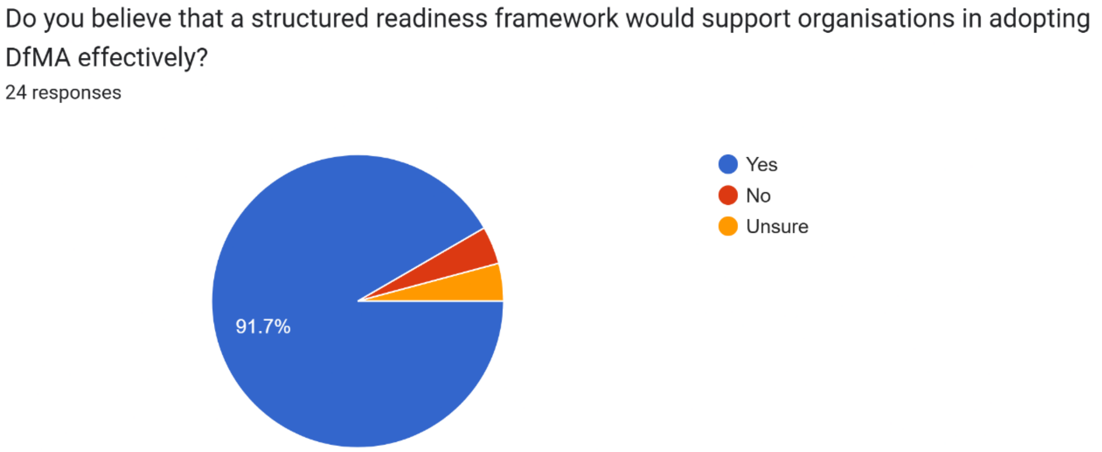


Figure 5-19:Need for Structured framework

Inference:

- 91.7% agreed

There is a strong industry demand for a structured DfMA adoption framework, validating the relevance of this research.

5.8 DfMA Adoption Readiness Assessment (TOE Framework)

In addition to technological availability, the adoption of Design for Manufacture and Assembly (DfMA) in India's construction industry is dependent upon an organisation's and the overall industrial environment's willingness to adopt DfMA. This section analyses the current degree of industry preparedness for adopting DfMA based on empirical data collected through a survey and through interview with experts using the TOE (Technology-Organisation – Environment) Framework.

This analysis has identified key differences between what currently occurs within construction processes and what is required for successful DfMA.

5.8.1 Technological Readiness

The results suggest that while knowledge of DfMA exists at high levels across all respondent groups, the capacity for technological advancement required to implement

DfMA is relatively low. While there are existing uses of Building Information Modelling (BIM) within the survey group, this use has been limited to basic applications such as 3-D modelling. There have also been no reported instances where BIM was utilized for manufacturing level detailing or integrated project coordination.

To achieve DfMA will require an additional layer of digital integration into the design process; namely, the creation of a single model from multiple disciplines using a common data environment; the ability to detect clashes during the design phase; and the opportunity for designers and fabricators to link directly with each other's processes. Currently however, these technologies do not exist, thus illustrating a large gap between awareness of digital technology and actual functionality of digital tools in order to support a successful transition to DfMA.

Additional interview feedback indicated a number of barriers to implementing DfMA in their organization(s); specifically, a lack of interoperability between their CAD systems and manufacturing systems and a general lack of knowledge/understanding of how to use BIM enabled workflows. These represent significant limitations on both the technological and organizational readiness for the transition to DfMA.

5.8.2 Organisational Readiness

The major barrier to DfMA was organisational Readiness. Our survey indicated that there were significant numbers of design amendments (changes), inadequate co-ordination by all stakeholders involved in the process, and substantial amounts of rework during the project delivery phase. All of these are indicative of a fractured and reactive work flow pattern which is typical of traditional RCC building processes.

Conversely, for DfMA it is necessary for design to be completed at an earlier stage than traditionally used; there needs to be good coordination amongst stakeholders; and there must be a commitment to lead and implement this approach by leaders. Unfortunately, our data has identified reluctance to adopt new approaches based upon historical methods; a lack of experience with manufacturing led work flows; and a lack of structured relationships between stakeholders.

Therefore, we can identify a sizeable 'Organisational Readiness Gap', especially in terms of co-ordination practices, skills development and implementing leadership driven change. Siloed work environments have severely constrained the ability to implement DfMA.

5.8.3 Environmental Readiness

Environmental factors affect the opportunity for the adoption of DfMA in addition to those previously identified. It was found that there is little or no Government support through policies; there are many fractured supply chains and there are still strong economic conditions which favor labor intensive construction processes.

It appears from existing examples (such as prefabricated housing under government programs) that while there is some evidence of an attempt to develop this technology at scale, widespread implementation will be difficult to achieve due to lack of standards governing the use of industrialized construction technologies and inadequate capacity within the manufacturing sector to produce these products.

Interview responses indicate that there are significant logistics issues with obtaining reliable suppliers of materials/products for use in industrialized construction. Therefore it can be said that there exists a moderate to high level of environmental un-readiness relative to supporting the adoption of industrialized construction techniques.

5.8.4 Synthesis of Readiness Gaps

The results from this integrated study of all five TOE factors indicate that Indian manufacturing faces barriers to adopting DfMA due to a complex array of related gaps:

- Technological gap: Limited application of BIM and digital capabilities
- Organizational gap (the most significant barrier): A lack of coordination; resistance to change; and an absence of relevant technical skills
- Environmental gap: A lack of strong government support for environmental sustainability; and fragmented supply networks

5.9 Qualitative Insights from Expert Interviews

5.9.1 Introduction

In addition to the data collected from the surveys, an expert interview was also conducted with a DfMA design professional who has experience working on modular high-rise construction projects.

The purpose of conducting this expert interview was to gather additional insight into the practical workflows that exist within DfMA implementation; as well as, industry-wide constraints or limitations associated with DfMA implementation.

This information provides context to the data collected via the surveys.

5.9.2 Key Themes Identified

Theme 1: The Inherent Inefficiencies of Site-Centric RCC Construction

The expert said that traditional RCC construction is built upon a set of inherent limitations:

- It is site-dependent
- It relies heavily on labour
- It can be sequential by its very nature

As such, it inherently has issues with:

- Variance in quality
- Productive inefficiencies
- Dependence on site conditions

Therefore: This conclusion further supports the survey's results for:

- High levels of delay (Average=4.46)
- Frequent need for rework

So, this reinforces the idea that there are systemic, rather than situational problems related to RCC construction

Theme 2: The critical importance of finalizing early designs

- Unlike RCC (where the design develops while the project is being executed), DfMA requires that there be an early "freeze" on the design; constraint-based planning; and incorporation of manufacturing process into the design; Late changes to the design require more time and money.

