# Barriers to Adoption of 3D Concrete Printing in Indian Construction Industry

A Directed Research Project

by

**TANMAY DESAI**

**PCM24414**

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: **Sh. Siddharth Panjwani**

Co-guide: **Dr Amarnath CB**

CEPT UNIVERSITY

## Faculty of Technology

**Kasturbhai Lalbhai Campus, University Road, Navrangpura,**

**Ahmedabad-380 009 India.**

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# ABSTRACT

This thesis, titled *"Barriers to Adoption of 3D Concrete Printing in the Indian Construction Industry,"* examines the critical challenges limiting the integration of Three-Dimensional Concrete Printing (3DCP) within India's construction sector. While 3DCP presents transformative potential through enhanced productivity, reduced material waste, and design innovation, its adoption remains constrained due to a complex interplay of technical, economic, regulatory, and socio-organizational barriers.

The study adopts a mixed-method approach, beginning with qualitative insights gathered from industry stakeholders including contractors, consultants, and technology experts to identify a comprehensive set of adoption barriers. This is followed by a qualitative analysis to prioritize the most significant constraints affecting implementation in the Indian context.

Based on these findings, the research proposes the *3DCP Adoption Readiness Framework*, a structured tool designed to assess industry preparedness and guide strategic decision-making. The framework integrates key barrier dimensions with actionable pathways for adoption, ensuring contextual relevance to India's construction ecosystem.

The research contributes by bridging the gap between emerging construction technologies and practical implementation, offering a systematic approach for facilitating informed adoption of 3DCP in India.

# UNDERTAKING

I declare hereby that the work presented in this Directed Research Project document **Barriers to Adoption of 3D Concrete Printing in Indian Construction Industry** by me, **TANMAY DESAI**, **PCM24414** 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 **Sh. Siddharth Panjwani**, and **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.

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| | |
|---|---|
| Name of student | : TANMAY DESAI |
| Code No.: | : PCM24414 |
| Date | : 03 Apr 2026 |
| Place | : Ahmedabad, Gujarat |

*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 : **Barriers to Adoption of 3D Concrete Printing in Indian Construction Industry**

Name of the Student : TANMAY DESAI

Code No. : PCM24414

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 : Siddhe ........................
30 April 2026

Signature of the Co-guide : Amarnath C. B ........................

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# ABBREVIATIONS

| | |
|---|---|
| BIM | Building Information Modeling |
| BIMC | Building Information Modeling Coordination |
| BIS | Bureau of Indian Standards |
| BMTPC | Building Materials and Technology Promotion Council |
| BOQ | Bill of Quantities |
| CB | Concrete Barrier |
| CIB | Construction Industry Board |
| COBOD | Construction Of Buildings On Demand |
| CON | Construction |
| CPWD | Central Public Works Department |
| DCP | Digital Construction Printing |
| DFMA | Design for Manufacture and Assembly |
| DP | Detailing Plan |
| DRP | Dissertation Research Project |
| ESG | Environmental, Social and Governance |
| HR | Human Resources |
| HUD | Housing and Urban Development |
| IIM | Indian Institute of Management |
| IIT | Indian Institute of Technology |
| IP | Intellectual Property |
| IS | Indian Standards |
| LCA | Life Cycle Assessment |
| MEAT | Most Economically Advantageous Tender |
| NOC | No Objection Certificate |
| OF | Organizational Factors |
| ORS | Organizational Readiness Score |
| PAC | Project Advisory Committee |
| PCM | Project Cycle Management |
| PESTEL | Political, Economic, Social, Technological, Environmental and Legal |
| PWD | Public Works Department |
| QC | Quality Control |
| RCC | Reinforced Cement Concrete |
| ROI | Return on Investment |
| SDG | Sustainable Development Goals |
| SOP | Standard Operating Procedure |
| SPSS | Statistical Package for the Social Sciences |
| TOEP | Technology, Organization, Environment, Policy |
| VCPT | Vertical Concrete Printing Technology |

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# CHAPTER-1: INTRODUCTION

Three-Dimensional Concrete Printing (3DCP) is an emerging construction technology with the potential to transform conventional RCC construction through automation, reduced labour dependency, material efficiency, and enhanced geometric flexibility (Reddy et al., n.d.). While large-scale projects in Europe, China, and the Middle East have demonstrated its technical and economic feasibility, India's construction sector—employing nearly 50 million workers and facing a projected shortage of 20 million skilled labourers by 2030—continues to rely on conventional RCC methods that suffer from high material waste, labour-intensive processes, frequent time and cost overruns, environmental impacts from cement production, and limited design adaptability (Pan et al., n.d.). Although 3DCP promises 30–60% faster construction, 20–35% waste reduction, and 15–20% labour savings, its adoption in India remains below 1% and is confined to a small number of pilot projects, with early trials reporting cost premiums and unverified long-term durability (Forcada et al., 2017).

The failure of 3DCP to transition from experimental demonstrations to mainstream practice is driven not by only technical barriers but by regulatory, economic, organizational, and ecosystem barriers across stakeholders and project phases (Pan et al., n.d.). These include the absence of 3DCP-specific design codes, conservative approval processes, unclear cost–benefit evaluation in procurement, limited availability of specialized materials, weak training pathways, and insufficient post-occupancy performance data (Shivendra et al., 2024) (Mawas et al., 2025). Addressing these multi-level barriers is essential to determine whether 3DCP can become a scalable and sustainable construction methodology aligned with India's labour needs and sustainability goals. This study therefore seeks to identify and analyze the key barriers to 3DCP adoption in the Indian construction industry and to develop a Barriers and Readiness Assessment Framework to support informed decision-making by policymakers, contractors, and technology providers.

## 1.1 Aim/Objectives

To identify, analyze, and classify the key technical, economic, organizational, and regulatory barriers affecting the adoption of 3D Concrete Printing in the Indian construction industry.

## 1.2 Research Questions

**"How do interconnected technical, economic, regulatory, social, and environmental barriers impede the adoption of 3D Concrete Printing (3DCP) in construction, and what strategies can mitigate them?"**

- What specific material, standardization, and quality control challenges in 3DCP limit scalability and reliability?
- How do high costs, uncertain ROI, and supply chain gaps (e.g., procurement, skilled labor shortages) affect 3DCP project feasibility?
- In what ways do absent building codes, policy delays, and certification hurdles block 3DCP commercialization?
- How do workforce resistance, skills gaps, and sustainability concerns influence stakeholder acceptance of 3DCP?

## 1.3 Scope of Work

<u>In Scope:</u>

- Indian and International case studies, contractors, technology provider
- Technical and organizational barriers
- Cost perceptions and readiness assessments
- Interviews and surveys from industry experts
- Literature comparison with global examples

<u>Out of Scope:</u>

- Structural design calculations or material testing
- Developing new 3DCP printing systems
- Creating manufacturing-ready DFMA modules
- On-site execution or prototype printing

## 1.4 Research Methodology

This study adopts a mixed-methods exploratory research design to investigate the barriers to the adoption of 3D Concrete Printing (3DCP) in the Indian construction industry. The methodology combines a structured literature review, expert interviews, quantitative survey validation, and framework development to ensure rigor and practical relevance.

The study develops a Barriers and Readiness Assessment Framework to support early-stage decision-making on 3DCP adoption, including go/no-go decisions, pilot versus full-scale implementation, and readiness evaluation during the concept design, feasibility, and tendering stages. The research is organized into five sequential phases to systematically identify and validate technical, economic, regulatory, organizational, and skills-related barriers across stakeholders and project phases.

## 1.5 Tools And Techniques

- Reading: Google Scholar, SpringerLink
- Interviews: Google Meet, Otter
- Analysis: Excel, Miro, SPSS
- Writing: Word / LaTeX

## 1.6 Schedule

**Weeks 1 - 4**

- Literature review
- Defining barrier categories
- Identifying stakeholders for interviews and surveys

**Weeks 5 – 8**

- Conduct interviews
- Distribute and collect survey responses
- Preliminary analysis
- Research Paper Outline Drafting

**Weeks 9 – 12**

- Develop Barriers Framework
- Map Readiness Factors
- Cross Compare Indian and Global Findings
- Integration of Findings in Research Paper

**Weeks 13 – 16**

- Final Report Preparation

- Research Paper Draft
- Presentation and Submission

# CHAPTER-2: LITERATURE REVIEW

## 2.1 Introduction

Three-dimensional concrete printing (3DCP) has emerged globally as a transformative digital construction technology capable of improving productivity, reducing material waste, and enhancing design flexibility. Over the past decade, academic research has extensively explored material rheology, interlayer bonding, reinforcement strategies, and sustainability potential. However, despite technological advancement and successful pilot demonstrations, large-scale adoption within mainstream construction markets remains limited.

In the Indian context, adoption is particularly slow despite the country's rapid urbanization, housing demand, and national sustainability commitments. This chapter synthesizes global and Indian literature to identify and structure the barriers to adoption of 3D concrete printing in the Indian construction industry. The review is organized into five categories:

1. Technical / Technological
2. Economic / Business Model
3. Administrative / Regulatory
4. Social / Organisational
5. Environmental / Sustainability Governance

This structured classification emerged from systematic literature analysis and informed the development of the semi-structured interview questionnaire used in the empirical phase of this study.

## 2.2 Technical / Technological Barriers

The earliest body of 3DCP research focused on material science and process optimization. Studies have established that printability depends on precise control of yield stress, viscosity, thixotropy, and setting time. (Ambily et al., 2024)identify workability, hardening time, reinforcement integration, and process optimization as primary technical challenges restricting widespread deployment.

One of the most persistent technical concerns is interlayer bonding strength. Because 3DCP constructs elements layer-by-layer, structural integrity depends on interface adhesion rather than monolithic casting. Literature consistently reports variability in interlayer shear and tensile strength depending on time gap and environmental exposure (Ambily et al., 2024).

Buildability and geometric stability represent additional technical constraints. Material must retain sufficient early-age strength to support subsequent layers without deformation. Process integration between printer mechanics and rheological behaviour becomes critical. The HUD market research report (Department of Housing & Development, n.d.) highlights that successful deployment requires coordinated calibration of mix design, extrusion pressure, and machine control.

Reinforcement remains another unresolved domain. While fibre reinforcement and hybrid RCC approaches are proposed, standardized detailing methods are still evolving (Ambily et al., 2024).

In India, BMTPC Performance Appraisal Certificates (PAC) for Tvasta (83_PAC_Tvasta_1068, 2023) and L&T VCPT (Limited, n.d.) demonstrate that printed systems are treated as certified proprietary systems rather than codified mainstream technologies. This reinforces the idea that technical validation remains system specific.

These technical insights directly informed interview questions exploring rheology control, reinforcement strategies, geometric stability, and quality assurance practices under real site conditions.

## 2.3 Economic / Business Model Barriers

While technical feasibility determines whether 3DCP can function, economic viability determines whether it will scale.

High capital expenditure is repeatedly identified as a major barrier. The HUD report

(Department of Housing & Development, n.d.) identifies printer procurement, infrastructure setup, and training as significant upfront investments.(Ambily et al., 2024) similarly emphasize cost intensity and lack of optimized supply chains as adoption constraints.

Return on Investment (ROI) uncertainty further complicates adoption. (Shivendra et al., 2024) found that Indian firms invest in 3DCP more for automation and branding than immediate financial returns. This suggests unclear payback structures.

(Adaloudis & Bonnin Roca, 2021) demonstrate that firms adopt 3DCP when strategic positioning outweighs cost risk, but procurement systems rarely reward sustainability benefits sufficiently to justify premium investments (Weng et al., n.d.).

Further identifying financial risk perception and technological skepticism as significant inhibitors under Innovation Resistance Theory. Utilisation risk compounds capital barriers. A printer must maintain high deployment frequency to justify investment. Fragmented project pipelines reduce equipment productivity (Department of Housing & Development, n.d.).

These economic findings informed interview questions on payback expectations, utilisation thresholds, capital allocation decisions, and market demand predictability.

## 2.4 Administrative / Regulatory Barriers

Institutional clarity is essential for diffusion of structural innovations. (Shivendra et al., 2024) identify regulatory gaps and lack of formalized BIS standards as significant barriers in India. While PAC certifications exist (83_PAC_Tvasta_1068, 2023), (Limited, n.d.), they are project- or vendor-specific rather than universally codified standards. (Aswin & Vaardini, n.d.), applying the TOEP framework, highlight regulatory clarity as a key environmental factor influencing adoption decisions.

Public procurement misalignment intensifies institutional barriers. L1-based tender systems prioritize lowest cost rather than lifecycle or sustainability performance. (Adaloudis & Bonnin Roca, 2021) argue that government procurement structures insufficiently reward environmental innovation. (Mogaji et al., n.d.) similarly categorize policy and institutional barriers as dominant constraints in empirical studies.

These findings shaped interview questions addressing approval delays, additional documentation requirements, BOQ compatibility, and procurement misalignment.

## 2.5 Social / Organisational Barriers

Even when technical and regulatory conditions are favorable, adoption depends on internal organisational readiness. (Aswin & Vaardini, n.d.) emphasize technological readiness and organisational capability as decisive adoption drivers in Indian firms. (Shivendra et al., 2024) observe that firms invest in 3DCP partly to develop skilled workforce capability. However, lack of trained operators and digital modelling expertise remains a constraint. Identifies psychological resistance and technological skepticism as adoption inhibitors.

The IIM stakeholder perception study (Forcada et al., 2017)reveals varied perceptions among industry actors regarding feasibility and scalability.

Additionally, automation potential raises labour displacement concerns, particularly in labour-intensive markets such as India (Adaloudis & Bonnin Roca, 2021) (Shivendra et al., 2024).

These social insights informed interview questions probing skill gaps, resistance to change, cross-functional coordination, and labour acceptance.

## 2.6 Environmental / Sustainability Governance Barriers

3DCP is often promoted as environmentally beneficial due to reduced formwork, optimized material usage, and design efficiency (Albalkhy et al., n.d.).

However, literature indicates that sustainability is rarely the primary adoption driver. (Adaloudis & Bonnin Roca, 2021) show that firms prioritize automation and productivity gains over environmental motivations. (Shivendra et al., 2024) emphasize that lack of sustainability-linked procurement incentives restricts adoption in India.

(Wijethunge et al., 2025) identify environmental and legal challenges under the PESTEL framework, including lifecycle assessment and circularity uncertainties.

(Ambily et al., 2024) discuss unresolved durability and reinforcement challenges affecting sustainability claims. Without policy incentives, environmental advantage remains latent rather than catalytic (Hassan et al., 2024).

## 2.7 Synthesis of Literature and Research Gap

The literature collectively reveals that:

- Technical feasibility is improving but requires standardization.
- Economic uncertainty remains a primary deterrent.
- Regulatory frameworks are fragmented in India.
- Organisational readiness varies significantly.
- Sustainability benefits are insufficiently incentivized.

While individual studies examine subsets of these barriers, there remains limited empirical validation within the Indian contractor ecosystem, particularly from Tier-1 construction firms and developers.

Therefore, this study advances the literature by:

1. Structuring 25 identified barriers across five categories.
2. Validating these barriers through stakeholder interviews in the Indian construction industry.
3. Developing a contextual framework for accelerating adoption.

# CHAPTER-3: RESEARCH METHODOLOGY

This study adopts a mixed-methods exploratory research design to systematically investigate the barriers affecting the adoption of 3D Concrete Printing (3DCP) in the Indian construction industry. The methodology integrates a structured literature review, qualitative expert interviews, quantitative survey validation, and framework development to ensure methodological rigor and practical relevance.

The outcome of the study is a Barriers and Readiness Assessment Framework intended to support early-stage adoption decisions related to 3DCP. Specifically, the framework assists contractors, developers, and consultants in making informed go/no-go, pilot versus full-scale deployment, and readiness assessment decisions during the concept design, feasibility, and tendering stages of construction projects. The research process is organized into five sequential phases, enabling systematic identification, classification, and validation of technical, economic, regulatory, organizational, and skills-related barriers across stakeholders and project phases.

## 3.1 Systematic Literature Review

A systematic literature review was conducted to establish a comprehensive theoretical and empirical foundation for the study. Peer-reviewed journal articles, conference proceedings, industry reports, and technical standards related to 3D Concrete Printing (3DCP), construction automation, and technology adoption barriers were systematically identified and screened using predefined inclusion and exclusion criteria. The review focused on extracting key themes related to technical, economic, regulatory, organizational, and skills-based challenges. This process enabled the identification of research gaps, informed the conceptual structure of the study, and provided the basis for developing preliminary barrier categories for subsequent empirical investigation.

## 3.2 Research Questions and Scope Development

Based on insights derived from the systematic literature review, clear research questions and the scope of the study were formulated to guide the investigation. The research questions were designed to examine the nature of barriers affecting 3DCP adoption and to assess organizational readiness for its implementation within the Indian construction context. The scope was defined in terms of stakeholder groups (contractors, developers, consultants, and technology providers), and barrier dimensions (technical, economic, regulatory, organizational, and skills-related). This step ensured a focused, structured, and context-specific research framework for data collection and analysis.

## 3.3 Empirical Research: Qualitative and Quantitative Phases

The empirical phase of the study adopts a mixed-methods approach, integrating qualitative and quantitative techniques to ensure systematic exploration and validation of barriers to the adoption of 3D Concrete Printing (3DCP). This phase is structured into three sequential sub-phases to enable progressive refinement of findings from exploration to validation.

