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Path Dependencies in Construction 3D Printing Adoption: A Comparative Interpretive Structural Modelling Study of India and Australia

Ayaz Ahmad Khan [1,*], Mohammad Arqam [2], Joeri Tuijn [2] and Mehdi Amirkhani [1]

[1] Adelaide University Online and Learning Futures, Adelaide University, Adelaide, SA 5000, Australia; mehdi.amirkhani@adelaide.edu.au
[2] The Ignition Chamber, Unit 8/8 George St, Bunbury, WA 6230, Australia; arqam@straightcurve.com.au (M.A.); joeri@straightcurve.com.au (J.T.)
* Correspondence: ayaz.khan01@adelaide.edu.au

Abstract

Construction 3D printing (C3DP) is increasingly viewed as a transformative construction technology that can reduce material waste, shorten project timelines, enable geometric complexity, and support low-carbon material strategies. However, its large-scale deployment remains limited and uneven across contexts. This study examines barriers to C3DP adoption in India and Australia through 17 semi-structured expert interviews (8 from India, 9 from Australia) involving stakeholders from academia, industry, and government. Using thematic content analysis and Pareto prioritisation, barriers were grouped into six domains, policy, economic, social, technological, environmental, and legal, with the "vital few" factors accounting for ~80% of influence identified. Findings reveal that institutional barriers, particularly the absence of standards, certification pathways, and insurer-recognised liability frameworks, are the most significant constraints in both countries. Economic barriers (high capital costs, uncertain return on investment) and technological barriers (skill shortages and lack of performance-validated QA/QC protocols) also rank highly. Contextual differences are evident: in India, regulatory fragmentation, material variability, and cultural reliance on masonry limit adoption; in Australia, risk-governance norms, procurement conservatism, and strict compliance dominate. Overall, C3DP adoption is framed as a socio-technical transition rather than purely technological diffusion.

Keywords: additive manufacturing; construction 3D printing; PARETO analysis; barriers; India; Australia

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1. Introduction

The global construction sector is under increasing pressure to enhance productivity, reduce material waste, and transition toward low-carbon building practices [1,2]. Despite being one of the world's largest industrial activities, responsible for approximately 37% of global energy- and process-related CO_2 emissions, the industry continues to rely heavily on labour-intensive, resource-intensive, and sequential production techniques that have changed little over recent decades [3,4]. Conventional construction methods frequently experience schedule overruns, material inefficiencies, workforce shortages, and safety risks, while rapid urbanisation and housing affordability pressures further intensify the demand for innovation [5,6]. These structural challenges have stimulated interest in advanced

fabrication technologies capable of simultaneously addressing productivity, sustainability, and cost imperatives [7].

Additive Manufacturing (AM) has emerged as one such transformative pathway within the broader agenda of Construction 4.0 [8,9]. Defined as the layer-by-layer fabrication of components directly from digital models, AM enables geometric flexibility, process automation, and localised material deployment, thereby reducing reliance on fragmented supply chains and minimising waste [10,11]. Within the AM family, Construction 3D Printing (C3DP) or 3D Concrete Printing has gained significant attention over the past decade, enabling the automated production of building elements and, increasingly, entire structural systems either on-site or in prefabricated settings [12–14]. Research increasingly positions C3DP as a digital-physical integration technology capable of linking parametric design, robotics, and material science in a unified workflow, thereby reshaping construction processes and value chains [15,16].

Although C3DP has attracted growing market, academic, and policy interest, its benefits have not yet translated into routine construction practice. Empirical studies report potential advantages such as reduced material use, shorter construction times, improved safety, and greater design flexibility; however, these remain largely concentrated in pilot projects and controlled demonstrations rather than widespread industry adoption [17–20].

Despite these advantages, global adoption remains uneven and fragmented. While technologically advanced regions have established research hubs, commercial demonstrators, and early regulatory discussions, many developing economies face persistent constraints related to capital cost, regulatory ambiguity, skills shortages, and supply chain immaturity [21–23]. Even in developed markets, diffusion is often slowed by certification conservatism, liability allocation concerns, and entrenched procurement cultures [8,24]. This uneven trajectory suggests that the viability of C3DP is not determined solely by technological readiness, but by the alignment of institutional, economic, and socio-cultural conditions, a proposition consistent with socio-technical transition theory [25].