Inference:

This directly supports:

- The high rate of design change experienced with RCC projects;
- The need for front-loading of plans in DfMA projects;
- A major paradigm shift from one way of working to another

Theme 3: From fragmented to integrated workflows

Requires:

- Coordination of multiple processes simultaneously
- Stakeholders involved early
- Information flowing continuously

Inference:

- Survey results indicate poor coordination by respondents (70.8%)
- Why the need for high level of coordination for successful implementation of DfMA (Mean ≈ 4.3 +)

Theme 4: Production and logistics flexibility

The expert clarified that:

- Production can happen in small areas (eg; 60x60ft)
- Existing ready-mix concrete (RMC) plant can be modified or adapted.
- Systems are flexible.

Inference:

- Contradicting many assumptions about the feasibility of DfMA production because of limited space/logistics.

- Reality: Space/logistic constraints are possible but not insurmountable

Theme 5: Influence of procurement and industry structure

The expert emphasised that DfMA challenges are not technological but organisational; this is reflected by key issues such as:

- Lack of skilled professionals
- resistance to change
- Absence of integrated workflows
- Limited awareness of systems

Inference:

This has been concluded from the surveys findings (coordination, skills, resistance), TOE analysis and confirmed through the identification of an organisation gap as most critical

Theme 6: Influence of Procurement and Industry Structure
Key points:

- L1 procurement discourages innovation
- fragmented industry limits collaboration
- project based nature prevents standardization

Inference:

Shows that the adoption is influenced by constraints at the system level

5.9.3 Integration with Questionnaire Findings

Qualitative research supports and explains the data found in this study:

- RCC has many long delays and much rework because of how it is done at the site.
- Design change occurs often due to lack of completion of designs prior to start of work on them.
- The study confirms that there are workflow problems as indicated by the fragmented nature of all processes used.

- Benefits from DfMA (e.g., efficiency; coordination) were also shown in these results and show that the process was completed with a coordinated effort to achieve integration.

5.10 Integrated Analysis of Findings

Although the level of awareness about technology for DfMA currently exists in India, it has very little impact on how DfMA is applied in actuality. More than anything else, organisational constraints (e.g. poor collaboration; resistance to change; absence of structured workflows) are seen as the greatest obstacle to DfMA adoption.

In addition to these organisational limitations, environmental constraints (i.e. fragmented supply chain structure; uncoordinated procurement processes), which make the creation of a cohesive DfMA ecosystem difficult, also limit DfMA adoption

5.11 Key Challenges in DfMA Adoption (Integrated Analysis)

Based on combined quantitative and qualitative analysis, the major challenges are:

Table 5-1: Key Challenges in DfMA Adoption

Challenge	Type	Severity
Poor coordination	Organisational	Very High
Resistance to change	Organisational	High
Limited BIM capability	Technological	High
Weak policy support	Environmental	Moderate
Fragmented supply chain	Environmental	High

Inference:

Organisational factors emerge as the most critical barriers, followed by technological and environmental constraints.

5.12 Summary of Key Findings

Although the level of awareness about technology for DfMA currently exists in India, it has very little impact on how DfMA is applied in actuality. More than anything else, organisational constraints (e.g. poor collaboration; resistance to change; absence of structured workflows) are seen as the greatest obstacle to DfMA adoption.

In addition to these organisational limitations, environmental constraints (i.e. fragmented supply chain structure; uncoordinated procurement processes), which make the creation of a cohesive DfMA ecosystem difficult, also limit DfMA adoption.

5.12.1 Implications for Framework Development

The DfMA transition framework will be developed based on the readiness gaps found. To fill those gaps, technological enhancements, organizational restructuring and environment supporting mechanisms need to be applied.

Next, this paper develops the theoretical underpinnings from which a practically applicable DfMA transition framework can be proposed to support the transition towards DfMA in the Indian construction industry.

Both the qualitative results supported the quantitative results and both strengthened the validity of the study by means of data triangulation.

CHAPTER-6: WORKFLOW TRANSFORMATION AND FRAMEWORK DEVELOPMENT

6.1 Introduction

This Chapter outlines the data collected from both a Questionnaire Survey and Stakeholder Inputs and provides an Analysis based on the Research Questions/ Objectives of this Study. The Analysis will be presented according to the Three Key Areas:

- Limitations of Conventional RCC Construction and Influencing Factors Using the TOE Framework.
- The Workflow Transformation from RCC to DfMA-Based Delivery
- Organisational Readiness and Framework Development for Adoption of DfMA

6.2 Analysis of RCC-Based Construction and TOE Factors (RQ1)

6.2.1 Limitations of Conventional RCC Construction

Based on Section B of the questionnaire, the traditional cast-in-situ RCC approach has many common problems.

There are many design changes made by owners/construction companies at the time of construction (late stage), which is a sign of poor coordination.

Delays in completing projects as well as an inefficient workflow where each step depends on the previous one and/or site execution delays are two major contributors to low project completion rates.

Also, high rework rates occur because there is no clash checking until it occurs during construction, instead of when designing the building.

The results show that RCC work flows have a "reactive" nature versus a "proactive" nature, where all issues are dealt with once they occur on-site.

6.2.2 Technological Factors Affecting DfMA Adoption

Based on the information from sections C and D in this response, we can identify several areas where there is limited application of Building Information Modelling (BIM) to coordinate and implement design and execution processes digitally. This includes:

- The lack of utilising the full range of BIM capabilities outside of visualization, which indicates an inability to fully utilize a variety of digital coordination tools.

- There is no connection or linkage between the various software systems utilized by designers and construction teams during the project delivery process.
- The absence of standardized digital work flows associated with the production of pre-fabricated components.

This demonstrates that although awareness of BIM's potential applications exist; however the technological aspects of BIM are being applied partially and inconsistently.

6.2.3 Organisational Factors Affecting Adoption

Organisational impediments are likely to be the largest barrier for a successful transition.

- Lack of engagement with stakeholders early on, particularly the manufacturers
- Poor communication among all consultant disciplines (structural; architectural; mechanical, electrical & plumbing)
- Resistant to adoption of newer project management workflows e.g. Design for Manufacture and Assembly (DfMA), etc.
- Skilled professional capacity is limited due to lack of training in BIM and prefabricated construction

6.2.4 Environmental Factors Affecting Adoption

External constraints identified include:

- Fragmented supply chain for prefabricated components
- Lack of standardisation in design and manufacturing practices
- Limited regulatory push or policy support for industrialised construction

6.3 Workflow Transformation: RCC to DfMA (RQ2)

6.3.1 Existing RCC Workflow Characteristics

The conventional RCC workflow, as observed from industry practices and survey inputs, follows a linear and sequential process, where:

- Design stages are completed in isolation
- Coordination occurs at later stages
- Construction begins before full design resolution
- Issues such as clashes and errors are resolved on-site

This leads to inefficiencies such as delays, rework, and cost escalation.