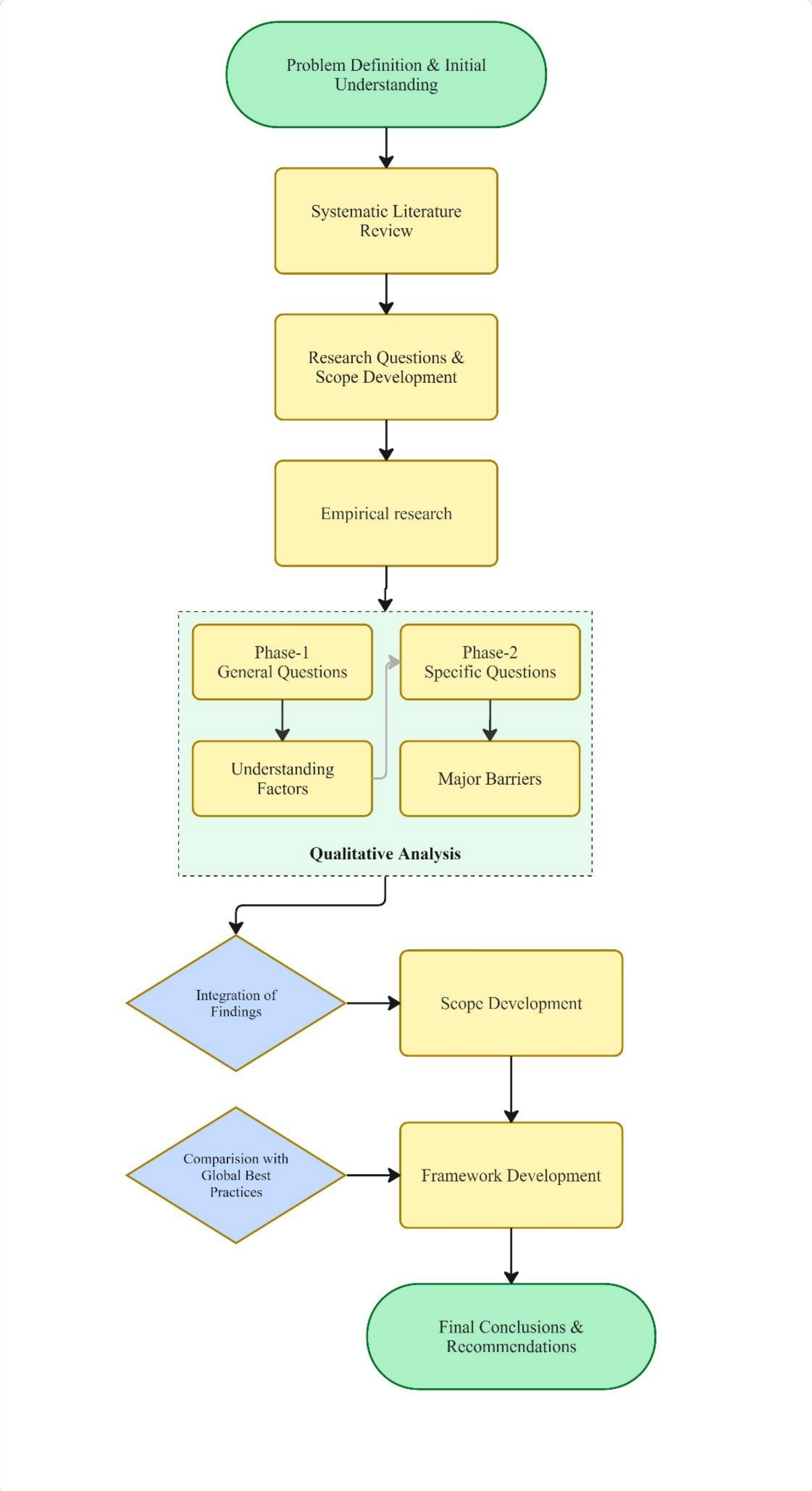



**Figure 3-1 Research Methodology Flowchart**

### 3.3.1 Phase 1 (Qualitative - General Questions):

In Phase 1, general exploratory questions were developed based on insights obtained from the systematic literature review. Semi-structured interviews were conducted with eight industry professionals possessing relevant experience in construction practices and emerging technologies. The objective of this phase was to understand contextual factors influencing 3DCP adoption and to capture practitioner perspectives on challenges and opportunities. The qualitative findings were analyzed thematically to identify preliminary factors affecting adoption.

### 3.3.2 Phase 2 (Qualitative - Specific Questions):

The findings from Phase 1 were used to formulate more focused semi-structured questions aimed at identifying the major barriers to 3DCP adoption. This phase sought to refine and consolidate the initially identified factors into key barrier categories. The analysis enabled the classification of dominant technical, economic, regulatory, organizational, and skills-related barriers, forming a validated qualitative foundation for subsequent quantitative investigation.

The Data Collection Method is as below:

**Participant Selection Criteria:**

- **Contractor representatives:** Minimum 5 years of experience in project execution, with exposure to technology adoption decisions or pilot innovation projects.
- **Structural consultants:** Minimum 3 years of professional practice in structural design and certification, with direct involvement in innovative construction systems or early-stage technology evaluations.
- **Real estate developers:** Project managers or development heads with decision-making authority on construction method selection, preferably with experience in mass housing or large-scale commercial projects.
- **Technology providers/vendors:** Representatives from 3DCP equipment suppliers, material manufacturers, or service providers active in the Indian market.

- **Architects and design consultants:** Professionals engaged in design-technology integration, DFMA workflows, or advanced geometry projects.
- **Government/regulatory representatives (optional):** Officials involved in construction code development, BIS standards committees, or building approval authorities.

**Sample Size:** Min.10 interviews distributed across stakeholder categories to ensure diverse perspectives.

**Recruitment Strategy:**

- Personal professional network developed through internships and industry projects
- Referrals from DRP guides (BIMCrew and Madesai networks)
- Direct outreach via LinkedIn to professionals at L&T Construction, Tvasta, Godrej Properties, Shapoorji Pallonji, and other early-stage 3DCP participants
- Introductions through CEPT alumni network and India BIM Association contacts
- Snowball sampling from initial interviewees

**Interview Protocol:**

- 45–60 minute semi-structured interviews conducted via Google Meet or in-person
- Open-ended questions focused on lived experience, not opinions (e.g., "Describe a situation where you evaluated 3DCP for a project" rather than "What do you think about 3DCP?")
- Questions structured around: technology exposure, perceived barriers, decision-making criteria, cost-benefit evaluation experiences, regulatory encounters, skills/training gaps, and inter-stakeholder coordination challenges
- Interviews will be recorded (with consent), transcribed, and anonymized

### 3.3.3 Integration of Findings

**Compilation of Findings:** Results from Phase 1 (general qualitative interviews), Phase 2 (specific qualitative interviews) will be compiled into a unified dataset.

**Barrier Categorization:** Qualitative findings from Phases 1 and 2 will be coded and grouped into defined barrier categories (technical, economic, regulatory, organizational, and skills-related).

**Stakeholder Mapping:** Qualitative survey responses from Phase 2 will be mapped against the identified barrier categories to examine variations in perceived severity across stakeholder groups.

**Severity Assessment:** Barriers will be prioritized based on combined qualitative relevance and quantitative significance, enabling assessment of their relative severity from a stakeholder lens.

**Table 1 Flow of Findings**

| ***Level of Integration*** | **Method** | **Output** |
|---|---|---|
| *Data Development* | Phase 1 → Phase 2 | Empirically grounded questionnaire |
| *Analysis* | Thematic coding + statistical ranking | Prioritized barrier list |
| *Interpretation* | Stakeholder comparison | Validated barrier framework |

## 3.4 Scope of Development for Framework

The purpose of the *Scope Development for Framework* stage is to define the boundaries, structure, and functional applicability of the Barriers and Readiness Assessment Framework being developed in this study. Based on the integrated findings from qualitative and quantitative phases, this process delineates which barrier categories, stakeholder groups, and adoption stages the framework will address, and establishes how these elements will be operationalized to assess readiness for 3D Concrete Printing (3DCP) adoption in the Indian construction industry.

In research on technology adoption frameworks, scholars emphasize the importance of anchoring framework scope in empirical evidence and contextual realities to ensure relevance and applicability. For example, studies that develop strategic adoption frameworks for emerging technologies integrate systematic literature synthesis and stakeholder data to identify core variables and structure the framework around them, rather than applying a generic model without contextual adaptation . Similarly, technology adoption research highlights the need to classify variables into meaningful categories (e.g., technological, organizational, environmental) and to specify how they influence adoption in real settings, to guide both analysis and practical application .

In this study, the scope development process will involve: (1) mapping identified major barriers to relevant adoption stages (concept design, feasibility, tendering); (2) aligning barrier categories with stakeholder perspectives obtained through survey responses; (3) defining the decision contexts (go/no-go, pilot vs full-scale) in which the framework will be used; and (4) specifying the framework's analytical dimension (severity, priority, stakeholder importance). This precise scoping ensures that the framework not only reflects empirical understanding of barriers but also supports targeted decision-making for practitioners considering 3DCP implementation.

### 3.5 Analysis of Data for Framework

This stage focuses on analyzing the integrated findings from Phase 1, and Phase 2 to generate structured inputs for framework development. Qualitative data are thematically coded to consolidate barrier categories, while quantitative survey data are analyzed to assess the relative severity and importance of each barrier from a stakeholder perspective. The results are mapped across key project stages and stakeholder groups to enable prioritization of barriers. This analysis ensures that the framework is empirically grounded and directly applicable to early-stage decision-making for the adoption of 3D Concrete Printing (3DCP).

### 3.6 Framework Development

The Framework Development stage synthesizes the analyzed and prioritized findings into a structured Barriers and Readiness Assessment Framework for 3D Concrete Printing (3DCP) adoption. The framework organizes barrier categories according to stakeholder relevance and project stages, enabling systematic evaluation of readiness. By integrating qualitative insights with quantitative validation, the framework functions as a decision-support tool to guide go/no-go decisions and to distinguish between pilot and full-scale implementation strategies. This ensures that the framework is empirically grounded, context-specific to the Indian construction industry, and operationally applicable for practitioners.

# CHAPTER-4: DATA COLLECTION

## 4.1 Phase-1 (Qualitative - General Questions)

Phase 1 involved semi-structured interviews with **eight industry stakeholders** using general exploratory questions developed from the systematic literature review **(Annexure 1 Phase-1 Generic Question )**. All interviews were transcribed verbatim, and the complete transcripts are included in the Appendix **(Annexure 2 Phase-1 Interview)**.

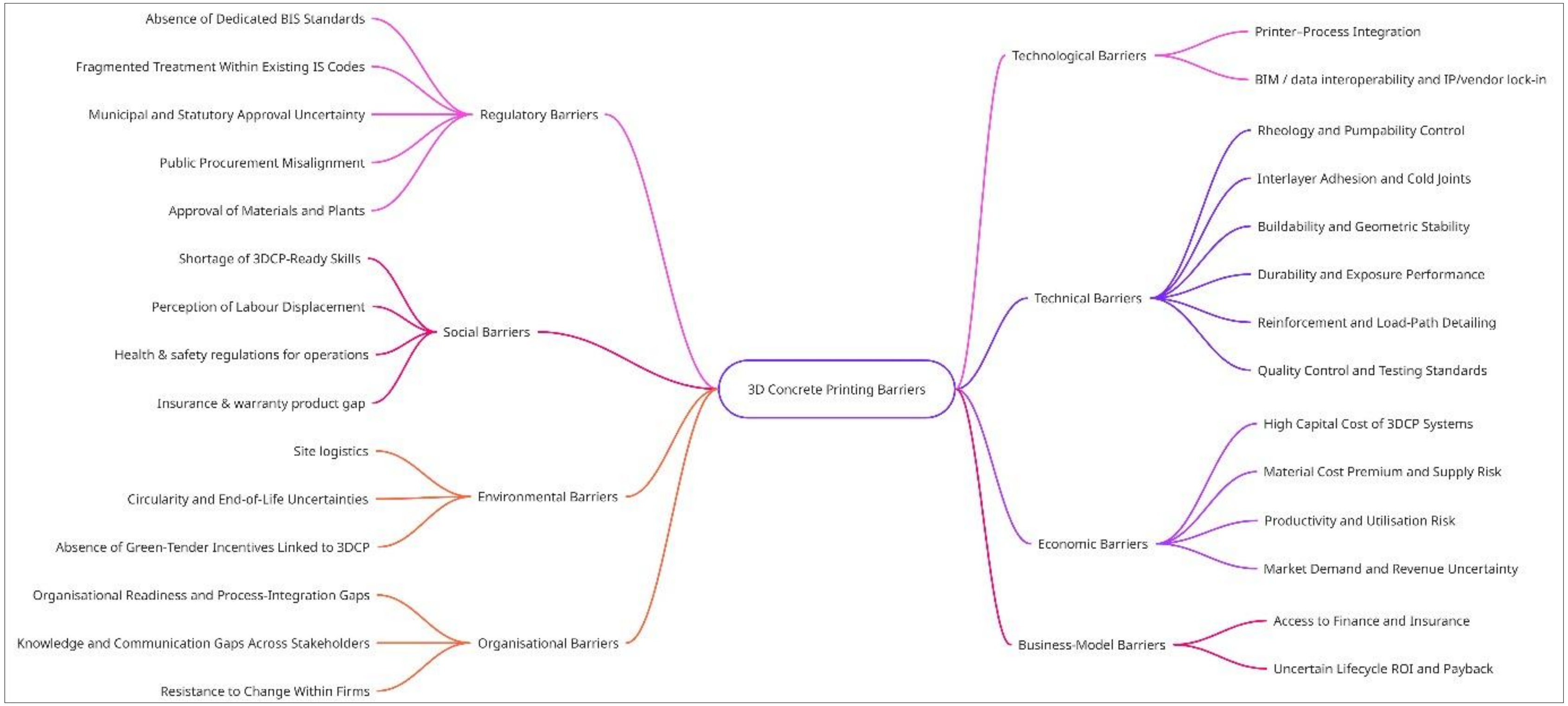



**Figure 4-1 Phase-1 - Barriers Results**

Through systematic coding and thematic analysis, a total of **29 distinct barriers** were identified from the Phase 1 data. These barriers represent preliminary factors affecting 3DCP adoption and encompass technical, economic, regulatory, organizational, and skills-related dimensions. The identified barriers were subsequently organized and visualized using an open mind map to illustrate their interrelationships and breadth.

The mind map **Figure 4-1 Phase-1 - Barriers Results** presents a comprehensive overview of all barriers derived from Phase 1 and serves as the foundational input for Phase 2, where these preliminary barriers were further refined and validated through specific semi-structured questioning.

### 4.1.1 Technological Barriers

1. Printer–Process Integration

Discontinuity between BIM models, slicing software, G-code generation, and printer control systems causes operational errors, file incompatibility, and coordination delays.

2. BIM / data interoperability and IP/vendor lock-in

Dependence on specific printer vendors, proprietary software ecosystems, and limited interoperability increases long-term operational risk.

### 4.1.2 Technical Barriers

1. Rheology and Pumpability Control

Maintaining consistent extrudability under Indian site moisture and temperature variability is difficult, leading to nozzle clogging, pressure fluctuations, inconsistent layer dimensions, and interruptions during continuous printing operations.

2. Interlayer Adhesion and Cold Joints

Time gaps between layers reduce bond strength, causing delamination risks, reduced shear transfer capacity, and aesthetic defects without standardized interlayer testing or acceptance criteria.

3. Buildability and Geometric Stability

Early-age deformation, cumulative alignment errors, and lack of closed-loop feedback systems result in dimensional deviations, instability in tall prints, and rework.

4. Durability and Exposure Performance

Limited long-term field data on chloride penetration, carbonation resistance, fire behavior, and thermal performance reduces confidence in structural and lifecycle reliability.

5. Reinforcement and Load-Path Detailing

Absence of standardized detailing for embedding reinforcement within printed elements complicates structural load transfer, particularly in seismic zones.

6. Quality Control and Testing Standards

No defined Indian protocols for interlayer shear testing, fresh-state rheology acceptance, or on-site validation methods create ambiguity in performance verification.

### 4.1.3 Economic Barriers

1. High Capital Cost of 3DCP Systems

Significant upfront investment in printer hardware, mixing systems, automation software, and calibration tools creates financial risk, especially for contractors without guaranteed pipeline projects.

2. Material Cost Premium and Supply Risk

Specialized admixtures, silica fume blends, and controlled fine aggregates increase material cost and expose projects to supply chain variability.

3. Productivity and Utilisation Risk

Low machine utilization rates and downtime due to approvals, maintenance, or learning curves reduce financial viability.

4. Market Demand and Revenue Uncertainty

Client hesitation, lack of resale benchmarks, and uncertainty in buyer acceptance limit predictable revenue streams.

### 4.1.4 Business Model Barriers

1. Access to Finance and Insurance

Limited availability of insurance products and cautious financial institutions restrict capital access for pilot or scaled projects.

2. Uncertain Lifecycle ROI and Payback

Absence of proven lifecycle cost comparisons and limited operational data make long-term return-on-investment calculations uncertain.

### 4.1.5 Regulatory Barriers

1. Absence of Dedicated BIS Standards

No prescriptive national standards define material properties, testing methods, or structural design parameters for 3D printed concrete.

2. Fragmented Treatment Within Existing IS Codes

Printed elements are inconsistently interpreted under existing IS codes, creating uncertainty in structural equivalence classification.

3. Municipal and Statutory Approval Uncertainty

Local authorities lack defined approval pathways, often requiring case-by-case structural justification and extended peer review.

4. Public Procurement Misalignment

Traditional L1-based tendering and rigid BOQ formats do not accommodate performance-based or innovation-driven construction methods.

5. Approval of Materials and Plants

Project-specific validation of printers and mixes, even after national certification, increases administrative burden.

### 4.1.6 Social Barriers

1. Shortage of 3DCP-Ready Skills

Insufficient availability of trained printer operators, rheology specialists, digital modelers, and additive manufacturing technicians constrains scalability.

2. Perceived Labour Displacement Risk

Concerns about automation replacing traditional labor generate social resistance and internal HR policy hesitation.

3. Health and Safety Compliance Gaps

Exposure to fine powders, moving robotic systems, and high-pressure pumping systems introduces safety risks not yet fully addressed in existing site regulations.

4. Insurance & warranty product gap

Limited insurer familiarity with 3D printed structures and absence of standardized warranty frameworks create trust deficits among stakeholders, slowing acceptance and increasing perceived reputational and liability risks.

### 4.1.7 Environmental Barriers

1. Site Logistics and Infrastructure Constraints

Large gantry footprint, power demand, continuous material feed requirements, and urban site congestion limit onsite deployment feasibility.

2. Circularity and End-of-Life Uncertainty

Unclear recycling standards, limited reuse pathways for printed waste, and absence of defined deconstruction guidelines create lifecycle ambiguity.

3. Absence of Green-Tender Incentives Linked to 3DCP

Government procurement rarely rewards lifecycle carbon reduction or material efficiency, weakening sustainability-driven adoption motivation.

### 4.1.8 Organisational Barriers

1. Organisational Readiness and Integration Gaps

Lack of coordination between design, procurement, digital modeling, and site execution teams disrupts process integration.

2. Knowledge and Communication Gaps

Limited understanding among clients, regulators, consultants, and contractors creates misalignment and slows decision-making.

3. Resistance to Change within Firms

Middle-management risk aversion and preference for established RCC workflows slow internal acceptance of disruptive technologies.

## 4.2 Phase-2 (Qualitative - Specific Questions)

Phase 2 involves conducting semi-structured interviews using specific questions developed from the findings of Phase 1. To date, interviews with **8 stakeholders** have been completed, for finalizing the industry facing Barriers for Adoption on 3DCP. Upon completion of all interviews, the collected data has been analyzed to refine and validate the major barriers to the adoption of 3D Concrete Printing (3DCP).

To ensure that the shortlisted barriers were not arbitrarily selected, a **structured qualitative analysis process** was followed. The interview transcripts from different stakeholders (Architects, Developers, Contractors, Technology Providers, and Academicians) were systematically examined using a **three-stage analytical chain**:

1. **Interview Statement** – Raw qualitative input from stakeholders
2. **Code (Condensed Interpretation)** – Key idea extracted as keywords or short phrases
3. **Barrier Mapping** – Alignment with final barrier categories and specific indicators

This process ensured that each barrier in the final framework is **traceable to actual industry insights**.

The following sections present one detailed example for each stakeholder category.

### 4.2.1 Architect (Technology + Technical Barrier Link)

**<u>Interview Statement (from Architect transcript)</u>**

"The printed elements are designed as hollow sections with separate zones for services and structure… reinforcement is not embedded like traditional RCC… it depends on system design."