Within this context, India and Australia provide a particularly meaningful comparative setting. India, a rapidly developing economy facing substantial housing deficits and urban infrastructure demands, has shown growing interest in C3DP for affordable and rapid applications [26]. However, adoption remains constrained by limited codification, uneven technological capacity, workforce training gaps, and fragmented investment in research and development. Australia, by contrast, represents a technologically advanced and highly regulated construction environment with active academic and industrial experimentation in C3DP. Yet uptake remains moderated by industry conservatism, certification and insurance concerns, and gradual standardisation processes [23]. The two countries also maintain strong bilateral ties in education and research collaboration, suggesting potential for policy learning and knowledge transfer across differing developmental contexts [27].

Although the existing literature has examined C3DP adoption within individual jurisdictions, comparative empirical studies across developed and developing contexts remain limited. Research in India has largely focused on materials development and prototype demonstrations [26], while Australian studies frequently emphasise digital integration, regulatory readiness, or organisational innovation [23]. Global reviews categorise barriers broadly, highlighting cost uncertainty, skill shortages, standardisation gaps, and material reliability, but provide limited insight into how these barriers interact hierarchically or reinforce one another across different socio-economic environments [14,24]. There remains insufficient understanding of the structural interdependencies among barriers and the path dependencies that shape adoption trajectories in distinct national contexts.

The scientific novelty of this study lies in moving beyond the identification and categorisation of C3DP adoption barriers toward a comparative structural explanation of how

these barriers interact across different institutional settings. While previous studies have commonly reported barriers such as cost uncertainty, skill shortages, material limitations, regulatory gaps, and certification challenges, they have provided limited explanation of which barriers act as upstream drivers, which operate as downstream outcomes, and how these relationships differ between developing and developed construction ecosystems. This study addresses this gap by integrating Political, Economic, Social, Technological, Environmental, Legal (PESTEL), Pareto analysis, and Total Interpretive Structural Modelling (TISM) to identify the dominant barriers and model their hierarchical and path-dependent relationships in India and Australia.

Addressing this gap, the present study investigates the barriers to C3DP adoption in India and Australia using a PESTEL analytical framework supported by qualitative expert interviews in both countries. Moving beyond descriptive categorisation, the study employs Pareto analysis and TISM to identify the "vital few" barriers and theorise their hierarchical and transitive relationships. The central research problem is therefore to explain why C3DP remains difficult to scale despite demonstrated technical feasibility, and how these adoption barriers are structurally interrelated across different national settings.

Accordingly, the study pursues the following objectives:

i. To identify and empirically validate the barriers to C3DP adoption in India and Australia;
ii. To categorise and structure these barriers using the PESTEL framework;
iii. To model the hierarchical interrelationships and path dependencies among the vital barriers using interpretive structural modelling techniques.

This study makes three main contributions. First, it provides a comparative empirical analysis of C3DP adoption barriers in India and Australia, two contexts with different institutional maturity, regulatory structures, and market conditions. Second, it advances methodological understanding by integrating PESTEL, Pareto analysis, and TISM to move from descriptive barrier categorisation toward structural modelling of barrier interdependencies. Third, it contributes practical insight by identifying context-specific leverage points for policymakers, regulators, technology providers, and industry stakeholders seeking to move C3DP from pilot experimentation to scalable implementation.

2. Literature Review

2.1. C3DP Within the Digital Transformation of Construction

The construction industry has long been characterised by low productivity growth, fragmented supply chains, labour-intensive processes, and high levels of cost and schedule uncertainty [28]. Compared with manufacturing and other industrial sectors, automation penetration in construction remains limited, while its environmental footprint, particularly from cement-based production, contributes significantly to global carbon emissions [3,29]. These persistent inefficiencies have intensified interest in digitalisation and automation under the broader Construction 4.0 paradigm [30,31].