6.3.2 DfMA-Based Workflow with BIM Integration

In contrast, the DfMA-based workflow demonstrates:

- Early integration of stakeholders, including manufacturers
- Use of BIM for coordinated design development
- Continuous feedback between design and manufacturing stages
- Shift from site-based construction to off-site fabrication and on-site assembly

This enables improved coordination, reduced rework, and enhanced efficiency.

6.4 Comparative Workflow Analysis

6.4.1 Conventional RCC-Based Workflow in Indian Construction (Based on real case study)

The majority of construction in india uses cast-in-situ reinforced cement concrete (RCC), and although it's the most commonly used method, it is generally disorganized due to inadequate communication between stakeholders; sequential processes; and few effective methods of coordination.

Because there are little to no formal documentation systems in place within traditional projects, a structured workflow was created from available data from one industry example (a BIM enabled company). Although this is not an entirely traditional RCC process, it will serve as a baseline for understanding how typical stakeholders interact with each other; how they navigate their individual processes; and how they work together in the Indian construction industry.

Workflow Characteristics

There is a linear and sequential nature to the workflow:

- the project starts when the client defines the project brief. After that, the client hires an architect.
- the architect creates conceptual and schematic designs which he/she/they then reviews and approves.
- subsequently, structural, mechanical/electrical/plumbing (MEP), facade consultants and possibly others are hired sequentially after some initial Design has been completed.
- each consultant develops his/her/their own set of drawings independently of other consultants which ultimately creates silo's among disciplines.
- coordination usually takes place much later in the process; i.e., at the detail Design or construction phases.
- the contractors are only brought into the project at the time of the execution phase. Thus, contractors have little opportunity to provide input related to constructability during the Design phase.

Observations and inferences of interest to project managers

In addition to being inefficient; this workflow has many inherent shortcomings:

- fragmentation of stakeholders: consultants (e.g., architects, engineers, etc.) work independently without adequate cooperation with each other at an early stage of the project.
- sequential dependency: each activity depends on obtaining approval and/or completing all Activities preceding it in the sequence. Thus, Activities are delayed.
- late clash detection: conflicts arise late in the Design process. Thus, changes required to resolve these conflicts frequently result in increased costs and/or additional labor.
- repetitive approval Cycles: feedback loops and revisions occur repeatedly throughout the course of the project resulting in wasted resources and decreased productivity.
- delayed contractor input: contractors do not become involved in the Design process until the execution phase. Therefore, contractors' ability to improve the Design relative to constructability and feasibility is severely impaired.
- ineffective communication: a single source of truth does not exist; therefore, stakeholders experience difficulties communicating effectively and coordinating efforts.

Limitations of traditional RCC workflows

Traditionally, RCC workflows reflect a largely reactive and fragmented workflow methodology. Coordination is accomplished through iterative correction as opposed to proactively integrating all aspects of the process. As such, traditionally designed RCC workflows lead to:

- longer project durations
- higher potential for budget overrun
- lower production rates
- superior inter-disciplinary coordination.