**<u>Interpretation and Coding</u>**

From this statement, the following key ideas emerge:

- The structural system in 3DCP is **non-conventional**
- Reinforcement is **not monolithically integrated**
- Load transfer depends on **customized system logic**
- There is a **disconnect between conventional RCC understanding and 3DCP execution**

These are condensed into the following **codes**:

- Non-conventional structural behaviour
- Segmented structural zones

- Lack of embedded reinforcement continuity
- System-dependent load transfer

**Barrier Mapping**

**Primary Barrier Group:** Technical Barriers

**Specific Indicator:** Reinforcement and Load-Path Detailing

### 4.2.2 Developer (Economic + Business Model Barrier Link)

**Interview Statement (from Developer transcript)**

"Even if the technology is technically viable, developers prioritize cost efficiency… financial justification is lacking unless the project is high-value or specialized."

**Interpretation and Coding**

Key insights extracted:

- Decision-making is driven by **cost and ROI**
- Technology is viable only in **niche or premium projects**
- Lack of **financial justification for mainstream adoption**
- Weak alignment with **mass-market construction economics**

Condensed **codes**:

- Cost-driven decision environment
- Weak ROI justification
- Limited applicability to niche markets
- Lack of scalable financial model

**Barrier Mapping**

**Primary Barrier Group:** Economic Barriers

**Specific Indicator:** Market Demand and Revenue Uncertainty

**Secondary Barrier Group:** Business-Model Barriers

**Indicator:** Uncertain Lifecycle ROI and Payback

### 4.2.3 Contractor (Execution + Economic Risk Link)

**Interview Statement (from Contractor transcript we generated)**

"If the mix is slightly off or the print pauses, the whole element can fail… that becomes a cost issue, delay issue, and liability issue for us."

**Interpretation and Coding**

Extracted meanings:

- High sensitivity to **material consistency and process continuity**
- Execution is vulnerable to **interruptions**
- Failures directly impact **cost, time, and liability**
- Contractors bear **risk exposure**

Condensed **codes**:

- Process sensitivity and instability
- Execution interruption risk
- Direct cost and delay implications
- Contractor liability exposure

**Barrier Mapping**

**Primary Barrier Group:** Economic Barriers

**Specific Indicator:** Market Demand and Revenue Uncertainty

**Secondary Barrier Group:** Business-Model Barriers

**Indicator:** Uncertain Lifecycle ROI and Payback

### 4.2.4 Technology Provider (System Integration + Business Model Link)

**Interview Statement (from Technology Provider transcript)**

"The printer is only one part… the real challenge is integrating material, machine, site, and digital workflow… every project requires customization."

**Interpretation and Coding**

Key extracted meanings:

- Technology is **not a standalone system**
- Lack of **integration across components**
- High **project-specific customization**
- Absence of **standardization and repeatability**

Condensed **codes**:

- Fragmented system integration
- Multi-component dependency
- High customization requirement
- Lack of standardization

**Barrier Mapping**

**Primary Barrier Group:** Technological Barriers

**Indicator:** Printer–Process Integration

**Secondary Barrier Group:** Business-Model Barriers

**Indicator:** Uncertain Lifecycle ROI and Payback

### 4.2.5 Academician (Market + Policy + Systemic Insight)

**Interview Statement (from Professor transcript)**

"The technology is design-driven, not demand-driven… without demand, policies and commercialization pathways do not develop."

**Interpretation and Coding**

Extracted meanings:

- Innovation is **supply-driven**
- Lack of **market demand pull**
- Weak **commercialization pathways**
- Policy development is **reactive to demand**

Condensed **codes**:

- Demand-side weakness
- Supply-driven innovation
- Lack of commercialization pathway
- Policy dependency on market adoption

**Barrier Mapping**

**Primary Barrier Group:** Economic Barriers

**Indicator:** Market Demand and Revenue Uncertainty

**Secondary Barrier Group:** Regulatory Barriers

**Indicator:** Public Procurement Misalignment

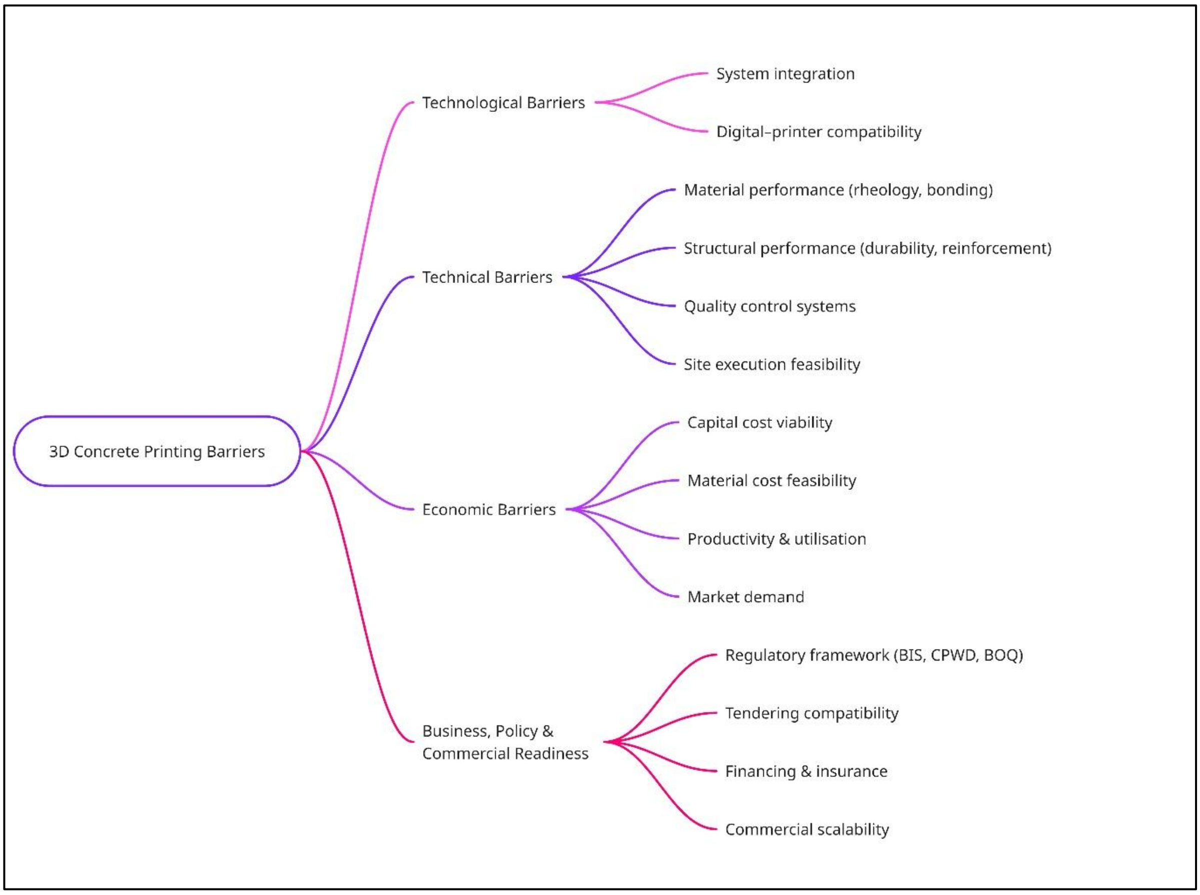



**Figure 4-2 Phase-2 - Specific Barriers to the Industry**

The shortlisted barriers were not arbitrarily selected but were derived through a structured qualitative coding process. Interview statements from multiple stakeholders were systematically reduced into codes representing recurring themes, which were then grouped into higher-order barrier categories. The examples above demonstrate the traceability from raw stakeholder inputs to final barrier classification.

# CHAPTER-5: FRAMEWORK DEVELOPMENT

The first step in developing a research framework for this study is to clearly define its structure. A framework is not merely a visual diagram or a set of headings; it is the logic that connects the research problem, the key variables, the actors involved, and the method of assessment. In the present study, the framework has been designed to examine how ready the Indian construction ecosystem is for the adoption of **3D Concrete Printing (3DCP)**. Since 3DCP is still an emerging construction technology in India, adoption cannot be understood through one single factor alone. It depends on technology, technical feasibility, economics, business conditions, policy support, and stakeholder coordination. For this reason, the framework has been structured as a multi-dimensional and stakeholder-driven model.

## 5.1 Defining Framework Structure

### 5.1.1 Framework Name

The framework has been titled:

**"Stakeholder-Driven, Barrier-Driven 3DCP Adoption Readiness Framework for Indian Construction"**

This name has been chosen carefully because it reflects the three central ideas of the study.

First, the framework is **stakeholder-driven**, which means that adoption is not seen as the responsibility of one party alone. Instead, different actors in the construction ecosystem influence readiness in different ways. Second, the framework focuses on **3DCP adoption readiness**, which means it is concerned not only with whether the technology exists, but whether the environment is prepared for its practical use. Third, the framework is specific to **Indian construction**, which is important because adoption conditions in India are shaped by local regulations, cost sensitivity, labour structures, procurement systems, and market behaviour.

This title is useful for thesis consistency because it clearly communicates the subject, context, and theoretical direction of the study. It also makes the framework sound academically grounded and directly linked to the research problem.

### 5.1.2 Core Objective of the Framework

The core objective of the framework is:

**To assess the readiness of the Indian construction ecosystem for adopting 3D Concrete Printing (3DCP) by evaluating multi-dimensional barriers and identifying stakeholder-specific responsibilities for enabling adoption.**

This objective is the foundation of the entire framework. It defines what the study intends to measure and why it matters. The framework does not treat adoption as a simple yes-or-no question. Instead, it recognises that readiness is a gradual condition made up of many interrelated factors.

The phrase **Indian construction ecosystem** is important because 3DCP adoption depends on the coordination of multiple participants, such as government bodies, developers, contractors, consultants, technology firms, and financial institutions. The framework therefore aims to understand how each of these actors contributes to or obstructs adoption.

The second important part of the objective is **multi-dimensional barriers**. This means that barriers are not only technical. For example, a project may be technically possible but economically unviable, or policy support may exist but the market may still not trust the technology. The framework therefore examines readiness across multiple dimensions.

The third important part is **stakeholder-specific responsibilities**. This reflects the reality that adoption does not happen in isolation. Different stakeholders influence different aspects of readiness. Government bodies shape regulation, contractors influence execution, technology firms shape technical capability, and financial institutions affect funding and risk perception. By identifying these responsibilities, the framework becomes more practical and action-oriented.

### 5.1.3 Framework Architecture

The framework is organised into **three interconnected layers**:

**Layer 1: Readiness Dimensions — What needs to be ready**

This layer identifies the major conditions that must exist for 3DCP adoption to become feasible. It answers the question: **What aspects of the ecosystem must be prepared?**

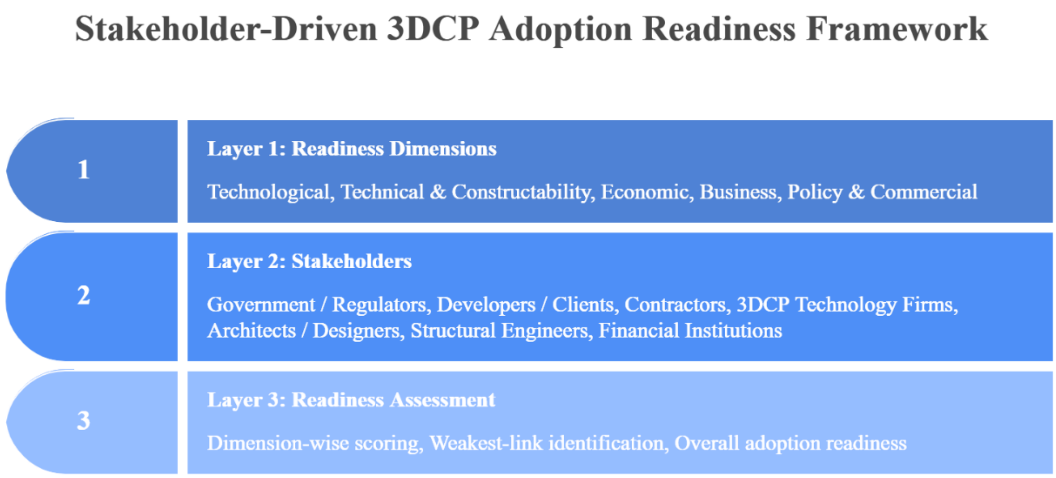
**Layer 2: Stakeholders — Who influences readiness**

This layer identifies the key actors in the construction ecosystem and connects them with the readiness dimensions they shape. It answers the question: **Who has influence over each readiness condition?**

**Layer 3: Readiness Assessment — How ready the system is**

This layer evaluates the overall level of readiness by examining how strong or weak each dimension is. It answers the question: **How prepared is the ecosystem for adoption?**

These three layers create a complete logic chain. The framework begins by identifying the conditions for adoption, then assigns responsibility across stakeholders, and finally evaluates readiness levels. This makes the framework both analytical and practical.




This diagram shows that the framework is not linear in a simple sense. Rather, it is interconnected. Each dimension is shaped by multiple stakeholders, and the readiness score is derived from the combined condition of all layers.

### 5.1.4 Readiness Dimensions

The framework is built around four final readiness dimensions. These dimensions have been selected because they capture the most important barriers and enabling conditions for 3DCP adoption in India.

#### *5.1.4.1 Technological Readiness*

Technological readiness refers to the extent to which the digital and mechanical systems required for 3DCP can function together efficiently. Since 3DCP depends heavily on software, automation, printing hardware, and process coordination, this dimension is essential.

It includes issues such as system integration, workflow interoperability, and digital–printer compatibility. For example, a project may have advanced design software, but if the printer cannot interpret the digital instructions accurately, the system will fail. Similarly, if the design process, material batching, and printing sequence do not communicate well with each other, the technology cannot be deployed reliably.

This dimension is important because 3DCP is a digitally enabled construction method. Without technological readiness, even a financially strong project may face operational difficulties. Therefore, this dimension acts as the basic foundation of implementation.

#### 5.1.4.2 Technical and Constructability Readiness

Technical and constructability readiness relates to whether 3DCP can perform as a safe, durable, and buildable construction method in real-world site conditions. This dimension is broader than technology alone because it concerns the physical and engineering performance of the printed structure.

It includes material performance, such as rheology and bonding behaviour, as well as structural performance, such as durability, reinforcement integration, and load-bearing capacity. It also includes quality control systems and site execution feasibility. In other words, even if the printer works correctly, the output must still satisfy engineering standards and construction requirements.

This dimension is especially important in India because the construction industry is highly sensitive to quality, safety, and compliance. Stakeholders will not trust 3DCP unless it can demonstrate structural reliability and repeatable performance. Therefore, technical and constructability readiness is a key determinant of adoption confidence.

#### 5.1.4.3 Economic Readiness

Economic readiness refers to whether 3DCP can be justified in financial terms. A technology may be innovative, but if it is too expensive or difficult to scale, adoption will remain limited. This dimension therefore examines the cost side of the technology.

It includes capital cost viability, material cost feasibility, productivity, utilisation rate, and market demand. For example, if a 3D printer is expensive but used only occasionally, the cost per unit becomes very high. On the other hand, if the technology improves productivity and reduces labour dependence, it may become economically attractive over time.

This dimension is critical in India because construction decisions are often highly cost-sensitive. Developers and contractors usually compare new technologies with conventional methods based on cost, speed, and return on investment. Therefore, economic readiness directly influences whether the technology is seen as commercially practical.

#### 5.1.4.4 Business, Policy and Commercial Readiness

Business, policy and commercial readiness refers to the extent to which the external environment supports the use of 3DCP in formal construction practice. This includes regulations, standards, procurement systems, financing mechanisms, and commercial acceptance.

It covers aspects such as the regulatory framework, BIS and CPWD compatibility, BOQ integration, tendering systems, financing, insurance, and scalability in the market. A technology may be technically strong, but if it cannot fit within existing procurement or approval structures, adoption will remain slow.

This dimension is especially important because construction in India operates within established legal and commercial systems. For 3DCP to become mainstream, it must move beyond pilot projects and enter standard project workflows. This requires policy clarity, tendering compatibility, and commercial confidence.

**Table 2 Readiness Dimensions**

| Readiness Dimension | Main Focus | Typical Issues Covered | Importance for 3DCP Adoption |
|---|---|---|---|
| Technological Readiness | Digital and machine integration | Software compatibility, printer integration, workflow coordination | Ensures the system can operate smoothly |
| Technical & Constructability Readiness | Engineering and site feasibility | Material performance, bonding, reinforcement, quality control | Ensures the structure is safe and buildable |
| Economic Readiness | Cost and financial viability | Capital cost, material cost, productivity, utilisation | Determines commercial attractiveness |
| Business, Policy & Commercial Readiness | External support environment | Regulations, tendering, BOQ, financing, insurance | Enables mainstream market adoption |

### 5.1.5 Stakeholder Groups

The framework identifies seven major stakeholder groups. These groups have been selected because they represent the major actors who influence 3DCP adoption in the Indian construction ecosystem.

#### 5.1.5.1 Government / Regulators

This group includes public authorities, ministries, and standard-setting bodies. Their role is to create an enabling regulatory environment, issue standards, and define acceptable construction practices. Without support from regulators, new technologies often remain outside the mainstream construction system.

#### 5.1.5.2 Developers / Clients

Developers and clients are the decision-makers who demand construction outcomes. Their interest usually lies in cost, speed, quality, and risk. If they see 3DCP as reliable and beneficial, demand for the technology will increase.

#### 5.1.5.3 Contractors

Contractors are responsible for actual project execution. They are important because they translate design intent into built output. Their willingness to adopt 3DCP depends on site practicality, workforce adaptation, equipment handling, and project efficiency.

#### 5.1.5.4 3DCP Technology Firms

These firms develop printers, software, materials, and technical support systems. They are central to innovation, testing, troubleshooting, and knowledge transfer. Their role is to make the technology usable in real project settings.

#### 5.1.5.5 Architects / Computational Designers

These professionals shape the design process. Since 3DCP requires digitally optimised and fabrication-aware design, architects and computational designers play a major role in making the technology structurally and aesthetically feasible.

#### 5.1.5.6 Structural Engineers

Structural engineers ensure that the printed structure satisfies load, safety, and durability requirements. Their involvement is critical because 3DCP must not only print forms but also perform structurally in the built environment.

#### *5.1.5.7 Financial Institutions / Insurers*

This group supports funding, risk management, and commercial confidence. Their role becomes important when new technology requires financing, risk evaluation, or performance assurance before large-scale adoption.

**Table 3 Stakeholder Roles in the Framework**

| Stakeholder Group | Main Role in the Framework | Influence on Adoption |
|---|---|---|
| Government / Regulators | Sets rules and standards | Enables or restricts formal adoption |
| Developers / Clients | Creates demand | Determines whether projects adopt 3DCP |
| Contractors | Executes the work | Affects practical implementation |
| 3DCP Technology Firms | Provides technology and support | Improves technical readiness |
| Architects / Computational Designers | Shapes digital design | Enables fabrication-ready design |
| Structural Engineers | Confirms safety and performance | Builds technical trust |
| Financial Institutions / Insurers | Supports funding and risk coverage | Improves commercial confidence |

### 5.1.6 Core Hypothesis of the Framework

The core hypothesis of the framework is:

**"Adoption of 3D Concrete Printing is governed by the weakest readiness dimension, and each dimension is influenced by specific stakeholders within the construction ecosystem."**

This hypothesis is highly important because it provides the theoretical logic behind the framework. It suggests that adoption does not depend on the average level of readiness alone. Instead, the weakest dimension becomes the limiting factor. For example, if technology and economics are favourable but policy support is weak, adoption may still not progress. Similarly, if the technical performance is weak, the whole system may fail regardless of other strengths.