AM, particularly C3DP, has emerged as a key technological pathway within this transformation. C3DP enables the layer-by-layer deposition of structural and non-structural materials directly from digital models, integrating computational design, robotic control, and material science into a continuous fabrication workflow [8,18]. Since 2014, advances in toolpath optimisation, printable mix design, robotic precision, and sensor-based monitoring have enabled the transition from laboratory prototypes to full-scale demonstrators, including residential units, bridges, and customised facade elements [13,14]. However, the technological capability of C3DP depends on the controlled interaction between material rheology, nozzle geometry, extrusion rate, robotic travel speed, layer height, open time, and

environmental conditions [32]. Poor alignment among these factors can reduce dimensional accuracy, filament continuity, inter-layer bonding, anisotropic strength, durability, and overall structural reliability [33]. Figure 1 summarises key C3DP benefit claims, which should be viewed as potential outcomes dependent on standards, material validation, quality assurance, procurement, and workforce capability. These include time and productivity gains through elimination of conventional formwork, cost efficiencies at scale, material optimisation via near-net-shape deposition, enhanced design freedom and customisation, improved safety through reduced manual handling, alignment with circular economy principles, supply chain localisation, and digital quality integration [9,34]. Rather than representing isolated advantages, these dimensions collectively suggest that C3DP constitutes a system-level innovation capable of reshaping construction workflows, resource use patterns, and project delivery models [16].

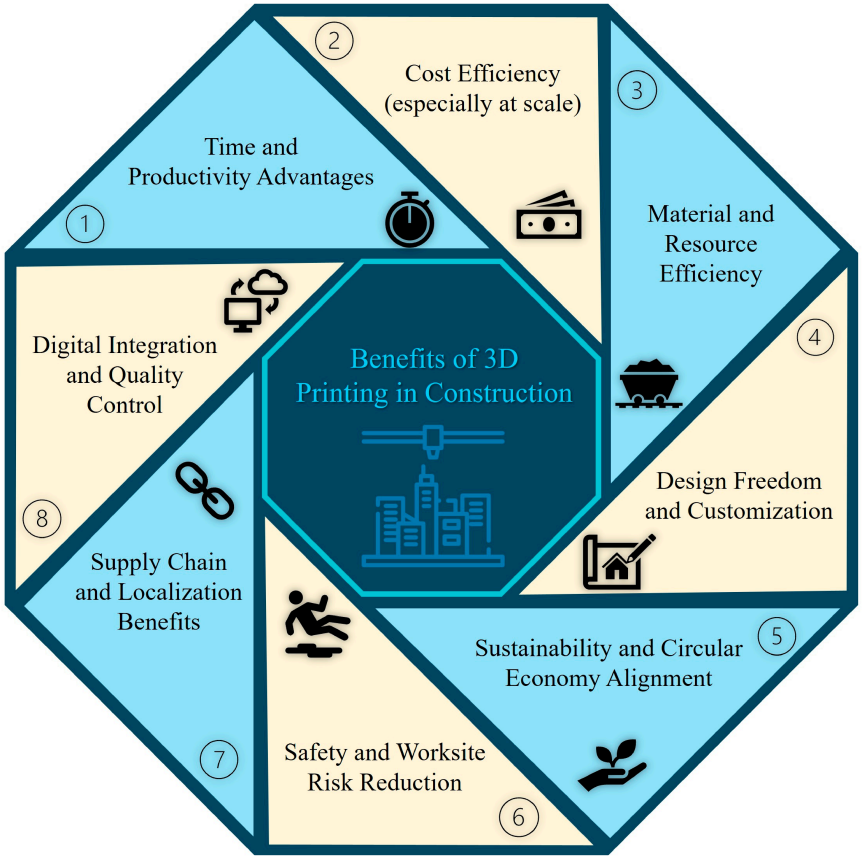


Figure 1. Benefits of C3DP in Construction.

Despite these promising attributes and strong market growth projections, C3DP adoption remains limited relative to its theoretical potential. Demonstration projects are increasing globally; however, mainstream diffusion across national construction ecosystems has not yet materialised, indicating the presence of structural and contextual constraints beyond purely technical feasibility. This creates an adoption contradiction: technical feasibility and high-profile pilots expand, yet routinised uptake remains constrained, implying that barriers operate as a coupled system rather than independent factors.

2.2. Multidimensional Barriers to C3DP Adoption

The existing literature consistently identifies C3DP adoption as a socio-technical challenge rather than a purely engineering problem. Barriers extend across political, economic, social, technological, environmental, and legal domains [35]. These recurring themes are synthesized in Figure 2, which structures the barriers within a PESTEL framework. This

classification reflects dominant patterns observed in prior studies and provides a structured analytical basis for examining how constraints interact across governance, market, and technical dimensions.