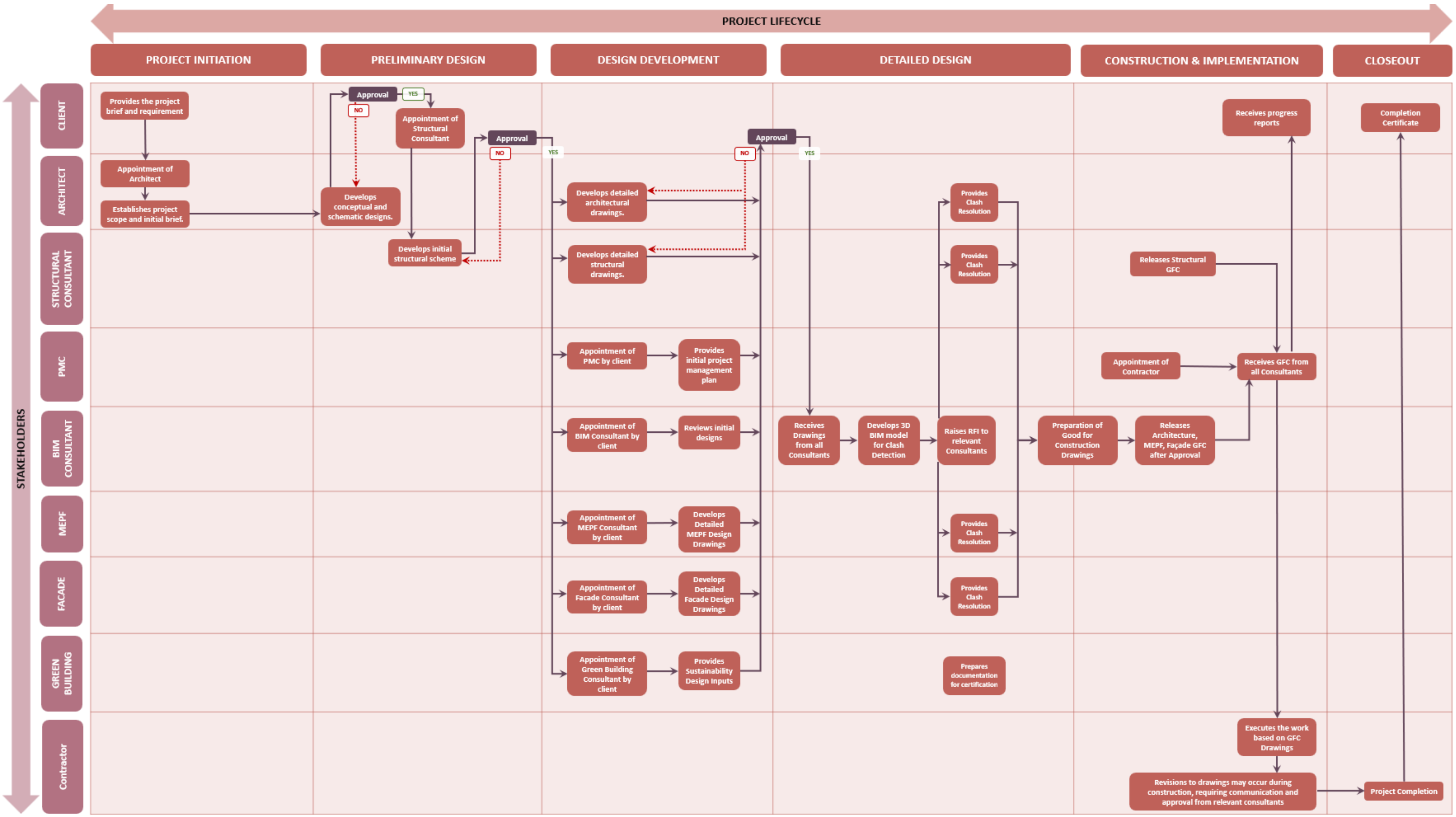


Figure 6-1: Conventional Cast in situ RCC Workflow

6.4.2 BIM-Enabled Integrated Workflow (Based on Industry Practice)

The use of BIM in a digitally enabled construction workflow represents a new form of integrated construction delivery that is being built using the experiences and knowledge of Ashir Engineering Pvt. Ltd., located in Ahmedabad, who have been implementing BIM for project coordination and management.

The use of BIM to develop an integrated construction process represents a transition from the more traditional fragmented forms of practice to a more collaborative and data driven approach to delivering buildings, supported by formalized information exchanges and model-based coordination.

Process Overview

The digitally integrated process begins at the earliest stages of digital planning:

- The PMC and BIM consultants are appointed by the Client.
- The EIR and BEP are produced to establish the project's standards and data needs.
- From the start of the design phases:
- The architect, structural engineer, MEP designer, façade designer, etc. all participate in coordinated meetings.
- The design is progressed through each stage of LOD (typically LOD 300 to LOD 400).
- A federated BIM model is developed through the combination of discipline specific models.
- On a regular basis, clashes and other conflicts are detected and resolved through meetings.

In the execution phases:

- The contractor receives drawings that are both coordinated and conflict free.
- BIM-based coordination and monitoring support the contractor during execution.
- The site activities are better aligned to the design intent due to greater clarity.

At the end of the project:

- The As-Built Models are developed and updated.
- The Digital Data is delivered for FM purposes.

Benefits of BIM Implementation

There are numerous benefits to utilizing a BIM-enabled construction workflow versus the conventional methods:

- Early Stakeholder Participation: Improves coordination among stakeholders; reduces potential design conflicts.
- Clash Detection/Resolution: Allows for the identification of problems prior to the commencement of construction.
- Parallel Activities: Reduces overall project duration by allowing multiple tasks to be performed concurrently.
- Better Design Quality: Higher levels of detail within models result in higher quality designs.
- Less Retrospective Work: Results in less costly corrections on-site.
- Facilitates Centralized Data Management: Enhances communication and transparency among stakeholders.
- Improves Decision Making: Provides decision-makers with visual representation and data rich information to make informed decisions.

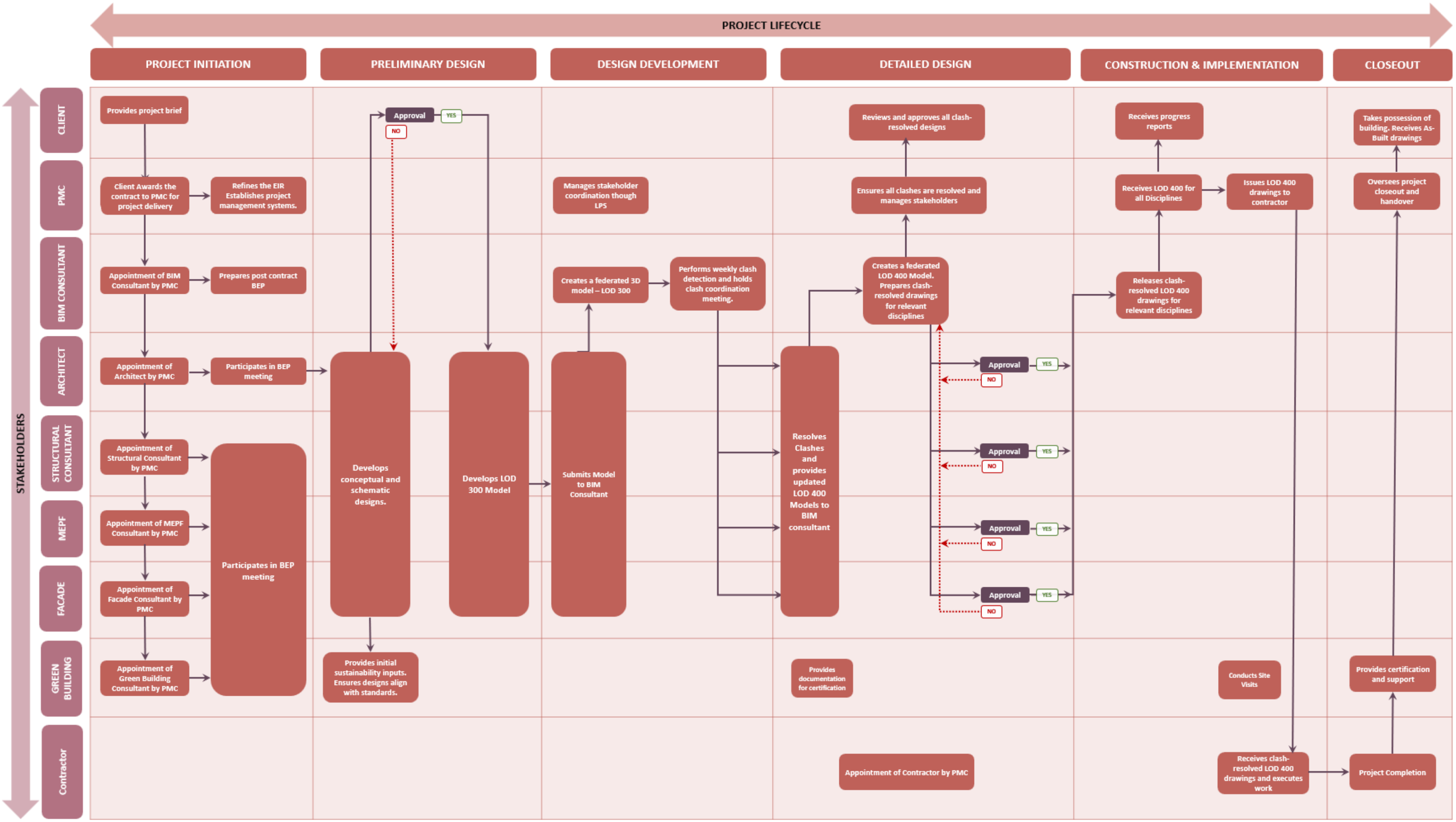


Figure 6-2: Conventional RCC workflow using BIM

6.5 DfMA Workflow Enabled by BIM

6.5.1 Project Initiation

The process of creating a project begins with the definition of a Project Brief and Objectives, where the Client will define the project's Scope, Performance Requirements and Overall Expectations for the project. In contrast to typical processes, DfMA encourages an earlier engagement of the principal stakeholders, primarily including manufacturers and contractors.