This is a useful assumption because it reflects real construction behaviour. In practice, projects are often delayed or rejected because one critical barrier is not resolved. The hypothesis therefore helps explain why technology adoption in construction is uneven and slow, even when innovation is available.

It also reinforces the role of stakeholders. Each dimension is shaped by specific actors, so readiness can only improve when stakeholders work together. This makes the framework both diagnostic and intervention-oriented.

### 5.1.7 Key Conceptual Relationships

The framework is built on several cause-effect relationships that explain how readiness evolves. These relationships will later form the arrows in the final diagram.

**Policy readiness → enables tendering → creates demand**

When policy systems are supportive, tender documents can accommodate 3DCP. Once tendering becomes possible, clients become more willing to consider the technology. This creates actual market demand.

**Demand → improves utilisation → reduces cost**

When demand increases, printers and related systems are used more frequently. Higher utilisation reduces idle time and helps spread fixed costs over more projects, making the technology more economical.

**Cost reduction → increases developer adoption**

When the technology becomes more affordable, developers are more likely to adopt it. Cost is one of the strongest decision factors in construction, especially in cost-sensitive markets.

**Technical reliability → builds trust → supports policy inclusion**

When 3DCP demonstrates reliable performance, confidence grows among stakeholders. This trust can encourage regulators to include the technology in standards and procurement systems.

**Stakeholder coordination → improves overall readiness**

Adoption is strongest when all stakeholders act in a coordinated manner. A connected ecosystem improves knowledge sharing, reduces uncertainty, and speeds up implementation.

**Table 4 Key Conceptual Relationships in the Framework**

| Cause | Intermediate Effect | Final Outcome |
|---|---|---|
| Policy readiness | Tendering becomes possible | Demand is created |
| Demand growth | Utilisation increases | Costs reduce |
| Cost reduction | Economic attractiveness rises | Developer adoption increases |
| Technical reliability | Trust improves | Policy inclusion becomes easier |
| Stakeholder coordination | Ecosystem becomes aligned | Overall readiness improves |

This framework structure provides the conceptual backbone of the entire study. It is designed to move from broad ecosystem conditions to specific stakeholder influence and then to readiness evaluation. By identifying the key dimensions, mapping stakeholder roles, and establishing cause-effect relationships, the framework becomes suitable for both academic analysis and practical interpretation.

Most importantly, it does not treat 3DCP adoption as a purely technical issue. Instead, it recognises that successful adoption in India depends on the interaction of technology, engineering, economics, policy, and institutional support. This makes the framework comprehensive, realistic, and suitable for a research project focused on construction innovation.

## 5.2 Indicator Development and Scoring System

To convert the proposed **Stakeholder-Driven, Barrier-Driven 3DCP Adoption Readiness Framework** into a usable research instrument, the broad readiness dimensions must be broken down into measurable indicators. A framework at the conceptual level is valuable for explaining the structure of a problem, but it cannot by itself produce a clear assessment of readiness. For that purpose, the abstract ideas of technological readiness, technical readiness, economic readiness, and business-policy readiness must be translated into observable variables that can be examined systematically.

This is the role of **indicator development**. Indicators act as the bridge between theory and assessment. They allow the researcher to move from general statements such as "the market is not ready" or "the technology is not fully integrated" to specific measurable conditions such as workflow standardization, regulatory support, cost feasibility, and quality control systems. In the context of 3D Concrete Printing (3DCP), this conversion is especially important because adoption is influenced by multiple barriers operating at the same time. Some of these barriers are technical, some are institutional, and some are economic. A structured indicator system makes it possible to capture this complexity in a logical and research-based manner.

The indicator and scoring system therefore serves three main purposes. First, it makes the framework measurable. Second, it allows comparison across stakeholders, projects, or adoption scenarios. Third, it helps identify which readiness dimensions are weak and which interventions are needed to improve adoption potential. In this way, the framework becomes not only descriptive, but also diagnostic and decision-oriented.

### 5.2.1 Approach to Indicator Development

The indicators in this framework are developed through a structured three-stage process. This process ensures that the final assessment tool remains closely linked to the original research problem and stakeholder evidence.

#### *5.2.1.1 Stage 1: Barrier to Indicator Translation*

The first stage involves converting each identified barrier into a measurable indicator. A barrier is usually broad and qualitative in nature. For example, the absence of a standard regulatory code is a barrier, but this cannot be directly scored unless it is reframed as a condition that can be measured. The corresponding indicator becomes the "availability of standardized regulatory codes." In this way, a negative barrier is transformed into a positive assessment criterion.

This translation is important because it ensures that the final scoring system is not built around vague impressions. Instead, it is based on specific conditions that can be observed, discussed, or rated by respondents.

#### *5.2.1.2 Stage 2: Indicator Structuring*

The second stage involves structuring each indicator in a consistent format. Each indicator should include the following elements: a clear title, a brief description, the aspect of readiness it represents, and the stakeholder group most closely associated with it. This gives the framework internal consistency and makes it easier to apply in interviews, expert validation, or scoring exercises.

For example, "Printer–Process Integration Level" is a technological indicator, but it is also linked to technology firms and design professionals because they are the actors responsible for ensuring that digital workflows and printing systems work together.

#### 5.2.1.3 Stage 3: Scoring Design

The third stage involves assigning a score to each indicator using a standardized scale. Since readiness is a gradational concept rather than a binary one, a 5-point scale is appropriate. It allows the researcher to capture subtle differences in readiness, instead of forcing all situations into simple yes/no categories. This is particularly useful for emerging technologies like 3DCP, where many projects may exist in partially developed forms.

The logic of this process can be represented as follows:

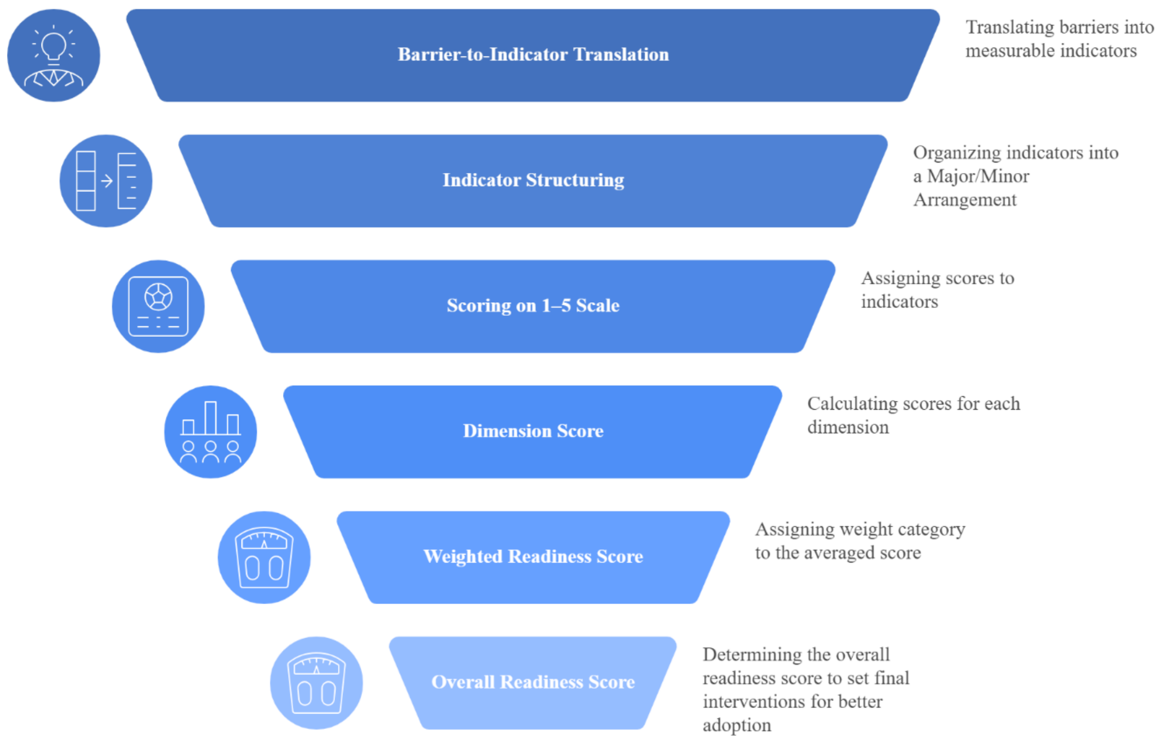



**Figure 5-1 Logic Flow for Indicators**

### 5.2.2 Scoring System Design

The scoring system is based on a **5-point Likert-type readiness scale**. This scale is designed to reflect increasing levels of maturity in the adoption environment. It balances simplicity with analytical depth, which makes it suitable for both qualitative interpretation and quantitative analysis.

**Table 5 Readiness Scoring Scale**

| Score | Readiness Level | Meaning |
| --- | --- | --- |
| 1 | Not Ready | The condition is absent, highly weak, or not established at all |

| Score | Readiness Level | Meaning |
|---|---|---|
| 2 | Low Readiness | The condition exists only in a fragmented or initial form |
| 3 | Moderate Readiness | The condition is partially developed but still inconsistent |
| 4 | High Readiness | The condition is largely established with only minor gaps |
| 5 | Fully Ready | The condition is standardized, stable, and industry-ready |

This scoring system is useful because it reflects the gradual nature of adoption. For instance, a project may have partial workflow integration but no formal standardization. Such a situation cannot be treated as fully ready, but it also cannot be treated as entirely absent. The 5-point scale captures this middle ground effectively.

In addition, the scale supports comparison. Two projects may both be attempting 3DCP adoption, but one may score higher in technical readiness while another may score higher in policy readiness. The scoring system makes such differences visible and interpretable.

### 5.2.3 Indicator Framework

The indicator framework is grouped according to the four readiness dimensions. Each dimension includes indicators that reflect the most important conditions influencing 3DCP adoption in the Indian construction context.

#### *5.2.3.1 Technological Readiness Indicators*

Technological readiness refers to the extent to which the digital and machine-based systems required for 3DCP can work together effectively. Since 3DCP depends on digital design, slicing software, machine control, and automated execution, this dimension focuses on integration and interoperability.

**Table 6 Technological Readiness Indicators**

| Indicator | Description | Measurement Focus | Main Stakeholders |
|---|---|---|---|
| Printer–Process Integration Level | Degree of coordination between design models and printing systems | Compatibility, automation, manual intervention | 3DCP firms, designers |
| Digital Workflow Standardization | Availability of standardized BIM-to-print workflows | Presence of repeatable workflow protocols | Designers, technology firms |
| Interoperability Across Platforms | Ability to transfer data across software and machines | Open formats, system flexibility | Technology firms |

| Indicator | Description | Measurement Focus | Main Stakeholders |
|---|---|---|---|
| Dependency on Proprietary Systems | Extent of vendor lock-in or closed systems | High dependency indicates lower readiness | Technology firms |

This dimension is important because even when a printing system is physically available, adoption can still fail if digital and mechanical systems do not communicate properly. Technological readiness therefore represents the operational backbone of the framework.

#### *5.2.3.2 Technical and Constructability Readiness Indicators*

This dimension evaluates whether 3DCP can perform as a safe, durable, and constructible method in real project conditions. It is not enough for the technology to function mechanically; it must also satisfy structural and construction requirements.

**Table 7 Technical and Constructability Readiness Indicators**

| Indicator | Description | Measurement Focus | Main Stakeholders |
|---|---|---|---|
| Material Rheology Control | Ability to maintain printability and consistency of material mix | Workability, stability, site adaptation | Technology firms, engineers |
| Interlayer Bond Strength | Strength of adhesion between printed layers | Continuity and structural integrity | Structural engineers |
| Structural Reliability | Ability of the printed element to transfer loads safely | Reinforcement integration, load path | Structural engineers |
| Durability Performance | Resistance to environmental and long-term exposure | Weathering, moisture, service life | Engineers, clients |
| Quality Control Framework | Existence of testing and acceptance methods | Inspection, standards, tolerance control | Engineers, contractors |
| Site Execution Feasibility | Suitability of site conditions for printing operations | Space, logistics, weather, access | Contractors, clients |
| Skilled Workforce Availability | Availability of trained operators and computational designers | Training, competency, experience | Contractors, designers |

This dimension is central to credibility. If the material is not stable, the bond between layers is weak, or quality control is unclear, stakeholders will hesitate to trust the technology. In practice, technical readiness often determines whether the technology is seen as experimental or deployable.

### *5.2.3.3 Economic Readiness Indicators*

Economic readiness reflects whether 3DCP can be justified in financial terms. Since construction decisions are strongly influenced by cost, productivity, and commercial return, this dimension is especially important in India.

**Table 8 Economic Readiness Indicators**

| Indicator | Description | Measurement Focus | Main Stakeholders |
|---|---|---|---|
| Capital Cost Viability | Whether the initial investment is feasible relative to project size | Equipment cost, payback logic | Developers, contractors |
| Material Cost Competitiveness | Comparison of printed materials with conventional materials | Unit cost, availability, wastage | Contractors, clients |
| Productivity Efficiency | Ability to improve speed and output compared to conventional methods | Time savings, output rate | Contractors, developers |
| Equipment Utilisation Rate | Frequency with which the technology is used across projects | Idle time, multi-project usage | Contractors, firms |
| Market Demand Strength | Level of demand from clients and developers | Interest, project pipeline | Developers, clients |
| Revenue Predictability | Stability of income generation through 3DCP projects | Consistency of orders, business continuity | Firms, investors |

This dimension is highly significant because many emerging technologies fail not due to technical weakness, but because they cannot achieve a stable economic case. A technology with low utilisation or uncertain demand may remain limited to pilot applications. Economic readiness therefore acts as the commercial filter for adoption.

### *5.2.3.4 Business, Policy and Commercial Readiness Indicators*

This dimension captures the institutional environment in which 3DCP must operate. A technically successful technology may still face adoption barriers if it cannot fit into existing regulations, tendering systems, or financing structures.

**Table 9 Business, Policy and Commercial Readiness Indicators**

| Indicator | Description | Measurement Focus | Main Stakeholders |
|---|---|---|---|

| Indicator | Description | Measurement Focus | Main Stakeholders |
|---|---|---|---|
| Regulatory Framework Availability | Presence of standards, codes, and formal guidelines | BIS/IS code support, policy clarity | Government, regulators |
| Tender Integration | Inclusion of 3DCP in BOQ and procurement systems | CPWD/PWD compatibility | Clients, contractors |
| Approval and Compliance Clarity | Ease of obtaining approvals and meeting compliance requirements | Permitting process, clarity of checks | Regulators, clients |
| Financing Accessibility | Availability of project finance or investment support | Loan access, investor confidence | Financial institutions |
| Insurance Coverage | Availability of risk coverage for 3DCP projects | Liability, warranty, performance risk | Insurers, clients |
| Commercial Scalability | Ability to replicate adoption across multiple projects | Repeatability, market expansion | Developers, contractors |
| Standardization of Contracts | Inclusion in standard contract documents | Contract clauses, legal clarity | Clients, contractors, legal advisors |

### 5.2.4 Weighting Strategy

The weighting strategy is a critical component of the framework because not all dimensions contribute equally to adoption readiness. A weighted system reflects the practical reality that some barriers are more influential than others. Based on stakeholder insights, the strongest concerns are usually related to economics and policy, followed by technical feasibility and technological integration.

**Table 10 Proposed Dimension Weighting**

| Dimension | Suggested Weight Range | Rationale |
|---|---|---|
| Economic Readiness | 30–35% | Cost, demand, and productivity strongly influence adoption decisions |
| Business, Policy and Commercial Readiness | 25–30% | Regulation and procurement determine whether adoption can enter the formal system |
| Technical and Constructability Readiness | 20–25% | Structural reliability and site feasibility are essential for trust |

| | | |
|---|---|---|
| Technological Readiness | 10–15% | Important as a foundation, but often less limiting than cost or policy |

The weight ranges may be finalized through expert judgment, stakeholder validation, or literature support. The purpose of weighting is not to create arbitrary numerical importance, but to reflect the actual conditions that influence adoption in practice.

In the Indian context, the higher weighting for economic and policy dimensions is justified because even strong technical solutions may fail if they are too expensive, lack regulatory support, or cannot be integrated into procurement systems. At the same time, technological readiness receives a lower weight not because it is unimportant, but because many of its components become meaningful only when economic and policy conditions allow real deployment.

If required for final scoring, the weights can be normalized so that their total equals 1.0 or 100 percent.

### 5.2.5 Readiness Score Calculation

The readiness score is calculated in a structured sequence. This makes the framework transparent and easy to apply.

**Step 1: Score each indicator**

Each indicator is rated on the 1–5 scale based on available evidence, expert opinion, or respondent judgment.

**Step 2: Calculate the average score for each dimension**

If a dimension has multiple indicators, the scores are averaged to produce a dimension-level readiness score.

**Step 3: Apply the assigned weight**

Each dimension score is multiplied by its respective weight.

**Step 4: Calculate the overall readiness score**

The weighted scores are added together to obtain the final readiness score.

**Formula**

**Let:**

- $\boldsymbol{D_1}$**= Technological readiness score**

- **$D_2$= Technical and constructability readiness score**
- **$D_3$= Economic readiness score**
- **$D_4$= Business, policy and commercial readiness score**

**Let the corresponding weights be:**

- $W_1, W_2, W_3, W_4$

**Then the overall readiness score (ORS) is:**

$$ORS = (D_1 \times W_1) + (D_2 \times W_2) + (D_3 \times W_3) + (D_4 \times W_4)$$

**Where:**

$$W_1 + W_2 + W_3 + W_4 = 1$$

This method ensures that the final score reflects both the internal condition of each readiness dimension and its relative importance in the adoption process.

### 5.2.6 Output Categories

The overall score can then be interpreted using readiness categories.

**Table 11 Readiness Interpretation Bands**

| Final Score Range | Interpretation |
|---|---|
| 1.0–2.0 | Not Suitable |
| 2.1–3.0 | Pilot Stage |
| 3.1–4.0 | Limited Adoption |
| 4.1–5.0 | Ready for Scaling |

These categories help convert numerical output into a meaningful decision tool. A score alone has limited value unless it is translated into a practical interpretation. The output bands therefore support project-level or policy-level decision-making.