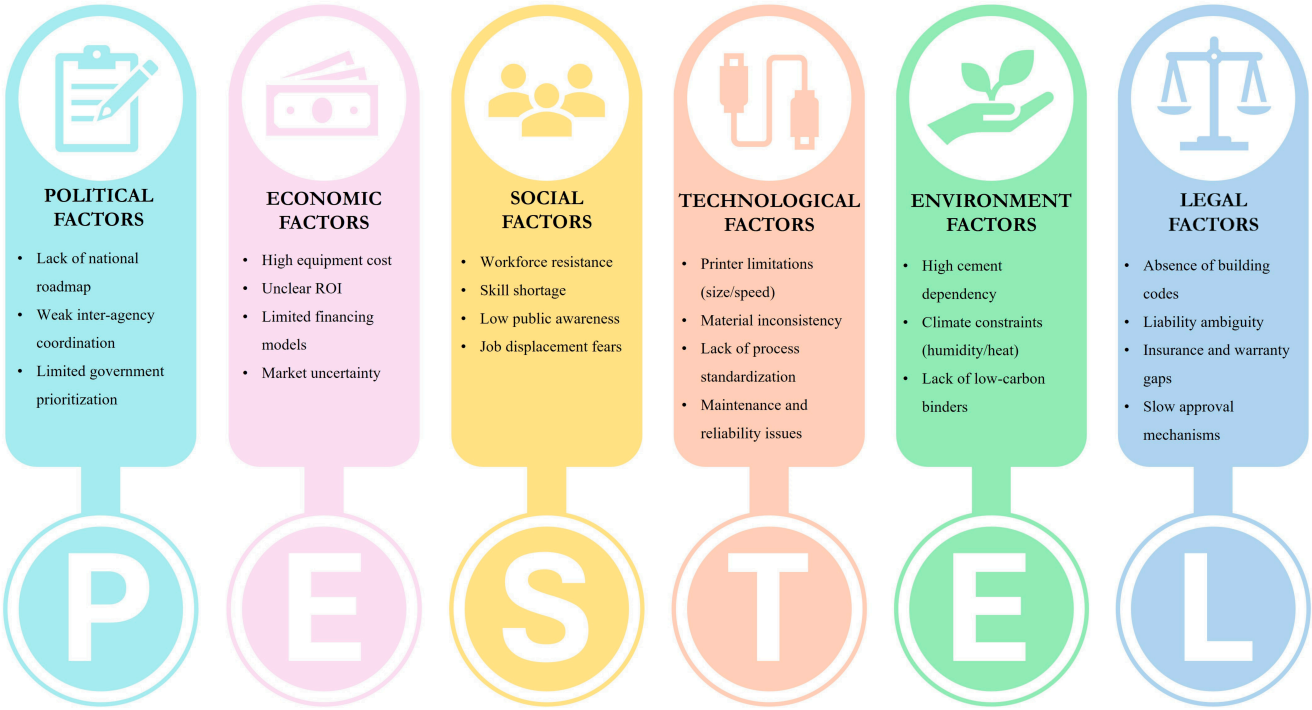


Figure 2. Barriers to C3DP application.

Politically and institutionally, the absence of unified roadmaps, limited inter-agency coordination, and slow policy integration creates uncertainty for investors and project sponsors. In several contexts, printed structures are approved through exceptional procedures rather than codified pathways, restricting scalability [23]. Economically, high capital costs of large-scale printers, proprietary pumping systems, and specialised material formulations combine with uncertain return-on-investment calculations and irregular project pipelines to discourage sustained investment [25].

Social barriers include workforce resistance, skill shortages, job displacement concerns, and limited acceptance among clients, professionals, regulators, and workers [22]. These barriers should not be viewed as fixed cultural resistance, but as technology acceptance issues shaped by perceived usefulness, reliability, compatibility with existing construction practices, and perceived risk. Concerns about printed textures, long-term durability, labour impacts, and unfamiliar construction processes reflect limited observability and trialability, reinforcing the need for successful pilot projects, professional training, and clearer evidence of relative advantage [36]. Technologically, unresolved issues in material consistency, interlayer bonding performance, reinforcement integration, dimensional tolerance, and process standardisation continue to influence structural assurance and certifier confidence [24]. Similarly, knowledge- and graph-based additive manufacturing studies show that process–performance relationships can be predicted where materials, process parameters, and mechanical outcomes are interdependent, offering a useful methodological parallel for C3DP quality assurance [37].