During this phase of work:

- Fabrication capabilities inform Design Decision Making due to the inclusion of Manufacturers at an Early Stage in the Process.
- The Employer's Information Requirements (EIR) will be created to determine the Digital Information Needs of the Employer.
- A BIM Execution Plan (BEP) will be developed as a guide for Data Management, Collaboration and Model Development.

Significance of DfMA:

The purpose of this phase is to move away from a Design Led Approach towards a Manufacturing Led Approach in terms of decision making right from the start.

6.5.2 DfMA Concept Design (Early Integration)

The purpose of this phase is to develop a conceptual design which takes into consideration manufacturing and assembly needs by bringing together key stakeholders at an early time.

Some Key Activities Include:

- Manufacturer and supply chain input regarding materials, production techniques and logistical restrictions related to the manufacture and delivery of products.
- Lifecycle performance and buildability.

1. Module Definition and Design Freeze

The building is broken down into standardised modules or components (e.g. walls, floors etc.), their geometric form and sizes are established early in the design development process. This has advantages such as:

- Ensuring compatibility with factory production processes
- Reduction in design variations later

2. **Standardisation/Prefabrication Potential**

Modules/components are assessed for their repetition/prefabrication opportunities allowing for large-scale manufactured production.

Importance of DfMA:

The goal of this phase is to transition from a design perspective to a product based perspective, i.e., structures will be designed as assemblies of manufactured components.

6.5.3 Integrated Design Development (DfMA Development)

In this stage, the concept design is refined into a detailed, fabrication-ready design, integrating both design and manufacturing considerations.

1. **DfMA Coordination**

   Design coordination is performed with a focus on:

- Buildability
- Assembly sequence
- Installation feasibility

   Unlike traditional workflows, this goes beyond clash detection to ensure that components can be efficiently manufactured and assembled.

2. **Tolerance and Connection Detailing**

   Precise detailing of joints, tolerances, and connections is carried out to ensure:

- Proper fit during assembly
- Minimal on-site adjustments

3. **BIM-Based Coordination and Clash Detection**

   BIM is used as a digital coordination tool to:

- Detect design conflicts
- Maintain consistency across disciplines
- Enable real-time collaboration

DfMA significance:

Design is no longer isolated; it is continuously validated against manufacturing and assembly requirements.

6.5.4 Off-Site Manufacturing (Factory Production)

This stage represents the core of the DfMA approach, where construction activities are shifted from site to factory.

1. **Design for Transport Constraints**

Designs are evaluated and adjusted based on:

- Transportation limits (size, weight)
- Route constraints

2. **Shop Drawings and Bill of Materials (BOM)**

Detailed fabrication drawings and material specifications are generated to support production.

3. **Component Production**

Building components are manufactCured in a controlled factory environment, ensuring:

- Precision
- Reduced variability

4. **Quality Control and Inspection**

Factory-based quality checks are conducted to ensure components meet required standards before dispatch.

5. **Pre-Assembly / Trial Assembly**

Components are partially or fully assembled in the factory to:

- Verify fit and alignment
- Identify issues before site installation

6. **Factory Production Planning**

Production schedules are developed to align manufacturing with delivery and assembly requirements.

DfMA significance:

This stage enables industrialized construction, improving quality, reducing waste, and minimizing site dependency.

6.5.5 Logistics and Supply Chain Integration

This stage ensures that manufactured components are delivered efficiently and in alignment with assembly requirements.

1. **Assembly Sequencing Logic**

The sequence of assembly is defined to determine:

- Installation order
- Interdependencies between components

2. **Delivery Planning and Scheduling**

Transportation and delivery schedules are aligned with the assembly sequence.

3. **Just-in-Time (JIT) Logistics**

Components are delivered:

- At the right time
- In the right quantity
- In the correct sequence

This minimizes:

- Storage requirements
- Material handling
- Site congestion

DfMA significance:

Logistics becomes assembly-driven rather than supply-driven, ensuring seamless project execution.

6.5.6 On-Site Assembly (Not Construction)

In the final stage, prefabricated components are transported to the site and assembled.

Key activities include:

- Installation of prefabricated components
- BIM-based site coordination
- Use of 4D BIM for progress tracking and scheduling

Simultaneously, site preparation activities such as foundations and services are carried out in parallel with off-site manufacturing.

DfMA significance:

Construction is replaced by assembly, significantly reducing time, labor dependency, and on-site risks.

6.5.7 Feedback Loops and Continuous Improvement

The workflow incorporates continuous feedback mechanisms:

- Design feedback loop: Manufacturing constraints inform design adjustments
- Assembly feedback loop: Site experiences improve future planning and sequencing

This ensures:

- Continuous optimization
- Reduced errors
- Improved efficiency

6.5.8 Key Outcomes of the DfMA Workflow

With BIM supporting the application of DfMA, there is also:

- Faster development and execution
- Greater product quality
- Less waste of materials
- Safer working conditions
- Lower costs

This new DfMA workflow made possible through the use of BIM shifts the focus for construction away from a process that has been traditionally driven by construction as a craft-based activity towards one that is based on design and manufacture and incorporates all elements of the value chain into a single seamless process..