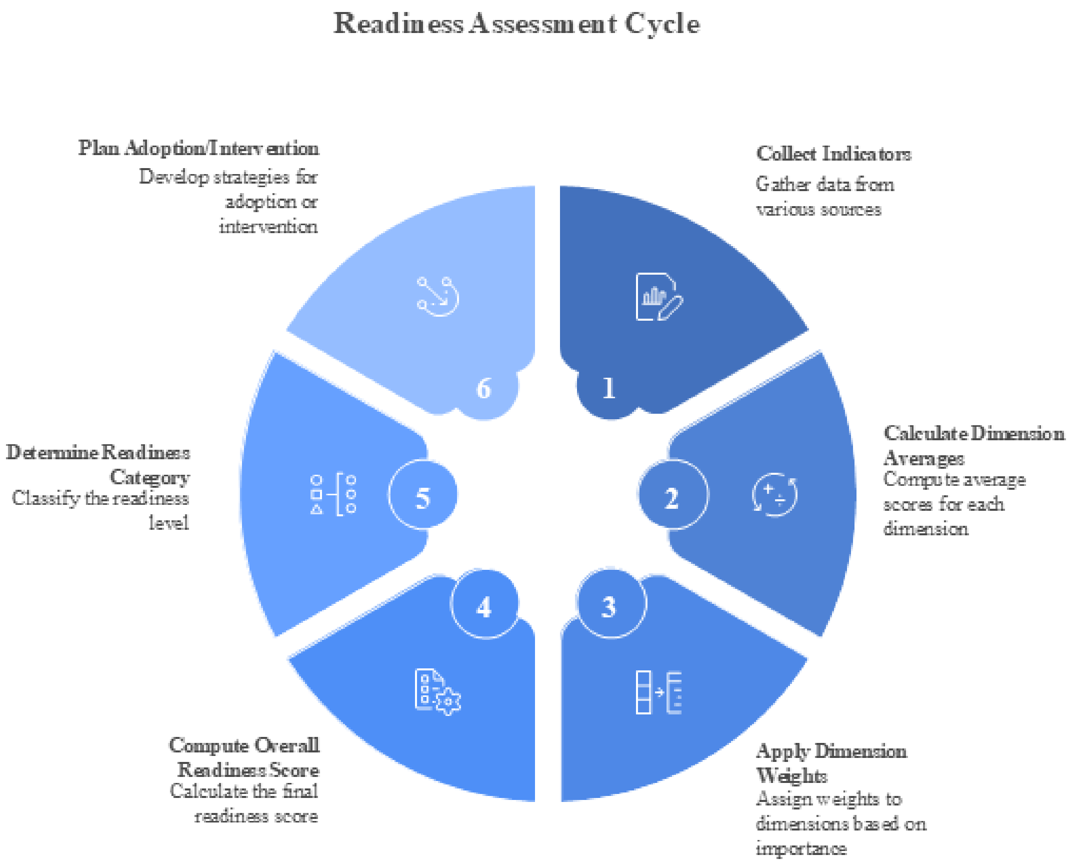



**Figure 5-2 Scoring Logic**

A radar chart can also be used to show the relative strength of each readiness dimension. This is useful because it visually highlights the weakest areas that require attention. In addition, a scorecard can present numerical performance, and a gap analysis can show which indicators are dragging down the overall readiness level.

The indicator development and scoring system transforms the framework from a conceptual model into a measurable assessment tool. It creates a disciplined way to evaluate the readiness of 3DCP adoption in the Indian construction sector by linking barriers, stakeholder insights, and operational conditions into one structured method. The four readiness dimensions, their indicators, the weighted scoring logic, and the final readiness interpretation together provide a strong research base for analysis.

This step is especially important because it makes the framework original, defensible, and academically useful. It does not merely describe what may affect adoption; it provides a method for assessing how ready the ecosystem actually is. In that sense, the scoring system becomes the quantitative core of the framework and the basis for further stakeholder mapping, validation, and final adoption analysis.

If needed, the next section can be written in the same format as **Step 3: Stakeholder–Indicator Mapping**, including a full matrix table that connects each indicator to the responsible stakeholder group.

## 5.3 Stakeholder–Indicator Mapping and Responsibility Matrix

Once the readiness indicators and scoring system have been established, the framework must move one step further from measurement to responsibility allocation. A readiness score can show how prepared the ecosystem is for 3D Concrete Printing (3DCP), but it does not by itself explain **who is responsible for the condition being measured** or **which stakeholder has the capacity to improve it**. In a multi-actor environment such as construction, this distinction is extremely important. Adoption of an emerging technology is rarely controlled by one single entity. Instead, it is shaped by the combined decisions, constraints, and actions of several stakeholders.

For this reason, the framework introduces a **Stakeholder–Indicator Mapping and Responsibility Matrix**. This matrix connects each readiness indicator with the stakeholder or stakeholders most closely associated with it. In doing so, it makes the framework more practical and action-oriented. The readiness dimensions identify the major conditions for adoption, the indicators translate those conditions into measurable variables, and the stakeholder matrix assigns responsibility for those variables. This creates a clear chain from **barrier identification** to **measurement** to **intervention**.

In the context of 3DCP, this is especially useful because the barriers are distributed across the construction ecosystem. Some barriers are technical and are influenced mainly by technology firms and engineers. Others are economic and depend on developers, contractors, and financial institutions. Still others are policy-driven and require intervention from government and regulatory bodies. The stakeholder matrix therefore ensures that the framework does not remain abstract. It becomes a tool for understanding the relationship between readiness gaps and the actors who can address them.

### 5.3.1 Role of Stakeholder Mapping in Framework Development

Stakeholder mapping performs three major functions within the framework.

#### 5.3.1.1 Attribution of Responsibility

The first and most important function is the attribution of responsibility. Every barrier or weak indicator must be linked to a stakeholder who influences that condition directly or indirectly. This does not mean that one stakeholder alone controls the issue. Rather, it means that there is usually a primary actor who has the strongest influence, along with supporting actors who contribute to improvement.

For example, the availability of regulatory codes is primarily a government issue, but engineers and industry bodies may support the development of those codes. Similarly, equipment utilisation is largely influenced by contractors and developers, but financial institutions may also affect whether multiple projects are feasible.

This responsibility attribution helps the framework move beyond diagnosis and into accountability.

#### 5.3.1.2 Alignment with Industry Reality

The second function is that it reflects how the construction industry actually works. In practice, adoption does not happen because one stakeholder simply decides to use a new technology. Instead, it depends on coordination between multiple parties. A technology firm may develop a printer, but without a supportive client, a willing contractor, clear design input, and a feasible regulatory environment, the technology cannot scale.

The stakeholder matrix therefore captures the collaborative nature of adoption. It reflects the interview-based understanding that barriers are interlinked and spread across the ecosystem, rather than concentrated in one place.

#### 5.3.1.3 Enabling Targeted Interventions

The third function is that it allows targeted interventions. If a dimension or indicator receives a low score, the framework can identify not only the gap but also the stakeholder most closely connected to that gap. This is extremely useful for analysis and recommendation writing. Instead of making general statements such as “adoption must improve,” the framework can generate more specific conclusions such as “regulatory clarification is required from government bodies” or “contractors need stronger workforce training.”

In this way, stakeholder mapping turns the framework into a decision-support mechanism.

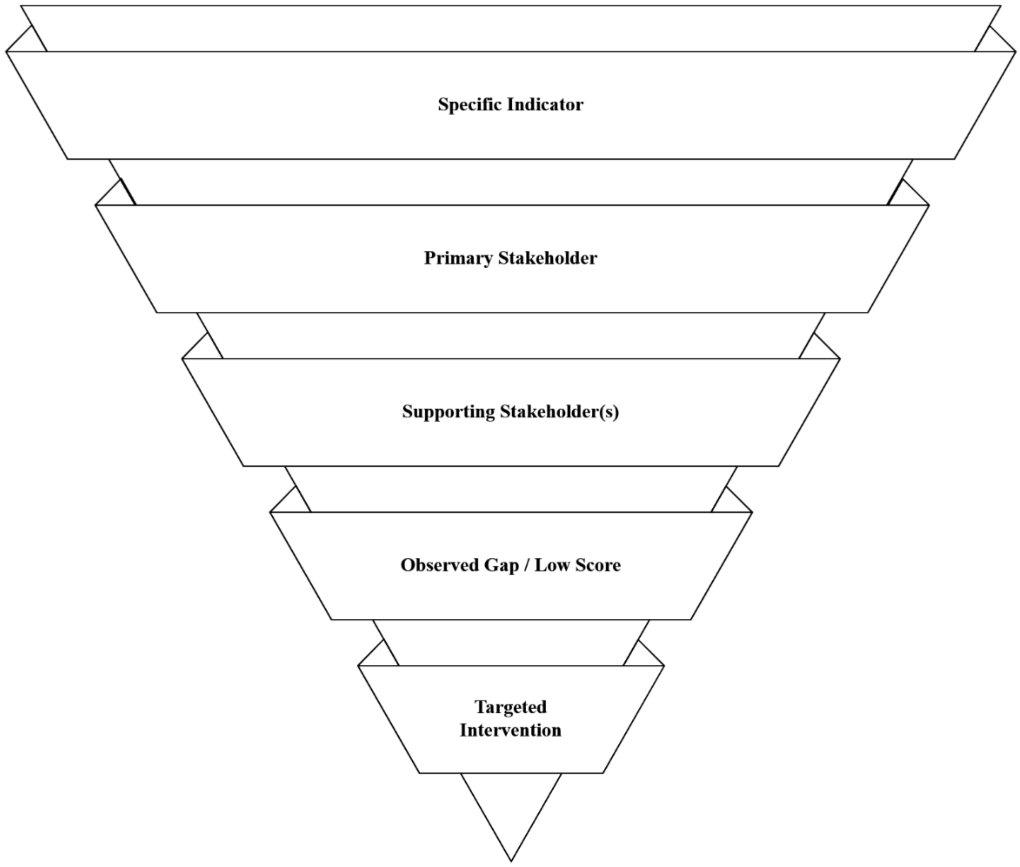



**Figure 5-3 Stakeholder–Indicator Relationship Logic**

This logic is central to the framework because it links measurement with responsibility and action.

### 5.3.2 Stakeholder–Indicator Responsibility Matrix

The following matrix presents the responsibility structure for all indicators under the four readiness dimensions. It identifies the primary stakeholder and the supporting stakeholders for each indicator, while also explaining the nature of the relationship.

#### *5.3.2.1 Technological Readiness Mapping*

Technological readiness concerns the digital and operational systems that make 3DCP possible. Since 3DCP is a digitally enabled process, the technology layer is heavily influenced by design compatibility, workflow coordination, and machine integration.

This dimension is strongly technology-led. The primary responsibility lies with technology firms because they control the hardware, software, and system architecture. However, design professionals also play an important role because 3DCP requires fabrication-aware modelling. Government support becomes relevant when proprietary systems create barriers to wider adoption.

**Table 12 Technological Readiness Responsibility Matrix**

| Indicator | Primary Stakeholder | Supporting Stakeholders | Nature of Responsibility |
|---|---|---|---|
| Printer–Process Integration | 3DCP Technology Firms | Architects / Designers | Technology firms develop the machine-process interface, while designers ensure that digital models can be translated into printable outputs |
| Digital Workflow Standardization | Architects / Designers | 3DCP Technology Firms | Designers structure the workflow; technology firms provide software and operational support |
| Interoperability Across Platforms | 3DCP Technology Firms | Contractors | Technology firms determine software and hardware compatibility; contractors influence implementation requirements |
| Dependency on Proprietary Systems | 3DCP Technology Firms | Government / Regulators | Technology firms create system openness or lock-in; regulators may encourage standards that reduce vendor dependency |

This dimension reflects the fact that technology readiness is not only about having a printer. It also depends on whether the printer can work in a stable, interoperable, and standardized workflow. If this layer is weak, the technology may remain in the pilot stage even if demand exists elsewhere.

#### *5.3.2.2 Technical and Constructability Readiness Mapping*

This dimension relates to whether 3DCP can produce safe, durable, and buildable structures in real project conditions. It is the most closely connected with engineering performance and site execution.

This dimension is execution-driven. Contractors are central because they control site feasibility, labour deployment, and implementation discipline. However, they cannot resolve constructability issues alone. Structural engineers are necessary for safety and reliability, while technology firms are needed for material formulation and process consistency.

**Table 13 Technical and Constructability Responsibility Matrix**

| Indicator | Primary Stakeholder | Supporting Stakeholders | Nature of Responsibility |
|---|---|---|---|
| Material | 3DCP | Contractors | Technology firms develop and test printable mixes; |

| Indicator | Primary Stakeholder | Supporting Stakeholders | Nature of Responsibility |
|---|---|---|---|
| Rheology Control | Technology Firms | | contractors manage site-level handling and execution |
| Interlayer Bond Strength | 3DCP Technology Firms | Structural Engineers | Technology firms influence printing quality; engineers validate structural continuity and performance |
| Structural Reliability | Structural Engineers | Contractors | Engineers design safe systems; contractors ensure correct execution on site |
| Durability Performance | Structural Engineers | Architects / Designers | Engineers assess long-term performance; designers influence geometry and exposure conditions |
| Quality Control Framework | Contractors | Government / Regulators | Contractors implement inspection; regulators and standards bodies define acceptable quality benchmarks |
| Site Execution Feasibility | Contractors | Developers / Clients | Contractors assess site logistics; clients influence space, access, and project planning |
| Skilled Workforce Availability | Contractors | 3DCP Technology Firms | Contractors train and deploy labour; technology firms provide technical training and support |

Technical readiness is the bridge between innovation and actual construction. A project may have a good printer and a willing client, but if material behaviour is unstable or quality control is unclear, the project cannot move confidently into mainstream use. This is why technical readiness is a core part of the framework.

#### *5.3.2.3 Economic Readiness Mapping*

Economic readiness examines whether 3DCP makes financial sense. Since construction projects are strongly influenced by cost, time, and return on investment, this dimension is often one of the most decisive in adoption decisions.

This dimension is market-driven. Developers are the key decision-makers because they determine whether the technology fits the project economics. Contractors also play a major role because they influence productivity, deployment frequency, and equipment use. This dimension strongly aligns with the stakeholder insight that cost and demand are dominant adoption barriers.

**Table 14 Economic Readiness Responsibility Matrix**

| Indicator | Primary Stakeholder | Supporting Stakeholders | Nature of Responsibility |
|---|---|---|---|
| Capital Cost Viability | Developers / Clients | Contractors | Developers decide on investment; contractors influence equipment and deployment cost |
| Material Cost Competitiveness | 3DCP Technology Firms | Contractors | Firms determine material supply and mix cost; contractors influence wastage and usage |
| Productivity Efficiency | Contractors | 3DCP Technology Firms | Contractors control site productivity; firms provide automation and process support |
| Equipment Utilisation Rate | Contractors | Developers / Clients | Contractors manage project deployment; developers influence project continuity and demand |
| Market Demand Strength | Developers / Clients | Government / Regulators | Developers create market demand; government policies can indirectly stimulate or discourage adoption |
| Revenue Predictability | Developers / Clients | Financial Institutions | Developers assess business continuity; financial institutions affect investment confidence |

The economic dimension is essential because a technically promising technology may still fail if it is too costly or uncertain to use repeatedly. High capital expenditure, low demand, and weak utilisation can make 3DCP commercially unattractive. This is why economic readiness receives strong weight in the overall framework.

#### *5.3.2.4 Business, Policy and Commercial Readiness Mapping*

This dimension captures the broader institutional environment that determines whether 3DCP can become part of mainstream construction practice. It includes standards, procurement, approvals, financing, insurance, and contract structures.

This dimension is institution-driven. Government and regulatory bodies have the greatest influence because they shape standards, approval systems, and tendering structures. Financial institutions and insurers are also crucial because they affect risk perception and commercial confidence.

**Table 15 Business, Policy and Commercial Responsibility Matrix**

| Indicator | Primary Stakeholder | Supporting Stakeholders | Nature of Responsibility |
|---|---|---|---|
| Regulatory Framework Availability | Government / Regulators | Structural Engineers | Regulators create standards; engineers contribute technical validation |
| Tender Integration | Government / Regulators | Contractors | Government structures procurement; contractors help align the method with execution requirements |
| Approval and Compliance Clarity | Government / Regulators | Developers / Clients | Regulators define approval pathways; clients require clear compliance conditions |
| Financing Accessibility | Financial Institutions | Developers / Clients | Financial institutions provide capital access; developers influence project viability |
| Insurance Coverage | Insurers | Contractors | Insurers manage risk; contractors provide performance and execution data |
| Commercial Scalability | Developers / Clients | Contractors | Developers expand market use; contractors enable practical replication |
| Standardization of Contracts | Government / Regulators | Legal and Industry Bodies | Regulators and related bodies formalize commercial terms and risk allocation |

This is the dimension that determines whether 3DCP remains a pilot innovation or becomes part of regular construction procurement. Even strong technical readiness will not lead to widespread adoption unless the policy and commercial environment becomes supportive.

### 5.3.3 Integration with the Scoring System

The stakeholder mapping does not operate separately from the scoring mechanism. Instead, it strengthens the interpretation of scores by linking each low-scoring indicator to a responsible actor. This makes the framework more analytical and more useful for recommendations.

**Integration Process**

1. Each indicator is scored on the 1–5 readiness scale.
2. Low-scoring indicators are identified.
3. The corresponding primary stakeholder is traced from the mapping matrix.

4. Supporting stakeholders are also noted where relevant.
5. Intervention measures are suggested based on responsibility allocation.

**Table 16 Example Table: Score-to-Responsibility Linkage**

| Indicator | Score | Primary Stakeholder | Possible Action |
|---|---|---|---|
| Regulatory Framework Availability | 1 | Government / Regulators | Develop standards and clarify code requirements |
| Market Demand Strength | 2 | Developers / Clients | Initiate pilot projects and awareness-building |
| Capital Cost Viability | 2 | Developers / Clients | Explore phased investment or shared-resource models |
| Skilled Workforce Availability | 2 | Contractors | Organize training and skill development programmes |

This integration is important because it converts a numerical score into an actionable diagnosis. It helps explain not only where the problem exists, but also who should respond to it.

**<u>Contribution to Framework Development</u>**

The stakeholder–indicator matrix contributes to the framework in several important ways.

First, it creates accountability. Instead of treating adoption barriers as abstract system problems, the framework assigns them to actors who can influence change. Second, it improves practical relevance. The framework becomes useful not only for academic analysis but also for policy planning, project strategy, and industry implementation. Third, it strengthens interpretive clarity. A low score on any indicator can now be read in relation to a responsible stakeholder, which makes the findings easier to discuss and defend.

The matrix also supports stronger recommendations. For example, if policy-related indicators score low, the recommendations can be directed toward regulators. If technical indicators are weak, then technology firms and engineers become the focus. If economic indicators are weak, then developers and financial institutions must be considered. This makes the framework much more targeted.

**Conceptual Advancement**

At this stage, the framework moves beyond a simple assessment model and becomes a **stakeholder-driven diagnostic and intervention framework**. This is an important conceptual shift.

Originally, the framework identifies what readiness is. Through indicator development, it measures readiness. Through stakeholder mapping, it identifies who influences readiness. As a result, the framework now answers four important questions:

- What is the issue?
- How serious is it?
- Who is responsible?
- What action is required?

This progression gives the framework both academic strength and applied value. It becomes suitable for research analysis because it is systematic and defensible, but it also becomes suitable for practice because it points toward intervention.