Environmental considerations present both opportunities and constraints. While C3DP can reduce material waste and enable alternative low-carbon binders, its current reliance in many cases on cement-rich mixtures and climate-sensitive curing behaviour may undermine sustainability claims unless validated and regionally adapted systems are

implemented [38]. Recent studies on low-carbon cementitious composites using industrial by-products, such as lithium slag, further highlight the need to assess C3DP sustainability through material performance, microstructural behaviour, and life-cycle evidence [39]. Legally, slow certification procedures, liability ambiguity, insurance conservatism, and limited explicit building code provisions for printed elements significantly delay procurement approvals and increase perceived risk exposure. A recurring limitation is that institutional, legal, and insurance constraints are often described separately, even though they function as a single assurance chain that determines whether printed elements are certifiable, insurable, and therefore procurable.

PESTEL organises C3DP barriers but can remain descriptive if categories are treated separately. In practice, barriers are interdependent: regulatory uncertainty delays certification, reduces insurer/procurement confidence, weakens investment, limits demonstrations, and slows training. Thus, the key challenge is how upstream governance barriers reproduce downstream technical, economic, and social constraints. Collectively, these barriers demonstrate that C3DP diffusion is embedded within broader institutional and regulatory architectures. Technology performance alone does not guarantee mainstream adoption; rather, alignment between policy frameworks, market incentives, and professional norms is required. Without modelling these dependencies, prior work cannot distinguish leverage points from symptoms, which motivates the use of interpretive structural modelling to recover hierarchy, transitivity, and path dependence among barriers. Additionally, most PESTEL-based reviews classify barriers, but they rarely explain which barriers are upstream drivers, which are downstream consequences, or how regulatory and market assurance mechanisms amplify technical uncertainties.

2.3. Context Sensitivity and National Ecosystems

A critical insight emerging across reviews is that C3DP barriers are not uniform across national contexts. In developing economies, constraints frequently relate to institutional formation and capacity-building: limited R&D investment, immature supply chains for printable materials, shortage of trained personnel, and absence of codified standards [26,40]. Regulatory ambiguity and fragmented governance structures may prevent pilot successes from translating into systemic adoption.

In developed economies, however, barriers are often anchored in regulatory conservatism and risk governance rather than technological immaturity. Established building codes, insurance systems, and procurement frameworks can slow integration when novel fabrication methods challenge traditional compliance logics [16,41]. Here, adoption bottlenecks arise from liability allocation, certification complexity, and integration within mature quality assurance (QA) ecosystems.

This distinction aligns with socio-technical transition theory, which posits that technological innovations must align with existing regulatory regimes, market structures, and socio-cultural expectations to achieve diffusion [42]. Thus, the same technology may encounter fundamentally different structural constraints depending on national institutional maturity and governance architecture. However, the developed versus developing framing can obscure the fact that adoption readiness varies by state, client type, and procurement pathway; therefore, national context should be treated as a structured institutional configuration rather than a simple category.

2.4. India and Australia as Comparative Cases

India and Australia represent analytically contrasting yet strategically relevant adoption ecosystems. India faces rapid urbanisation, housing deficits, and infrastructure expansion pressures, making efficient and resource-conscious construction methods highly

desirable. While pilot projects have demonstrated feasibility, widespread adoption remains limited by evolving codification, workforce capability gaps, and fragmented institutional coordination [26].

Australia, in contrast, operates within a technologically advanced and highly regulated construction environment. Research institutions and industry actors actively explore robotic fabrication and digital workflows; however, adoption remains moderated by certification conservatism, insurance ambiguity, and gradual incorporation of additive methods into established standards and procurement practices [23,43]. Here, integration within a mature compliance ecosystem represents the primary challenge.

This comparison is therefore interpreted as an analytical contrast between two stages of C3DP ecosystem maturity, rather than evidence of fixed national characteristics. Further, the comparison is not intended to treat either country as internally homogeneous; rather, it provides an analytical contrast between dominant institutional conditions identified in the expert data. India reflects an emerging adoption environment where regulatory formation, skills development, and material validation are still consolidating, whereas Australia reflects a more mature but risk-governed environment shaped by certification, insurance, procurement systems, and additive manufacturing knowledge-exchange capabilities [44].