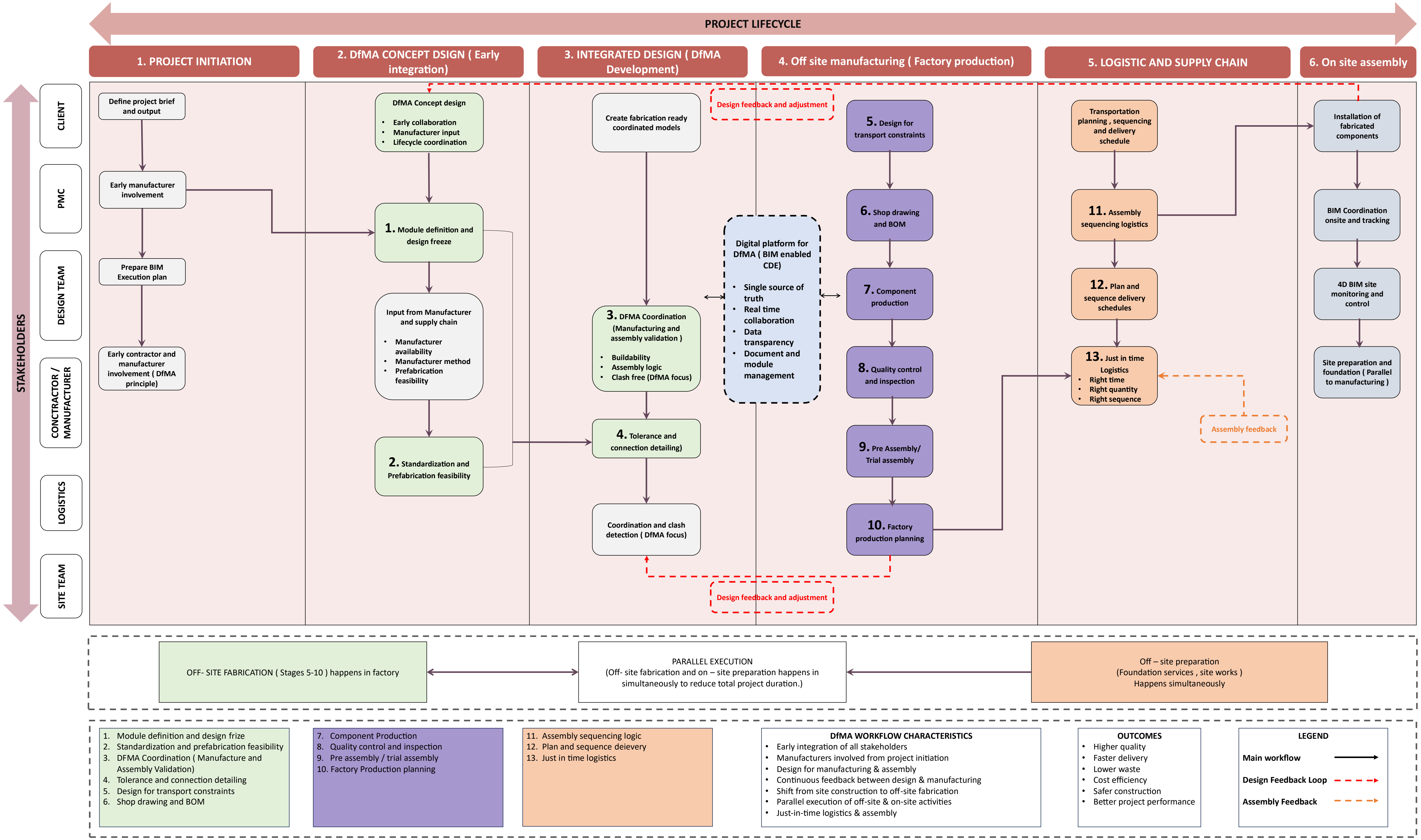


Figure 6-3: DfMA-Based Workflow with BIM Integration

6.5.9 Key Differences in Workflow

The comparison highlights:

- RCC is sequential, DfMA is integrated and iterative
- RCC coordination is reactive, DfMA is proactive (via BIM)
- RCC depends on site execution, DfMA relies on manufacturing + assembly
- RCC involves late decision-making, DfMA requires early design finalisation

6.6 DfMA Adoption Transition Framework

Based upon the findings related to Workflow Transformation (RQ2.1) and Readiness Gaps (RQ3.1) for the adoption of DfMA into the Indian Construction Industry; this research proposes an organised transition framework for DfMA adoption that will support organisations to adopt manufacturing led DfMA enabled Project Delivery by moving them through a systematic process from traditional Site Centric Construction Practices.

6.6.1 Framework Rationale

It was found that an array of technological, organisational and environmental factors act as barriers for adopting Design For Manufacture And Assembly (DfMA) in manufacturing organisations. As such, there needs to be a holistic, phased strategy to allow for effective and successful implementation.

The integrated framework includes:

- The need to transform existing workflow processes
- Organisation Readiness Factors
- Industry Constraints And Practical Considerations

6.6.2 Framework Structure

The framework is structured into four key stages:

Stage 1: readiness assessment

In this first stage, the organization will use the TOE model to assess its existing capacity in each dimension:

- Bim maturity and digital tools
- Coordination practices and level of skills required by the team members
- Level of external support and condition of the supply chain

At the end of this stage, organizations should have identified all the specific "readiness" gaps they need to address prior to implementing the new methodology.

Stage 2: strategic planning

Following identification of these gaps, organizations will create a transition plan as follows:

- Choice of DfMA systems (precassembled, modular or hybrid)
- Project delivery method definition
- Stakeholders' alignment for early collaboration

This second stage is to ensure that the projects objectives are aligned with those of the DfMA.

Stage 3: implementation and integration of DfMA

This third stage has two main goals, namely to integrate bim into operations and to implement DfMA through:

- Design coordination using bim
- Finalization of design at an early stage and standardization of it
- Manufacturing integration, logistics and site assembly

In this stage there is also a focus on moving away from sequential work flows toward both parallel and integrated work flows.

Stage 4: Monitoring and continuous improvement

The fourth and final phase of the process has three principal activities as follows:

- Monitoring of project Performance;
- Refining of processes based on feedback received from stakeholders;
- Development of continuous skills acquisition and process optimization;

Thus, the last stage is to ensure the long term sustainablity of the adoption of DfMA.

6.6.3 Gap–Strategy Alignment

The proposed framework addresses all of the readiness gaps as follows:

- Technological gaps → BIM technology and digital skills will be integrated into construction activities
- Organizational gaps → a new coordination structure (a project management office), appropriate education and training for stakeholders, and support from leadership to implement the changes
- Environmental gaps → strengthen supply chains through collaboration with suppliers on sustainable practices and aligning company policies to environmental regulations

This is critical because it means the framework has the potential to provide solutions that are both applicable in practice and relevant to local contexts.