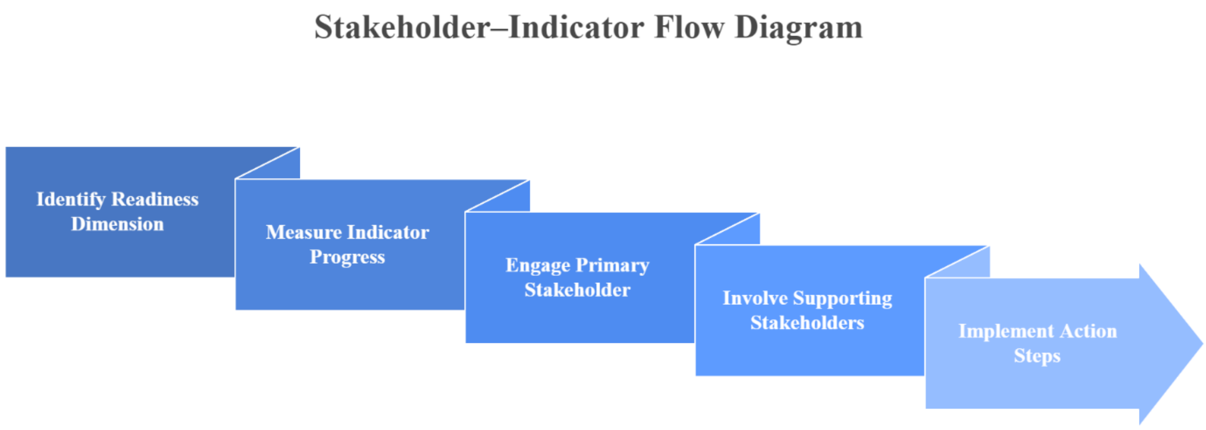



**Figure 5-4 Stakeholder–Indicator Flow Diagram**

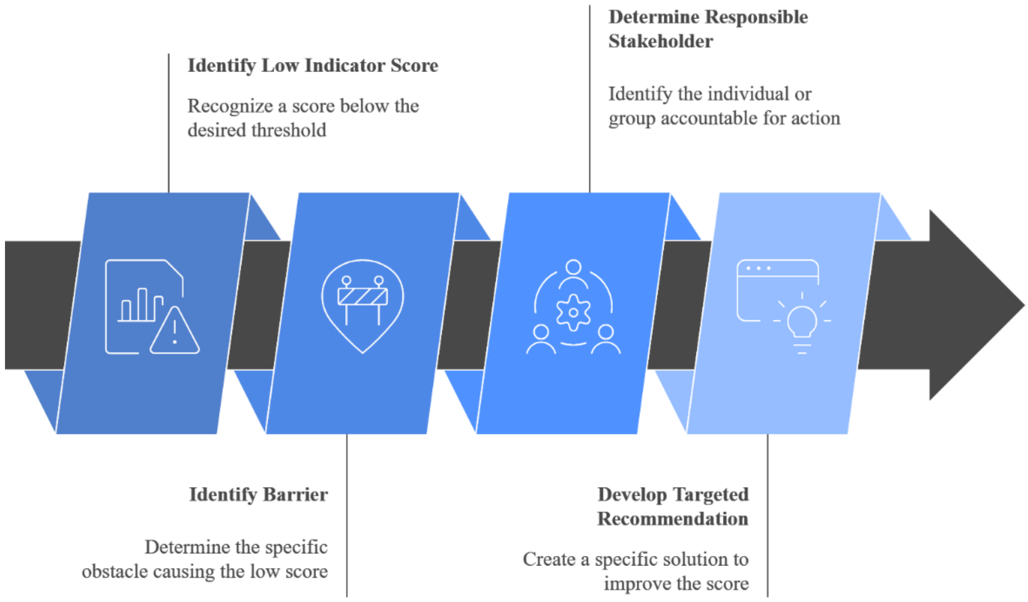



**Figure 5-5 Score-and-Responsibility Chain**

The stakeholder–indicator mapping and responsibility matrix form one of the most important parts of the framework because they connect measurement with action. By linking each indicator to the stakeholder most closely responsible for it, the framework becomes more than a diagnostic model. It becomes a structured tool for identifying adoption barriers, assigning responsibility, and guiding intervention. In the context of 3D Concrete Printing in India, where adoption depends on coordination among regulators, developers, contractors, technology providers, designers, engineers, and financial actors, this mapping is essential for making the framework realistic, defensible, and practically useful.

## 5.4 Framework Integration and Final Model Development

After defining the readiness dimensions, developing the indicators and scoring system, and mapping stakeholders to individual indicators, the framework reaches its final stage: **integration**. This stage is important because a framework becomes truly useful only when its different parts are brought together into one coherent model. Until this point, the study contains separate analytical components. In the integration stage, these components are connected into a single structure that can be applied for assessment, interpretation, and decision-making.

For the present study, the integrated model is designed to examine the adoption readiness of **3D Concrete Printing (3DCP)** in the Indian construction context. The purpose of this model is not only to identify whether the ecosystem is prepared, but also to explain **why** it is or is not prepared, **which dimensions are weak**, **which stakeholders are linked to those weaknesses**, and **what type of intervention is needed**. This makes the final framework more than a descriptive model. It becomes a practical research tool for evaluating adoption potential and guiding action.

The integrated model is especially relevant in the case of 3DCP because adoption depends on the interaction of technical, economic, business, and institutional factors. No single factor can explain readiness on its own. A project may be technically feasible but economically unattractive. It may also be financially viable but still face regulatory or tendering barriers. The final integrated framework therefore captures the adoption process as a connected system rather than as isolated variables.

### 5.4.1 Framework Integration Logic

The integration logic of the framework is based on a layered structure. Each layer performs a distinct role, but all layers are linked to one another. This structure ensures that the framework moves logically from barriers to indicators, from indicators to stakeholders, and from stakeholder responsibility to scoring and intervention.

**Table 17 Logic of Framework Integration**

| Layer | Main Function | Key Output |
|---|---|---|
| Layer 1: Readiness Dimensions | Defines the broad domains that affect adoption | System-level readiness categories |
| Layer 2: Indicators | Breaks dimensions into measurable conditions | Operational variables for assessment |
| Layer 3: Stakeholders | Identifies who influences each condition | Responsibility assignment |
| Layer 4: Scoring and Assessment | Quantifies readiness using the rating scale and weights | Numerical readiness score |
| Layer 5: Output and Intervention | Interprets results and guides action | Gap analysis and recommendations |

This layered structure is useful because it allows the framework to operate from both a conceptual and an applied perspective. The higher layers provide the logic of the framework, while the lower layers provide measurable and actionable results.

### 5.4.2 Layered Structure of the Final Framework

The final framework can be understood as a five-layer model. Each layer builds upon the previous one and makes the model progressively more practical.

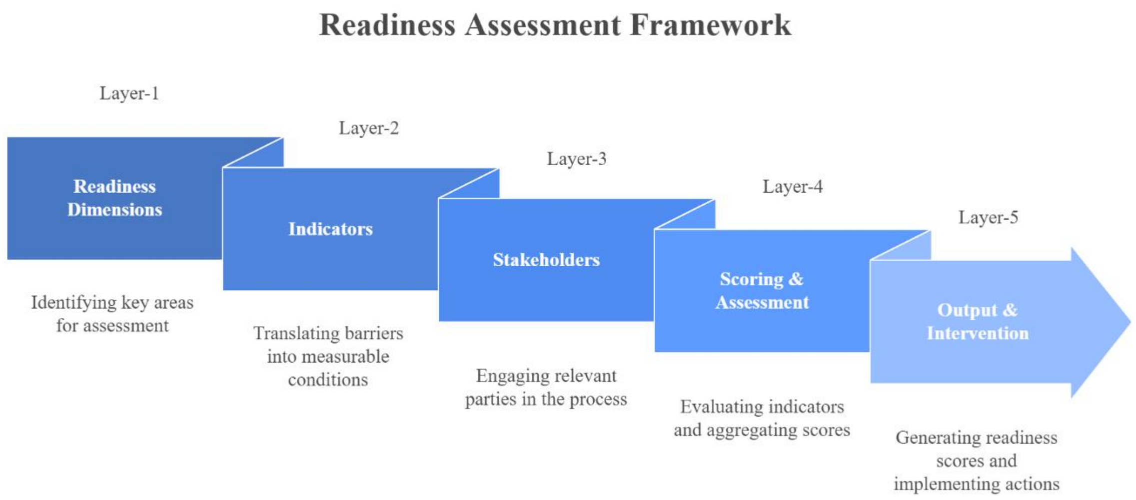



**Figure 5-6 Layers of the Framework**

This structure gives the framework a clear internal order. The readiness dimensions define the broad areas of concern. Indicators translate those concerns into measurable items. Stakeholders explain who influences the indicators. Scoring quantifies the situation. Finally, the output layer converts the score into a decision-oriented interpretation

### 5.4.3 Final Framework Model: Conceptual Representation

The complete model can be represented as a flow of information and assessment. It begins with barriers and stakeholder insights, moves through structured readiness dimensions, and ends with intervention recommendations.

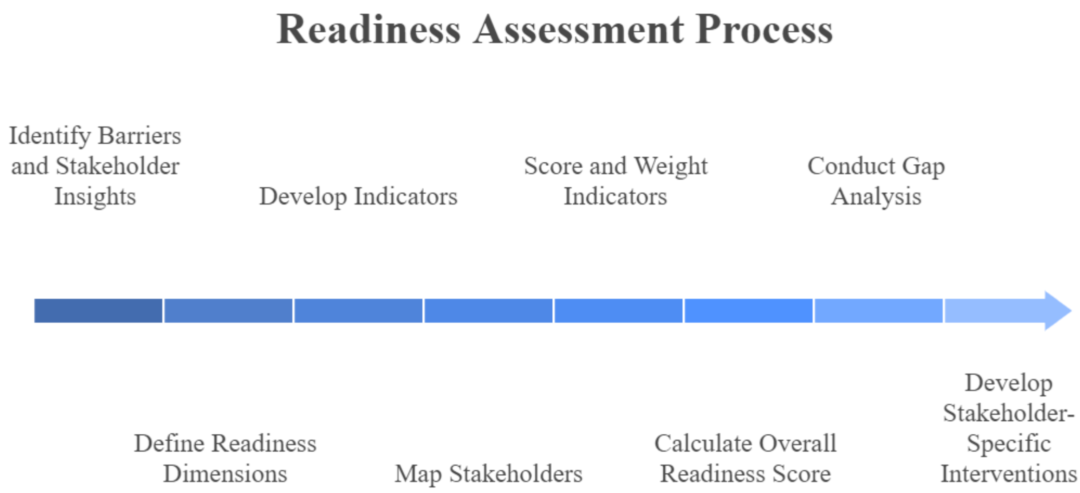



**Figure 5-7 Conceptual Flow of the Final Framework**

This flow shows that the framework is not merely descriptive. It is also diagnostic and corrective. It identifies the problem, measures its severity, determines responsibility, and suggests action.

The final model therefore operates at two levels simultaneously. At the analytical level, it evaluates readiness in a structured manner. At the practical level, it helps determine what must be improved before 3DCP adoption can move forward.

### 5.4.4 Core Principle of the Framework

The foundation of the framework is the following principle:

**"Adoption is governed by the weakest readiness dimension, and each dimension is controlled by specific stakeholders."**

This principle is critical because it explains how adoption works in a real construction environment. Readiness does not depend on the average condition of all factors. Instead, the weakest dimension often becomes the limiting factor.

For example, even if technological readiness is high, adoption may still remain low if policy support is weak or if the economic case is not convincing. Likewise, if the technical and constructability dimension is weak, the technology may be seen as unsafe or unreliable, regardless of other strengths.

This principle is particularly relevant to 3DCP because the technology is still emerging in India. Stakeholder interviews and barrier analysis suggest that the main constraints are not only technical. Cost, demand, policy clarity, and commercial compatibility are equally important. Therefore, the framework recognises that adoption will progress only when the weakest dimension is strengthened.

**Table 18 Meaning of the Core Principle**

| Situation | Effect on Adoption |
|---|---|
| Strong technology but weak policy | Adoption remains limited |
| Strong engineering but weak demand | Adoption remains commercially weak |
| Strong market interest but weak quality control | Adoption remains risky |
| Strong regulation but weak cost viability | Adoption remains difficult to scale |

This principle helps explain why new technologies in construction often remain in pilot stages for long periods. It also supports the logic of the weighted scoring system, where a single weak dimension can significantly influence the final output.

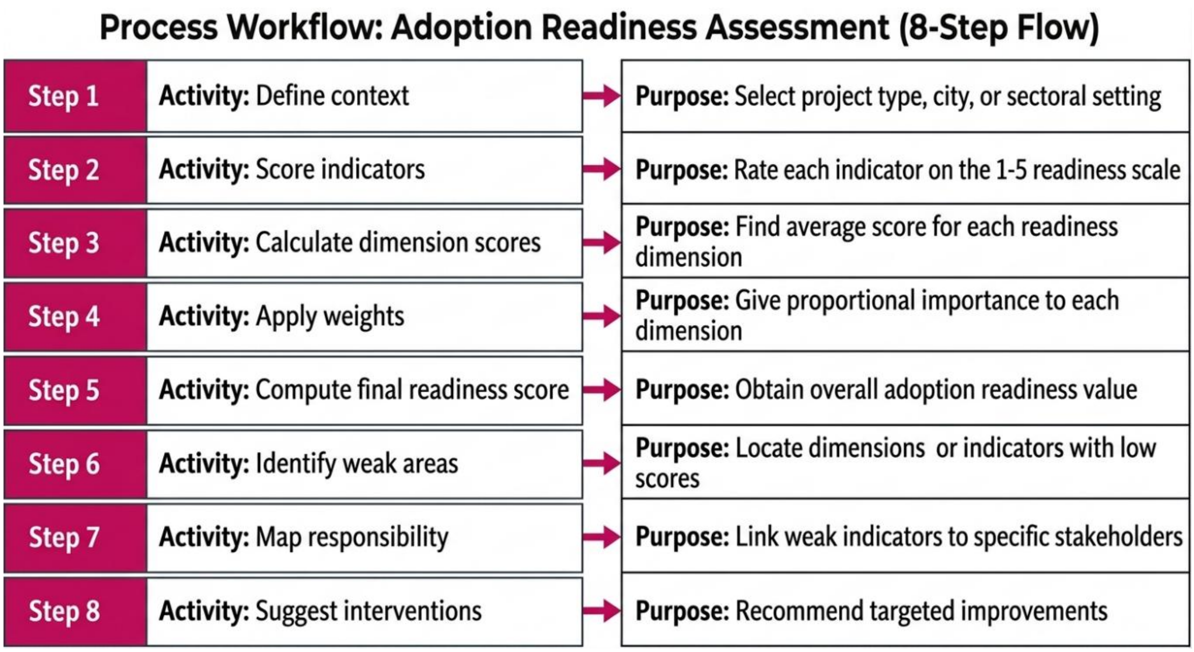
### 5.4.5 Framework Application Workflow

The framework is intended to be applied in a step-by-step manner. This makes it suitable for case-based analysis, expert assessment, or project-level evaluation.

**Table 19 Application Workflow of the Framework**

| Step | Activity | Purpose |
|---|---|---|
| Step 1 | Define context | Select project type, city, or sectoral setting |
| Step 2 | Score indicators | Rate each indicator on the 1–5 readiness scale |
| Step 3 | Calculate dimension scores | Find average score for each readiness dimension |
| Step 4 | Apply weights | Give proportional importance to each dimension |
| Step 5 | Compute final readiness score | Obtain overall adoption readiness value |
| Step 6 | Identify weak areas | Locate dimensions or indicators with low scores |
| Step 7 | Map responsibility | Link weak indicators to specific stakeholders |
| Step 8 | Suggest interventions | Recommend targeted improvements |

This process creates a structured decision pathway. It ensures that the framework does not end at scoring. It continues into interpretation and recommendation.




### 5.4.6 Interpretation of Outputs

The framework produces several kinds of output. Each output serves a different purpose in the research process.

#### *5.4.6.1 Overall Readiness Score*

The first output is the overall readiness score. This gives a summary view of how ready the system is for 3DCP adoption. It is useful for comparing different project settings or identifying whether a context is generally favourable.

#### *5.4.6.2 Dimension-wise Performance*

The second output is the performance of each readiness dimension. This is important because the overall score alone can hide critical weaknesses. A project may look moderately ready overall, but one dimension may still be very weak. Dimension-wise performance helps reveal those gaps.

#### *5.4.6.3 Stakeholder Responsibility Map*

The third output is the stakeholder responsibility map. This shows which actor is linked to which indicator. It helps identify who is responsible for addressing each weakness. This is especially important for writing recommendations.

#### 5.4.6.4 Adoption Recommendation

The fourth output is the practical adoption recommendation. Based on the final score, the context can be interpreted as suitable for no adoption, pilot adoption, limited adoption, or scaling.

**Table 20 Readiness Score Interpretation**

| Score Range | Interpretation | Meaning for Adoption |
|---|---|---|
| 1.0–2.0 | Not suitable | Major barriers remain unresolved |
| 2.1–3.0 | Pilot stage | Adoption possible only in controlled trials |
| 3.1–4.0 | Limited adoption | Adoption possible in selected cases |
| 4.1–5.0 | Ready for scaling | Environment is suitable for broader adoption |

This interpretation gives meaning to the numerical score. Without such interpretation, the score would remain only a technical output.

### 5.4.7 Dimension-wise Performance and Major Barriers

The final model is especially useful because it allows the researcher to see which dimension is strongest and which is weakest. This helps connect the framework back to the original barrier analysis.

For example:

- If **technological readiness** scores low, the issue may relate to interoperability, workflow standardization, or vendor dependence.
- If **technical and constructability readiness** scores low, the problem may lie in material behaviour, structural reliability, or quality assurance.
- If **economic readiness** scores low, the concern may be capital cost, utilisation, or weak market demand.
- If **business, policy and commercial readiness** scores low, the barrier may be missing standards, weak tender integration, or unclear approval systems.

**Table 21 Dimension-wise Meaning of Low Scores**

| Dimension | Possible Meaning of a Low Score | Likely Barrier Type |
|---|---|---|
| Technological | Digital and machine systems are not well integrated | Operational barrier |
| Technical & Constructability | Printing quality and structural safety remain uncertain | Engineering barrier |
| Economic | The technology is not financially attractive | Cost and market barrier |
| Business, Policy & Commercial | The system is not supported by regulation or procurement | Institutional barrier |

This type of interpretation ensures that the framework remains connected to the actual barriers identified in the research.

### 5.4.8 Stakeholder Responsibility Map

One of the most important strengths of the integrated model is the stakeholder responsibility map. It explains not only where the gaps are, but also who is best placed to address them.

**Table 22 Example of Stakeholder Responsibility in the Final Model**

| Low-Scoring Area | Main Responsible Stakeholder | Supporting Stakeholders | Suggested Response |
|---|---|---|---|
| Regulatory framework | Government / Regulators | Engineers, industry bodies | Develop codes and standards |
| Capital cost viability | Developers / Clients | Contractors | Explore phased investment |
| Skilled workforce availability | Contractors | Technology firms | Training and skill development |
| Material performance | Technology firms | Engineers | Improve mix and testing methods |
| Tender integration | Government / Regulators | Contractors | Include 3DCP in procurement formats |

This map is extremely useful in practice because it supports targeted action. It also strengthens the argument that adoption is a shared responsibility across the ecosystem.