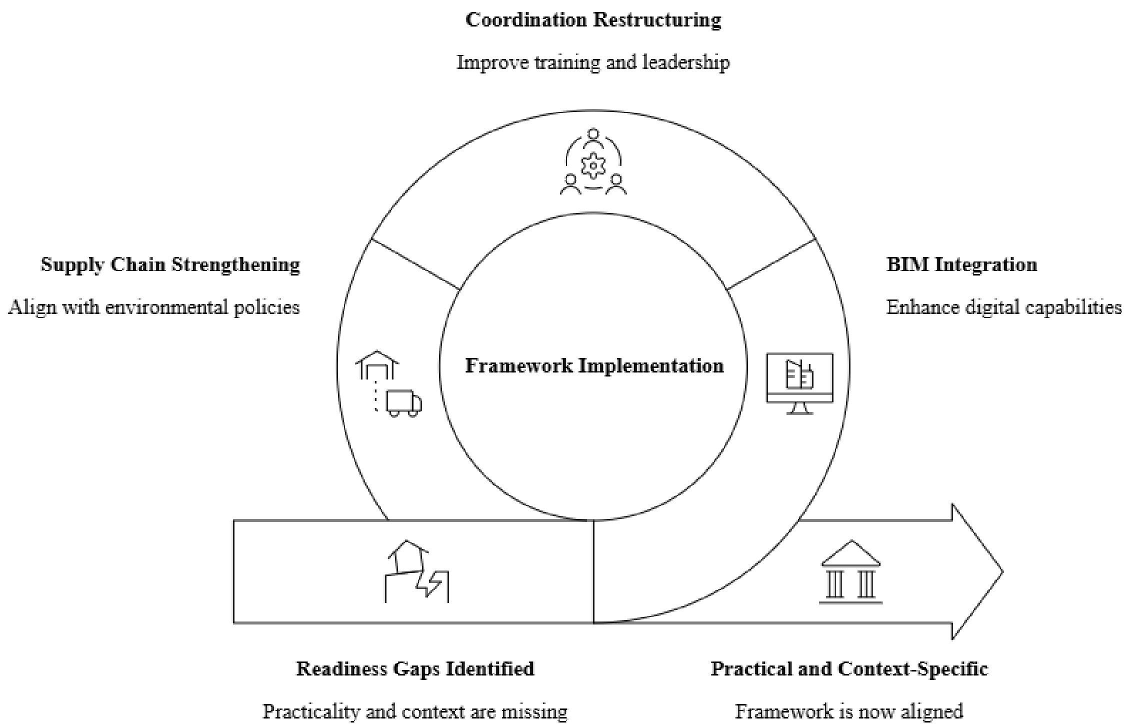


Figure 6-4:Bridging Readiness Gaps for Success

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6.6.4 Framework Outcome

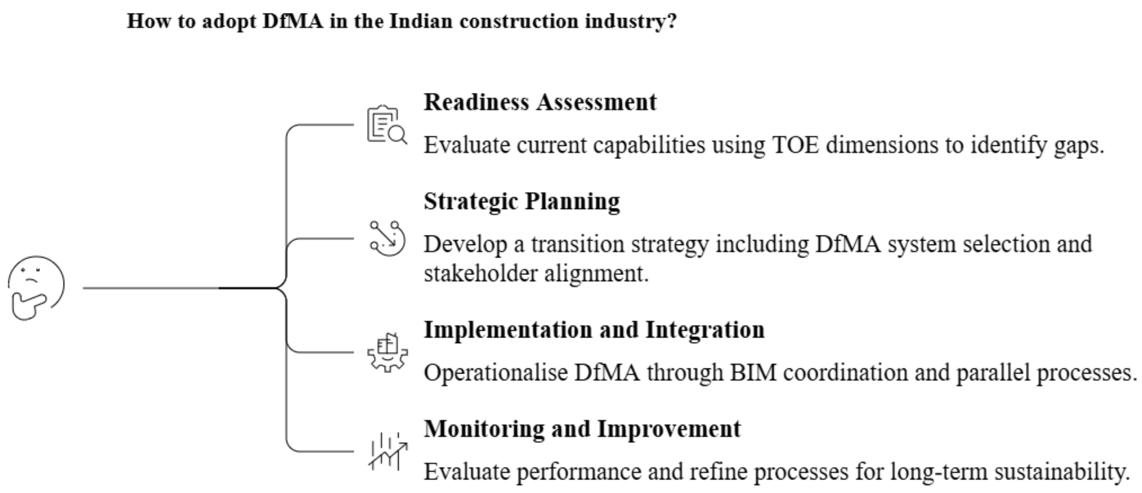

Figure 6-5:DfMA Adoption transition framework

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The proposed framework provides a structured roadmap for organisations to transition towards DfMA adoption. It enables:

- Improved coordination and workflow efficiency
- Reduced delays and rework
- Enhanced quality and productivity

Ultimately, the framework supports the transformation of the Indian construction industry from labour-intensive practices to more industrialised and digitally enabled project delivery systems.

CHAPTER-7: CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

This research investigated the adoption of Design for Manufacturing and Assembly (DfMA), within the Indian Construction Industry; focusing on Workflow Transformation, Organisational Readiness and Adoption Barriers. The research was directed by the Aims, Research Question and Objectives provided in Chapter One. Additionally the research addressed the research gaps identified during the Literature Review; specifically the lack of an India-specific understanding of RCC-to-DfMA Workflow Transformation, the lack of a Structured Readiness Framework and the requirement for a Practical Transition Roadmap for Construction Organisations.

The Findings indicate that while Cast-In-Situ RCC Construction remains predominant in India, it is becoming increasingly constrained by sequential site based execution, Labour Dependency, Quality Variability and Coordinating Difficulties. These constraints identified in Chapter Two; Section 2.1 and Section 2.1.2 were reinforced by empirical evidence in Chapter Five; Section 5.3 and Section 5.11. Conversely, DfMA provides benefits in project environments where Speed, Consistency, Coordination and Repeatability are critical. However, the Study indicates that the current level of DfMA adoption within India is low and fragmented due to the fact that the Industry operates under traditional Delivery Practices rather than those associated with Manufacturing Led Workflows.

Utilising the Technology – Organisation – Environment (TOE) framework outlined in Chapter One; Section 1.9 and expanded upon in Chapter Two; Section 2.5, the Study has identified that Organisational Factors represent the largest barrier to DfMA adoption. These include Poor Integration of Workflows, Limited Capability in terms of BIM, Resistance to Change, Limited Leadership Commitment and poor Communication amongst Stakeholders. Technological Factors including BIM Maturity and Interoperability and Environmental Factors including Disjointed Supply Chains and Weak Policy Support contribute to the Pace and Feasibility of adoption. The Study's findings therefore answer the First Objective of the Study and provide some explanation for why Global DfMA Drivers have had limited impact in translating their influence into India.

Furthermore the Study demonstrates that transitioning from RCC to DfMA represents a wider transformation in Project Delivery Logic rather than merely being a change in construction method. This is discussed in detail in Chapter Two; Section 2.6.1 and illustrated by the Workflow Analysis undertaken in Chapter Five; Sections 5.4 and 5.10. To achieve DfMA Early Finalisation of Design, Integrated Coordination, Off-Site Manufacture and Planned On-Site Assembly are required. This is significantly different from RCC Workflows whereby Design Changes can be accommodated later in Execution. Therefore, the Study has shown that this change in Workflow is fundamental to implementing DfMA and this is reflected in the Second Objective of the Study.

Another key contribution of this Study is the Development of a DfMA Adoption Readiness and Transition Framework which is presented in Chapter Six. This framework integrates technological, organisational and environmental factors into a practical pathway for Assessing Preparedness and Guiding Transition. The framework answers the Third

Objective of the Study and directly responds to one of the Research Gaps identified regarding the Lack of a Practical Adoption Roadmap for Indian Construction Organisations.

In summary the Study concludes that DfMA Adoption in India will depend less on Technology Alone and More on Organisational Readiness, Workflow Redesign and Ecosystem Support. The Study has shown that achieving a Successful Transition from RCC to DfMA will require Early Coordination, Stronger Leadership, Information Enabled through BIM Integration and Supporting Conditions within Supply Chain and Policy Domains. In Summary this Study Provides both an Analytical Understanding of the Barriers to Adopting DfMA in India and a Practical Framework for Implementing it Within the Indian Context.

7.2 Future Scope

Although the current study has provided a systematic framework of DfMA (Design for Manufacture & Assembly) in India; however, due to an explorative nature of the research there are numerous avenues of potential future research. As mentioned in Chapter 1: Section 1.13, the study did not have a detailed structural analysis of engineered structures, thorough cost-benefit models of DfMA or extensive comparison of materials used in the manufacturing processes. Therefore, a need for additional technical and economic research studies exist in future work.

Future studies can extend the study by increasing the sample size to include more diverse group of stakeholders from various geographical locations and project type. Due to the fact that this study was primarily based on a small amount of surveys and semi-structured interview with a small number of participants, future studies using a large-scale empirical study will allow researchers to verify the Readiness and Transition Framework proposed within this research and increase the generalizability of the Readiness and Transition Framework. In addition to providing the empirical validation of the Readiness and Transition Framework and generalizing the framework, the research can focus on expanding upon the Exploratory Design as discussed in Chapter 3: and the Data Collection Approach as outlined in Chapter 4:.

In addition to extending the study through increased sample size and diversity of stakeholders; future studies can conduct comparative studies examining differences between RCC (Reinforced Concrete Construction) and DfMA (Design for Manufacturing and Assembly) concerning cost, productiveness, time performance, quality outcome, and life cycle value. While the majority of this research focused on workflow transformation and organizational readiness; therefore, conducting a more quantitative performance-based evaluation will provide added practical value to industry stakeholders in making informed business-case decisions for adopting DfMA.

While the previous three areas are recommended for future studies; further research can continue developing and validating a formal DfMA Readiness Assessment Tool or Maturity Model. The conceptual transition pathway of Organizational Readiness in the framework established in this study can be expanded into an instrument that measures organizational readiness at a project or corporate level. Developing such a tool will enhance the practical application of the framework outlined in Chapter 6:

As previously stated, while the four recommendations above are recommended for future studies; additional case studies of DfMA implementation in India would be beneficial.

Conducting multiple project-based case studies of implemented or implementing DfMA projects will enable researchers to obtain deeper insights regarding the challenges faced by contractors during initial design freeze, factory coordination, logistics planning, and site assembly. The results of such studies will assist in transitioning the discussion from perceived based findings to implementation-based evidence.

Additionally, since this study indicated that there were significant environmental barriers including weak policy support, fragmented supply chain networks, and resistance to off-site methods in the Indian construction market; future studies can investigate how government incentives, regulatory approvals, and procurement practices can facilitate DfMA adoption in India.

Lastly, since emerging technologies such as automation, digital twin technology, advanced prefabricated systems, and 3D concrete printing were not included as part of this research; therefore, they represent viable areas of future investigations as the Indian construction industry continues to evolve.

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APPENDIX

To capture diverse perspectives on DfMA adoption, expert inputs were collected from professionals across multiple domains, including policy, digital construction, design, manufacturing, and project execution. The selected experts were not limited to academic researchers but included industry practitioners and decision-makers to ensure that the study reflects real-world challenges and opportunities. Their insights contributed to identifying key barriers, drivers, and workflow implications of DfMA in the Indian construction context.

Appendix 1: Summary of Expert Profiles, Key Insights, and Relevance to DfMA Adoption

Expert Name	Professional Background	Key Insights Contributed	Relevance to DfMA
Chaitanya Bharech	Construction Technology Consultant, Founder of Cognito Consulting; expertise in AI, digital twins, and digital transformation in AEC	Highlighted need for digital readiness, data integration, and AI-driven decision-making; identified fragmented systems as a key barrier	Acts as a digital enabler of DfMA, supporting integration of design, manufacturing, and construction through BIM, AI, and data platforms
Dr. Shailesh Kr. Agrawal	Executive Director at BMTPC under Ministry of Housing & Urban Affairs; works on national construction policies and technologies	Emphasised policy support, standardisation, and government push (PMAY); identified awareness gaps and need for certification systems	Represents policy-level implementation of DfMA, promoting prefabrication, industrialised construction, and scalable housing solutions
S. J. Vijay	Founder of Salmon	Introduced “Buildings as	Represents advanced

Expert Name	Professional Background	Key Insights Contributed	Relevance to DfMA
	Leap Ventures; experience across banking, infrastructure, and now manufacturing-based construction (BaaP concept)	a Product", stressed shift from project-based to manufacturing mindset; highlighted need for standardisation and repeatability	DfMA evolution, where construction becomes a manufacturing process using modular, mobile micro-factories
David John Varghese	Principal Engineer at AtkinsRéalis; expertise in digital engineering, BIM, computational design; worked on HS2 and infrastructure projects	Highlighted early-stage digital integration, standardisation, and automation; showed how data improves decision-making and coordination	Represents technical implementation of DfMA, using BIM and computational tools to enable constructability, modular design, and workflow efficiency
Avinash Mutha	Associated with Ashir Engineering, Ahmedabad; involved in construction project execution, contractor coordination, and site-level management	Highlighted practical execution challenges, including lack of skilled labour, resistance to new methods, and coordination gaps between design and site; emphasised issues in handling, logistics, and installation of prefabricated components	Represents the execution and implementation reality of DfMA, focusing on contractor readiness, workforce capability, and the gap between design intent and on-site feasibility in Indian construction projects

The selected experts represent a comprehensive cross-section of the construction ecosystem, including digital technology, policy, design, manufacturing, and execution. This diversity ensures that DfMA is analysed not only as a theoretical concept but as a multi-dimensional transformation involving technology integration, policy support, industrialisation, and on-ground execution. Their combined insights enable a holistic understanding of the barriers, drivers, and workflow implications of DfMA adoption in the Indian construction industry.