### 5.4.9 Adoption Recommendations

The final framework does not stop at evaluation. It also supports recommendations for adoption improvement. These recommendations should be based on the weakest dimensions and the stakeholders associated with them.

A low score in policy readiness suggests a need for standards, code development, and procurement reform. A weak economic score suggests the need for cost reduction, market expansion, or shared equipment models. A weak technical score suggests further testing, quality control, and engineering validation. A weak technological score suggests better software-hardware integration and workflow standardization.

This makes the framework actionable. It allows the researcher to say not only "adoption is low," but also "adoption can improve if the following areas are addressed by the following stakeholders."

### 5.4.10 Contribution of the Framework

The integrated framework contributes to the study in several important ways.

First, it bridges the gap between conceptual understanding and practical assessment. The earlier stages of the framework identify what matters. The final stage shows how those factors work together.

Second, it aligns the framework with industry reality. Construction adoption is not determined by one factor alone. The integrated model reflects this by combining technical, economic, institutional, and stakeholder dimensions.

Third, it supports decision-making. The final model can be used by researchers, developers, policymakers, and industry actors to identify readiness levels and intervention points.

Fourth, it is scalable. The framework can be applied to different project types, different cities, or different adoption scenarios. It can also be adapted for future studies on other emerging construction technologies.

**Table 23 Main Contributions of the Final Framework**

| Contribution Area | Value Added by the Framework |
|---|---|

| Contribution Area | Value Added by the Framework |
|---|---|
| Research gap bridging | Moves beyond simple barrier listing |
| Practical assessment | Provides measurable readiness scoring |
| Responsibility allocation | Links barriers to specific stakeholders |
| Decision support | Helps identify intervention priorities |
| Scalability | Can be applied across contexts and project types |

## 5.5 Integrated Framework Conclusion

The final integrated framework should be understood as a **dynamic adoption system model**. It is not just a list of barriers, nor is it only a scoring mechanism. It is a structured system that explains how readiness is created, where it breaks down, who influences it, and how it can be improved.

This integrated understanding is important because 3DCP adoption in India will not depend only on technical advancement. It will depend equally on whether the market is ready, whether the regulations are supportive, whether contractors can execute the work, whether developers see value in the technology, and whether the broader ecosystem is willing to adapt.

In this sense, the framework captures the real complexity of adoption in a practical and academically defensible way.

**"The proposed Stakeholder-Driven, Barrier Driven 3DCP Adoption Readiness Framework integrates technical, economic, and institutional dimensions with stakeholder responsibilities to evaluate and improve the adoption potential of 3D concrete printing in the Indian construction industry."**

## 5.6 Working example for Framework

### 5.6.1 Project context for the example

Assume a **private developer in Ahmedabad, Gujarat** is considering a **low-rise G+1 affordable housing demonstration block** using 3D concrete printing. The project is small enough to be technically possible, but it still needs municipal approval, contractor coordination, material planning, and a financial justification. This makes it a strong test case for the framework because it sits between **pilot feasibility** and **real market adoption**.

**<u>The project involves the following stakeholders:</u>**

- **Developer/Client**: decides whether the pilot is worth funding
- **3DCP technology firm**: provides printer, software, and printing support
- **Contractor**: manages site execution, logistics, and labour coordination
- **Structural engineer**: checks load path, reinforcement, and structural safety
- **Architect/computational designer**: adapts the design for printability
- **Municipal/regulatory authority**: handles approval and compliance
- **Financial institution/insurer**: evaluates risk and funding comfort

### 5.6.2 How the framework is applied

The framework is used in four steps:

1. **Score each indicator** on a 1–5 scale
2. **Average indicators within each dimension**
3. **Apply weights** to reflect importance
4. **Interpret the final readiness score** and identify the main barriers

### 5.6.3 Indicator scoring for the example

#### *5.6.3.1 Technological readiness*

This dimension checks whether the digital and machine systems can work together smoothly.

**Table 24 Technological Readiness Score**

| Indicator | Score | Reason for score |
|---|---|---|
| Printer–process integration | 3 | The technology firm can integrate design and printing, but some manual coordination is still needed. |
| Digital workflow standardization | 2 | BIM-to-print workflow exists only in a partially standard form. |
| Interoperability across platforms | 3 | Basic data transfer is possible, but not fully seamless across all software tools. |
| Dependency on proprietary systems | 2 | The setup still depends heavily on vendor-specific tools and settings. |

**Technological dimension score = (3 + 2 + 3 + 2) / 4 = 2.50**

**Interpretation:**

The technology is usable for a pilot, but it is not yet mature enough for broad or routine deployment. The main issue is not complete failure; it is lack of full standardization and interoperability.

### *5.6.3.2 Technical and constructability readiness*

This dimension checks whether the printed structure can be safely and practically built.

**Table 25 Technical and Constructability Readiness Score**

| Indicator | Score | Reason for score |
|---|---|---|
| Material rheology control | 3 | The mix can be controlled in a pilot setup, but site sensitivity remains. |
| Interlayer bond strength | 2 | Bonding is still a concern and needs careful monitoring. |
| Structural reliability | 2 | The engineer accepts the concept only with conservative assumptions and checks. |
| Durability performance | 2 | Long-term exposure performance is still not fully established. |
| Quality control framework | 2 | Testing exists, but no standard acceptance system is fully mature. |
| Site execution feasibility | 3 | A low-rise open site is workable, but space and logistics still need control. |
| Skilled workforce availability | 2 | Some trained people are available, but the workforce is still limited. |

**Technical dimension score = (3 + 2 + 2 + 2 + 2 + 3 + 2) / 7 = 2.29**

**Interpretation:**

The project is technically possible, but the main concern is build confidence. The largest issues are bonding, durability, quality control, and skill availability. This is exactly the kind of condition the framework is designed to expose.

### *5.6.3.3 Economic readiness*

This dimension checks whether the project makes financial sense.

**Table 26 Economic Readiness Score**

| Indicator | Score | Reason for score |
|---|---|---|
| Capital cost viability | 2 | Initial printer and setup cost is still high for a small pilot. |
| Material cost | 2 | Material costs are not yet clearly cheaper than conventional |

| | | |
|---|---|---|
| feasibility | | methods. |
| Productivity and utilisation | 3 | Printing speed is promising, but equipment use across projects is still limited. |
| Market demand | 3 | The developer is interested, but demand is still exploratory, not large-scale. |

**Economic dimension score = (2 + 2 + 3 + 3) / 4 = 2.50**

**Interpretation:**

The project has some economic promise, but the cost case is still weak. The technology looks more suitable for a demonstration or niche project than for normal market rollout.

#### *5.6.3.4 Business, policy and commercial readiness*

This dimension checks whether the legal and commercial environment supports adoption.

**Table 27 Business, Policy and Commercial Readiness Score**

| Indicator | Score | Reason for score |
|---|---|---|
| Regulatory framework availability | 1 | Dedicated BIS/IS standards are not yet in place. |
| Tender integration | 2 | The method does not fit standard BOQ/procurement structures easily. |
| Approval and compliance clarity | 2 | Municipal review is possible, but the approval route is not fully clear. |
| Financing accessibility | 2 | Funders show interest, but they remain cautious because the technology is new. |
| Insurance coverage | 1 | Insurance and warranty comfort is still weak. |
| Commercial scalability | 2 | The method may work as a pilot, but scale-up is uncertain. |
| Standardization of contracts | 2 | Contracting structures are possible, but not yet standardised. |

**Business/policy dimension score = (1 + 2 + 2 + 2 + 1 + 2 + 2) / 7 = 1.71**

**Interpretation:**

This is the weakest dimension. The project can move as a pilot, but the institutional environment is not yet ready for mainstream deployment. This is the clearest sign that the technology is still in an early adoption stage in India.

### 5.6.4 Weighting strategy and why it is used

The weighting is not arbitrary. It reflects the stakeholder interviews and the Indian adoption context.

**Table 28 Final weights used in this example**

| Dimension | Weight | Why this weight is justified |
|---|---|---|
| Technological | 0.15 | Important, but usually not the main blocker if suppliers can support the system. |
| Technical and constructability | 0.25 | Safety and buildability matter strongly in construction decisions. |
| Economic | 0.35 | Cost, utilisation, and demand were repeatedly highlighted as dominant barriers. |
| Business, policy and commercial | 0.25 | Regulations, approval, tendering, and insurance determine whether adoption can move beyond pilots. |

- The interviews suggest that even when the technology is available, adoption is often delayed by cost and uncertainty about demand. That is why economic readiness receives the strongest weight.
- Without code support, procurement fit, and insurance confidence, the technology cannot enter normal project systems. So policy has to carry significant weight.
- Without code support, procurement fit, and insurance confidence, the technology cannot enter normal project systems. So policy has to carry significant weight.
- Construction must remain safe and buildable. A weak technical base can stop adoption even if the market is willing.

### 5.6.5 Final readiness calculation

Using the weighted formula:

$$\text{Overall Readiness Score} = (T \times 0.15) + (Tech \times 0.25) + (E \times 0.35) + (B/P \times 0.25)$$

Where:

- Technological = 2.50
- Technical = 2.29
- Economic = 2.50
- Business/Policy = 1.71

**Calculation**

- Technological: 2.50 × 0.15 = **0.375**
- Technical: 2.29 × 0.25 = **0.5725**
- Economic: 2.50 × 0.35 = **0.875**
- Business/Policy: 1.71 × 0.25 = **0.4275**

**Final score**

$$0.375 + 0.5725 + 0.875 + 0.4275 = 2.25$$

**Overall readiness score = 2.25 / 5**

### 5.6.6 Interpretation of the final output

According to the framework bands:

**Table 29 Framework Bands**

| Score range | Meaning |
| --- | --- |
| 1–2 | Not suitable |
| 2–3 | Pilot stage |
| 3–4 | Limited adoption |
| 4–5 | Ready for scaling |

**<u>Final interpretation</u>**

A score of **2.25** places the project in the **pilot stage**.

That means:

- The project is **not ready for scaling**
- It may work as a **controlled demonstration**
- It still has serious gaps in **policy, insurance, and standardization**
- It needs **technical monitoring, cost justification, and stakeholder coordination**

This is exactly the kind of output the framework is meant to produce.

The framework does not merely say "adoption is low." It tells us **why**.

**<u>Main barriers surfaced by the example</u>**

- Lack of dedicated standards
- Weak insurance and warranty support

- High setup cost
- Limited repeat demand
- Incomplete workflow standardization
- Structural and durability uncertainty
- Limited workforce readiness

**Most critical bottleneck**

The weakest dimension is **business, policy, and commercial readiness**. That means the project may be technically possible, but it is not yet institutionally ready for broad use.

**Stakeholder responsibility**

- **Government/regulators**: develop code and approval pathways
- **Developers/clients**: create demand and accept pilot risk
- **Technology firms**: strengthen interoperability and reliability
- **Engineers**: improve structural confidence
- **Contractors**: manage site feasibility and skills
- **Insurers/financiers**: reduce commercial uncertainty

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# APPENDIX

**Annexure 1 Phase-1 Generic Question**

| Sr. No. | Question | Why Relevant | Targeted Barriers | Listen for |
|---|---|---|---|---|
| 1 | From your perspective, what are the major practical challenges in implementing 3D concrete printing in Indian construction projects? | Gateway question to surface dominant barriers organically without priming categories. | All categories (technical, economic, regulatory, organisational, environmental). | Cost, approvals, reliability, skills, testing, risk, demand. |
| 2 | How technically mature do you think 3D concrete printing is for Indian construction conditions today? | Reveals perceived technological readiness level. | Technical maturity, durability, QC standards, process integration. | Lab vs site gaps, need for R&D, pilot limitations. |
| 3 | What technical uncertainties make you hesitant (or confident) in using 3DCP for structural applications? | Encourages discussion on structural reliability. | Reinforcement detailing, durability, load-path, seismic concerns. | Structural equivalence, long-term performance, code validation. |
| 4 | How do Indian climatic and site conditions influence the feasibility of 3D concrete printing? | Explores environmental variability impact. | Rheology, pumpability, curing, geometric stability. | Heat, humidity, dust, monsoon, wind. |
| 5 | How compatible is 3DCP with existing construction workflows and site practices? | Assesses integration feasibility. | Process integration gaps, organisational readiness. | Coordination issues, sequencing challenges. |
| 6 | What additional technical validations or tests would you require before adopting 3DCP at scale? | Identifies trust gaps in standards. | QC/testing standards, BIS absence. | Shear tests, durability data, certification. |
| 7 | How do you see reinforcement being integrated into 3D printed structures in Indian projects? | Probes structural practicality. | Load-path detailing, hybrid systems, seismic compliance. | Manual insertion, conventional slabs, connectors. |
| 8 | What economic factors most influence your decision to invest in 3D concrete printing technology? | Explores investment drivers. | CapEx, utilisation risk, ROI uncertainty. | Payback years, capital recovery. |
| 9 | How would you compare the cost predictability of 3DCP projects with conventional construction? | Examines financial risk perception. | Productivity risk, supply risk, revenue uncertainty. | Uncertain material cost, downtime. |
| 10 | How do current procurement and tendering systems in India support or restrict the adoption of 3DCP? | Explores procurement misalignment. | BOQ format, L1 rules, tender barriers. | No line items, format mismatch. |
| 11 | What regulatory or statutory approvals would you anticipate as critical for 3D printed buildings? | Captures approval friction. | Municipal uncertainty, BIS standards absence. | Structural review, fire NOC. |
| 12 | How prepared do you think the current workforce is for handling 3DCP technologies? | Assesses skill readiness. | Skill shortage, training needs. | Printer operators, digital modelling gaps. |
| 13 | How receptive are clients and end-users toward 3D printed buildings? | Explores demand and perception. | Market demand uncertainty. | Durability concerns, resale value doubts. |
| 14 | What organisational changes would your firm need before deploying 3DCP at scale? | Surfaces internal readiness gaps. | Organisational resistance, process gaps. | New SOPs, workflow changes. |
| 15 | Does 3DCP currently offer measurable environmental or sustainability advantages? | Tests sustainability perception. | Circularity, green incentives absence. | Waste reduction, LCA evidence. |

| Sr. No. | Question | Why Relevant | Targeted Barriers | Listen for |
|---|---|---|---|---|
| 16 | What risks (technical, financial, reputational) do you associate with early adoption of 3DCP? | Captures risk perception. | Insurance gaps, structural liability. | Warranty concerns, performance guarantees. |
| 17 | How do existing Indian codes and standards accommodate or constrain 3DCP? | Examines regulatory compatibility. | Code fragmentation, absence of standards. | Equivalence interpretation issues. |
| 18 | Would you prefer to adopt 3DCP through in-house ownership, partnerships, or outsourcing? Why? | Explores business model preference. | Capital cost, utilisation risk, vendor lock-in. | Control vs risk sharing. |
| 19 | What type of projects do you believe are most suitable for 3DCP in India? | Identifies viable segments. | Demand uncertainty, feasibility constraints. | Low-rise housing, non-load-bearing elements. |
| 20 | What changes would make you more willing to adopt 3DCP? | Solution-oriented closing question. | All categories. | Need for standards, incentives, training. |

**Annexure 2 Phase-1 Interview Summary**

| Sr. No. | Category | Code | Analytic Write-up / Summary of What Stakeholder Said | Which interview questions are covered |
|---|---|---|---|---|
| 1 | Contractor | CON-1 | This stakeholder provided an integrated account of practical delivery constraints observed during their 3D concrete printing pilots. Their narrative mapped across the entire adoption chain: material science (rheology and site-driven mix variability), process control (pump choice, hopper recirculation, closed-loop controllers), structural detailing (interlayer bond weakness and hybrid reinforcement solutions), procurement and commercial considerations (BOQ ambiguity, utilization thresholds for CapEx recovery), regulatory and insurance friction (municipal review lead times, insurer hesitancy), workforce capability gaps, and environmental management (waste and slurry disposal). The stakeholder also outlined pragmatic remedies used on pilots: progressive cavity pumps, re-wetting passes for delayed layers, hybrid cast band-beams and dowels, laser-level feedback and temporary bracing, and preference for leasing in pilot phases. | Q1 (pump pressure / hopper behaviour) — detailed discussion of field moisture, sand grading, hopper recirculation and progressive cavity pumps.<br>Q2 & Q6 (interlayer bond measurement & tests) — cited interlayer gap thresholds (8–12 minutes), core shear reduction (approx. 15–20%), and acceptance pack approach.<br>Q3 (geometry deviations) — example of 5–7 mm drift on a 3.2 m wall; mitigation via layer-height sensing and thinner layers.<br>Q4 (reinforcement integration) — explained cast band-beams, couplers, manual insertion issues and seismic concerns.<br>Q5 (durability) — raised durability concerns and need for long-term test data.<br>Q8 & Q9 (CapEx & cost predictability) — utilisation threshold ~55% and leasing preference for pilots.<br>Q10 & Q12 (tender & approvals) — lack of BOQ lines and 4–8 week municipal review windows.<br>Q11 (insurance) — insurers asking for additional evidence, higher premiums/refusals.<br>Q13–Q14 (skills & resistance) — trained operator shortage, G-code/frame mismatch examples.<br>Q15 (waste/EoL) — over-extrusion waste handling, slurry disposal.<br>Q16 (LCA) — hints that green procurement could affect decisions.<br>Q17 (seismic) — explicit demand for couplers or conventional continuity in seismic zones.<br>Q18 & Q19 (site logistics & IP) — gantry footprint constraints; prefabrication favored in congested sites; mention of G-code errors and the need for trained digital modelers. |

| Sr. No. | Category | Code | Analytic Write-up / Summary of What Stakeholder Said | Which interview questions are covered |
|---|---|---|---|---|
| 2 | Contractor | CON-2 | This stakeholder, representing a major residential developer, frames 3DCP adoption primarily through a risk governance and lifecycle liability lens, rather than through operational or material science concerns. While acknowledging technical feasibility, the stakeholder emphasizes structural equivalence, long-term durability data absence, institutional approval uncertainty, cost predictability, and reputational risk as primary barriers.<br>Unlike the contractor (Stakeholder 1), who focused on pumpability and process control, this developer-centric response highlights:<br>-Absence of codified design standards<br>-Liability exposure in residential development<br>-Downstream trade coordination and tolerance sensitivity<br>-Market acceptance and buyer perception<br>-Governance and audit risks in procurement<br>-Insurance conservatism | Q3 & Q4 (Structural uncertainty & reinforcement integration) — highlighted slab-wall continuity and diaphragm action concerns.<br>Q5 (Durability & exposure) — emphasized lack of long-term performance data.<br>Q1 & Q4 (Pumpability & site effects) — observed extrusion inconsistency affecting surface finish.<br>Q3 (Geometric tolerances) — concern about dimensional deviation affecting downstream trades.<br>Q8 & Q9 (Economic factors & cost predictability) — lack of cost stability and productivity clarity.<br>Q10 (Tender & BOQ alignment) — governance risk due to absence of standardized BOQ.<br>Q11 (Insurance) — premium loading and conditional warranties.<br>Q12 (Approvals) — IIT certification requests, fire department documentation.<br>Q13 (Skills gap) — site engineers not trained in digital workflows.<br>Q15 & Q16 (Sustainability & LCA incentives) — sustainability claims not monetizable.<br>Q18 (Site logistics) — gantry footprint constraints.<br>Q20 (Reform pathways) — clear need for BIS guidelines and pilot approval frameworks. |
| 3 | Technology provider | TECH-1 | This stakeholder provides a technology-provider viewpoint, emphasizing system-level integration challenges. Unlike contractors or developers, this perspective focuses on machine sensitivity, mix design consistency, maintenance costs, and ecosystem immaturity. The respondent clearly distinguishes between:<br>-Technical constraints (material–machine interaction)<br>-Institutional barriers (standards & approvals)<br>-Commercial barriers (cost predictability & utilization)<br>-Workforce capability gaps<br>This layered framing is analytically valuable for your thesis because it reveals that 3DCP adoption barriers are not isolated but systemic. | Q1 (pump pressure & clogging) — detailed explanation of fines variation, pressure spikes, stator-rotor wear.<br>Q2 & Q6 (interlayer bond tests) — highlighted absence of standard test protocol and variability in test methods.<br>Q3 (geometry deviation) — discussed early-age creep and wind effects.<br>Q4 (reinforcement integration) — hybrid detailing required; consultants insist on conventional continuity.<br>Q5 (durability) — implied long-term performance uncertainty.<br>Q8 (capital cost) — printer CapEx and O&M cost issues.<br>Q9 (material procurement risk) — industrial sand and admixture supply variability.<br>Q10 (tender misalignment) — printed walls not fitting BOQ structures.<br>Q11 (insurance) — premium loading and validation requirements.<br>Q12 (approvals) — lack of BIS code leads to project-by-project negotiation.<br>Q13 (skills shortage) — interdisciplinary operator gap.<br>Q15 (waste & sustainability) — waste during trial runs; energy consumption.<br>Q18 (site logistics) — gantry footprint constraint.<br>Q19 (data/IP) — proprietary slicing algorithms and contract complexity.<br>Q20 (reform needed) — ecosystem alignment. |

| Sr. No. | Category | Code | Analytic Write-up / Summary of What Stakeholder Said | Which interview questions are covered |
|---|---|---|---|---|
| 4 | Technology provider | TECH-2 | This stakeholder introduces a critical systems-level insight: 3DCP is fundamentally an automation-control challenge interacting with a material science challenge. This perspective reframes common assumptions. While earlier stakeholders emphasized mix variability and regulatory barriers, this respondent highlights:<br>-Closed-loop vs open-loop control<br>-Synchronization between extrusion rate and robot velocity<br>-Calibration drift<br>-BIM-to-G-code translation errors<br>-Automation safety compliance gaps<br>-Vendor interoperability constraints | Q1 (pump pressure & clogging) — emphasis on control loop stability and sensor feedback.<br>Q2 (interlayer bonding) — link between Z-axis accuracy and bond quality.<br>Q3 (geometric deviation) — cumulative drift, thermal expansion, wind impact.<br>Q4 (reinforcement integration) — hybrid detailing due to lack of integrated robotic reinforcement.<br>Q7 (file conversion issues) — BIM-to-G-code translation bottlenecks.<br>Q8 (capital cost) — closed-loop systems increasing CapEx.<br>Q9 (utilization risk) — need for continuous pipeline.<br>Q10 (procurement culture) — project-based procurement limiting utilization.<br>Q11 (insurance) — experimental classification.<br>Q12 (approval & safety) — municipal unfamiliarity with automation.<br>Q13 (skills gap) — multidisciplinary operator requirement.<br>Q15 (sustainability) — limited embodied carbon reduction unless full system replacement.<br>Q18 (site logistics) — safety zoning requirements.<br>Q19 (vendor lock-in/IP) — proprietary control systems.<br>Q20 (reforms) — performance-based standards & certified training. |
| 5 | Technology provider | TECH-3 | This stakeholder emphasizes digital integration and ecosystem maturity as the core adoption barriers. Compared to earlier technology providers, this perspective places stronger focus on:<br>-BIM-to-fabrication maturity<br>-Print-aware design education gap<br>-Interoperability standards absence<br>-Data logging and quality monitoring discipline<br>-Economic viability depending on geometry complexity<br>-Cement content and sustainability tradeoffs | Q1 (pumpability) — variability in batching and water quality.<br>Q2 (interlayer bonding) — importance of timing and pressure.<br>Q3 (geometric deviation) — tall wall stability & path planning.<br>Q4 (reinforcement integration) — hybrid systems & seismic caution.<br>Q7 (file conversion issues) — lack of standard BIM-to-G-code workflows.<br>Q8 & Q9 (economic viability) — cost advantage conditional on geometry complexity and labor context.<br>Q10 (procurement misalignment) — L1 tender system discouraging innovation.<br>Q11 & Q12 (standards & approvals) — absence of BIS code and unpredictable approvals.<br>Q13 (skills gap) — interdisciplinary talent shortage.<br>Q15 (sustainability & embodied carbon) — cement content tradeoffs.<br>Q18 (site logistics) — power reliability and foundation requirements.<br>Q19 (IP & interoperability) — lack of universal file format standard.<br>Q20 (reforms needed) — ecosystem evolution required. |

| Sr. No. | Category | Code | Analytic Write-up / Summary of What Stakeholder Said | Which interview questions are covered |
|---|---|---|---|---|
| 6 | Technology provider | TECH-4 | This stakeholder provides a material-centric perspective, emphasizing rheological control, durability performance, testing standardization gaps, and supply-chain inconsistency as primary barriers to adoption. This response is especially important because it deepens the technical and environmental dimensions of your barrier framework with concrete (no pun intended) material science insights.<br>Unlike previous technology providers who focused on digital integration or control systems, this stakeholder stresses:<br>-Narrow rheological windows<br>-Moisture and grading sensitivity<br>-Fiber dispersion challenges<br>-Shrinkage and heat of hydration effects<br>-Carbon footprint tradeoffs<br>-Sampling variability in core extraction<br>-Supply chain immaturity for fine aggregates | Q1 (pump pressure & clogging) — attributed to aggregate grading variability and moisture inconsistency.<br>Q2 & Q6 (interlayer bonding & tests) — lack of BIS-specified bond thresholds; variability in shear/splitting tensile tests.<br>Q5 (durability & exposure) — shrinkage cracking, carbonation, chloride penetration, fire performance data gaps.<br>Q4 (reinforcement integration) — fiber reinforcement limits and hybrid necessity.<br>Q8 & Q9 (material cost & supply risk) — higher cement and admixture cost; supply inconsistency.<br>Q15 (sustainability) — carbon tradeoff due to increased binder.<br>Q11 & Q12 (standards & approvals) — absence of BIS guidance; additional lab validation burden.<br>Q13 (skills gap) — lack of rheology awareness among site engineers.<br>Q18 (logistics) — transportation and regional aggregate inconsistency. |
| 7 | Contractor | CON-3 | This stakeholder provides a commercial risk and project governance viewpoint within a large contractor organization. While Stakeholder 1 focused on operational and technical execution, this respondent emphasizes:<br>-Productivity predictability<br>-Cost certainty<br>-Risk allocation<br>-Insurance exposure<br>-Tender structure rigidity<br>-Auditor scrutiny<br>-Cash flow impact from approval delays | Q8 (capital cost & utilization rate) — uncertainty around real productivity vs theoretical output.<br>Q9 (cost predictability) — rework percentage and downtime risk.<br>Q10 (tender & BOQ alignment) — L1 system & lack of innovation scoring.<br>Q11 (insurance) — premium loading and risk management caution.<br>Q12 (approval delays) — structural validation affecting cash flow.<br>Q13 (skills gap) — dependency on vendor-trained teams.<br>Q18 (site logistics) — gantry feasibility limited to large sites.<br>Q15 & Q16 (sustainability incentives) — carbon reduction not monetized.<br>Q20 (reform pathways) — BIS standards, MEAT scoring, structured insurance. |
| 8 | Contractor | CON-4 | This stakeholder provides a design, ESG, and lifecycle asset management perspective within a major residential developer. This perspective deepens the sustainability and perception-related barriers while reinforcing structural reliability concerns.<br>Unlike CON-2 (who focused more on liability and procurement), this respondent emphasizes:<br>-Architectural integration<br>-Dimensional tolerance impact on downstream trades<br>-Lifecycle durability expectations (50+ years)<br>-ESG reporting alignment<br>-Brand equity and resale perception<br>-Maintenance protocol uncertainty | Q3 (geometric deviation) — tolerance affecting architectural components.<br>Q5 (durability & exposure) — carbonation, chloride penetration, fire performance.<br>Q2 (interlayer bonding skepticism) — structural review concerns.<br>Q15 & Q16 (sustainability & LCA) — carbon accounting and ESG recognition.<br>Q10 (procurement & governance) — audit scrutiny.<br>Q11 (insurance) — conservative risk assessment.<br>Q13 (skills gap) — print-aware design training need.<br>Q18 (site logistics) — urban plot constraints.<br>Q20 (reforms needed) — performance standards and demonstration projects. |

**Annexure 3 Phase-2 Specific Questionnaire**

| Sr. no. | Questions |
|---|---|
| Technological Barriers | |
| 1 | How well do the different digital tools and machine systems currently work together in a typical 3DCP workflow? |
| 2 | At what stage of the workflow do coordination gaps usually appear between design, planning, and printing operations? |
| 3 | How smooth is the transfer of information from digital design models to machine execution in practice? |
| 4 | What kinds of software or hardware compatibility issues are most commonly experienced during implementation? |
| 5 | To what extent do current systems depend on specific vendors or proprietary platforms? |
| 6 | How flexible are the existing digital workflows when project conditions, design requirements, or machine settings change? |
| 7 | What improvements would make the overall technology setup more reliable and easier to integrate into regular construction practice? |
| Technical Barriers | |
| 1 | How consistent is the printed material behaviour under different project and environmental conditions? |
| 2 | What are the main concerns when it comes to printed layer quality, bonding, and structural continuity? |
| 3 | How confident are stakeholders in the long-term performance of printed elements under real site conditions? |
| 4 | In your view, how effectively can current 3DCP practices address structural safety requirements? |
| 5 | What types of testing or quality checks are most necessary before a printed component can be accepted on site? |
| 6 | How suitable is 3DCP for actual construction site conditions, especially where access, space, or logistics are limited? |
| 7 | What kind of skills or training are currently needed to make on-site execution more dependable? |
| Economic Barriers | |
| 1 | How do stakeholders currently view the overall financial attractiveness of 3DCP compared with conventional construction methods? |
| 2 | Which cost elements appear to have the greatest influence on the feasibility of adopting this technology? |
| 3 | How practical is the current level of investment required for equipment, material systems, and setup? |
| 4 | To what extent does the technology show value through productivity or time savings in real projects? |
| 5 | How frequently can the equipment realistically be used across projects to justify the investment? |
| 6 | What kind of market response or project demand is necessary before the technology becomes commercially attractive? |
| 7 | How stable or predictable does the revenue potential appear for firms considering this technology? |
| Business, Policy & Commercial Readiness | |
| 1 | How well does the current regulatory environment support the use of 3DCP in formal construction projects? |
| 2 | What challenges arise when trying to fit 3DCP into existing tendering or procurement processes? |
| 3 | How clear are the approval, compliance, and documentation requirements for projects using this method? |
| 4 | What role do financing arrangements play in deciding whether this technology can move beyond pilot use? |
| 5 | How prepared are insurers or risk agencies to support projects involving this type of construction method? |
| 6 | How easily can 3DCP be incorporated into standard contract structures or project agreements? |
| 7 | What conditions would help the technology move from isolated cases to more regular commercial use? |
| Regulatory Barriers | |

| Sr. no. | Questions |
|---|---|
| 1 | How clear is the current regulatory path for approving 3DCP-based construction projects? |
| 2 | In your experience, how well do existing standards and codes accommodate this type of construction method? |
| 3 | At what stage do approval-related uncertainties usually appear in a 3DCP project? |
| 4 | How easy or difficult is it to align 3DCP with existing public procurement and tendering processes? |
| 5 | What kinds of issues arise when authorities review the materials, systems, or plant setup used for 3DCP? |
| 6 | How consistent is the interpretation of 3DCP-related provisions across different approving bodies or jurisdictions? |
| 7 | What changes in the regulatory environment would make this technology easier to adopt in mainstream projects? |
| Social Barriers | |
| 1 | How familiar do different stakeholder groups seem to be with 3DCP as a construction method? |
| 2 | What kinds of concerns are most commonly expressed by professionals when this technology is discussed? |
| 3 | How readily do you think the workforce can adapt to a process that involves more automation and digital coordination? |
| 4 | What is the general perception of this technology in relation to labour roles and workforce transition? |
| 5 | How prepared are current project teams to handle the operational and safety aspects of this method? |
| 6 | In your view, how strong is the trust in post-construction support, insurance, or warranty-related arrangements for such projects? |
| 7 | What would help improve acceptance of 3DCP among practitioners, clients, and the wider industry? |
| Environmental Barriers | |
| 1 | How suitable are typical project sites for handling the logistics required by 3DCP? |
| 2 | What environmental or site-related conditions tend to affect the smooth implementation of this technology? |
| 3 | How well do current 3DCP practices deal with material handling, storage, and movement on site? |
| 4 | In your view, how easy is it to manage waste, reuse, or circularity concerns in this construction method? |
| 5 | What challenges arise when considering end-of-life planning or reuse of printed elements? |
| 6 | How compatible is 3DCP with sustainability-based procurement or green project requirements? |
| 7 | What site or environmental improvements would make the method more practical and scalable? |
| Organisational Barriers | |
| 1 | How prepared are firms internally to introduce a technology like 3DCP into their existing workflows? |
| 2 | What changes are usually needed within an organisation before such a technology can be adopted successfully? |
| 3 | How well do teams across design, execution, and management functions communicate when working on new construction methods? |
| 4 | What kinds of coordination challenges appear when multiple stakeholders are involved in a 3DCP project? |
| 5 | How open are firms to changing established processes when a new technology is introduced? |
| 6 | What role does internal knowledge sharing or training play in making adoption smoother? |
| 7 | What organisational conditions would need to improve before 3DCP becomes easier to mainstream within firms? |
| Business-Model Barriers | |
| 1 | How convincing is the current business case for adopting 3DCP in Indian construction projects? |
| 2 | What factors most strongly influence whether a firm sees this technology as financially worthwhile? |

| Sr. no. | Questions |
|---|---|
| 3 | How clear is the long-term return on investment when compared with conventional construction methods? |
| 4 | What types of financial support or risk-sharing mechanisms seem necessary for wider adoption? |
| 5 | How comfortable are clients and developers with the payback period or lifecycle value of this technology? |
| 6 | What challenges arise when trying to align 3DCP with standard project financing or commercial planning? |
| 7 | What business conditions would make this technology more attractive for repeated use across projects? |

**Annexure 4 Phase-2 Interview Summary**

| Stakeholder | Summary of Interview/Interaction |
|---|---|
| Architect-1 | This discussion shows that 3D concrete printing in India is still in a developmental and experimental stage, with Tvasta and similar firms working mainly on iconic, high-value, private projects rather than mass-market construction. The respondent highlighted that the biggest barriers are R&D dependence, lack of industrial-level machine/material maturity, absence of strong government standards, limited site flexibility, and high skill requirements.<br>A major point from the interview is that the technology is not yet fully supported by BIS/IS-based regulatory systems, and much of the current work relies on company-specific certification and internal consultancy review rather than standardized public norms. The respondent also stressed that repetition, precision, and trained computational design skills are essential for successful implementation.<br>The conversation also suggests that cost is a major barrier, but not the only one. While 3D printing can reduce labour needs and save time, it requires specialized knowledge, custom software workflows, and controlled site conditions, which makes it difficult to adopt widely in ordinary Indian projects. End-of-life issues, demolition, and site logistics are also still unresolved. |
| Professor-1 | This interview strongly supports the argument that:<br>The primary barrier to adoption of 3D concrete printing in India is not technological limitation, but misalignment with market demand, cost structures, and commercialization pathways.<br>The adoption ecosystem is constrained by a chain of dependencies:<br>• High cost → Low demand → Weak policy support → Limited scalability<br>As a result, 3D concrete printing currently remains:<br>• A niche innovation<br>• Suitable for specialized or high-value projects<br>• Not yet viable for mainstream construction in India |
| Contractor-1 | This interview shows that contractors view 3D concrete printing as a full production system rather than a stand-alone machine. The main concerns are printer-process integration, BIM and data interoperability, site constraints, rheology and pumpability, interlayer adhesion, reinforcement detailing, durability, quality control, high capital cost, utilisation risk, material supply uncertainty, and weak market demand. The contractor's perspective makes it clear that adoption depends not only on technical feasibility, but also on whether the system can fit real site conditions and commercial realities. |
| Contractor-2 | This interview highlights the contractor's commercial and operational concerns around 3DCP. The response touches on material sensitivity, execution disruption, coordination difficulty, cost of equipment, training burden, revenue uncertainty, liability ambiguity, quality assurance gaps, supply chain risk, vendor lock-in, finance access, and insurance limitations. The contractor perspective shows that adoption depends on whether the technology can become reliable, repeatable, and commercially recoverable within standard project delivery systems. |
| Developer-1 | The stakeholder emphasizes that the primary barrier to 3DCP adoption is not just technological or economic, but institutional and systemic, particularly the lack of regulatory frameworks, standardized codes, and clear tender mechanisms. Barriers such as BIM integration, material performance, quality control, and high capital costs exist, but can be overcome if adoption is driven through government-led policies and tender requirements. A top-down approach—where higher authorities mandate and enforce adoption—can act as a catalyst for industry-wide transformation. Ultimately, embedding 3DCP into public procurement systems is seen as the most effective trigger for scaling adoption and developing the required ecosystem. |

| Stakeholder | Summary of Interview/Interaction |
|---|---|
| Developer-2 | This interview shows that developers judge 3D concrete printing primarily through commercial viability, not technological interest alone. The key concerns are capital recovery, weak ROI, high customization cost, low market demand, financing risk, vendor dependency, and the lack of a stable repeatable business model. The developer also reflects contractor caution, especially regarding liability, delays, and site-level execution risk. Overall, the response shows that adoption is limited because the technology has not yet become bankable, scalable, or easy to price into mainstream residential development. |
| Developer-3 | This interview highlights the developer's focus on repeatability, total project economics, cash flow, portfolio risk, and market acceptance. The main issues are high system-level cost, weak return visibility, incomplete support ecosystems, limited market demand, and uncertainty over long-term commercial viability. The developer also reflects contractor concerns around liability, pricing, and execution uncertainty. Overall, the response shows that 3DCP remains commercially promising but strategically difficult to position within standard Indian development models. |
| Technology Provider | This interview shows that technology providers view 3D concrete printing as an ecosystem challenge rather than a single-machine solution. The main technological barriers discussed are printer-process integration, site adaptability, repeatability, material consistency, BIM and data interoperability, vendor lock-in, quality control, durability, and the lack of stable testing standards. On the business-model side, the response highlights high capital cost, maintenance burden, recurring training needs, weak repeat demand, revenue uncertainty, and the difficulty of building a scalable service model. The overall message is that the market is interested but not yet mature enough to support widespread commercial adoption. |