Despite their developmental differences, both countries prioritise sustainable infrastructure, digital transformation, and resilient built environments [27]. India represents an emerging C3DP adoption context shaped by rapid urbanisation, housing demand, infrastructure expansion, and evolving regulatory, skills, and material validation systems. Australia represents a highly regulated developed-market context with stronger research and digital construction capacity, but where certification, insurance, procurement conservatism, and risk-governance expectations can slow adoption. Their contrasting institutional architectures make them suitable cases for comparative structural analysis. This contrast enables the study to examine whether C3DP barrier hierarchies are stable across contexts or re-ordered by institutional maturity and governance architecture, directly aligning the case selection with the TISM objective.

2.5. Research Gap and Study Positioning

Although prior studies have catalogued barriers to C3DP adoption, three key limitations remain evident. First, most investigations examine countries independently, limiting cross-context comparison. Second, barriers are frequently presented descriptively without modelling their systemic interrelationships. Third, few studies employ interpretive modelling techniques to explicate hierarchical ordering and path dependencies among barrier categories.

Previous C3DP studies identify barriers such as cost uncertainty, lack of standards, skill shortages, material limitations, certification delays, and market hesitation, but rarely explain how these barriers are structurally connected. This study addresses that gap by using PESTEL to organise barriers and TISM to identify their linkages, hierarchy, and transitive relationships. Here, "path dependency" refers to how early regulatory gaps, institutional routines, procurement norms, and capability limitations constrain later adoption. For example, absent standards can delay certification, reduce insurance confidence, restrict procurement and investment, and weaken wider market legitimacy. Consequently, there is limited understanding of which barriers function as foundational drivers, which operate as downstream outcomes, and how these configurations differ across developing and developed ecosystems. The present study addresses these limitations by developing a comparative PESTEL-based taxonomy of C3DP barriers in India and Australia, identifying the "vital few" constraints through Pareto analysis, and theorising their hierarchical and transitive relationships using TISM. By shifting from list-based identification to structured

systemic interpretation, the study advances understanding of how emerging construction technologies diffuse within distinct national socio-technical systems. Using socio-technical transition theory, this study views C3DP adoption as a regime-level alignment issue involving regulation, market trust, and verification, not just gradual technological diffusion.

While PESTEL classifies C3DP barriers, it does not explain how they reinforce one another. TISM addresses this limitation by identifying directional and hierarchical relationships, showing how upstream governance barriers, such as weak standards, certification uncertainty, liability ambiguity, and fragmented approvals, can reproduce downstream constraints related to investment confidence, quality assurance, workforce readiness, procurement acceptance, and end-user trust [36].

Conceptually, this study integrates PESTEL with socio-technical transition, institutional, and innovation diffusion theories. These perspectives explain how C3DP adoption depends on alignment among technology, regulation, markets, users, legitimacy, compatibility, trialability, observability, and perceived risk. Thus, PESTEL categories are interpreted not as isolated barrier groups, but as interconnected elements within national adoption systems.

A critical reading of the existing C3DP adoption literature shows that prior studies have made important contributions by identifying recurring barriers related to material performance, structural validation, cost uncertainty, skills, regulation, certification, and market acceptance [10,22,26,34,45]. However, much of this literature remains descriptive because barriers are commonly presented as parallel lists or broad thematic categories. This limits understanding of how barriers reinforce one another, which constraints act as root causes, and how adoption pathways differ across institutional contexts. In particular, limited attention has been given to the transition from barrier identification to structural explanation. The present study responds to this limitation by using PESTEL to organise the barrier domains, Pareto analysis to identify the most prominent constraints, and TISM to interpret the hierarchical and path-dependent relationships among them in India and Australia.

3. Materials and Methods

This study adopted a qualitative, multi-stage research design to identify, prioritise, and structurally interpret the barriers influencing C3DP adoption in India and Australia. The methodological sequence integrates semi-structured interviews, qualitative content analysis, Pareto-based prioritisation, and interpretive structural modelling. The overall research framework is illustrated in Figure 3. Given the emerging nature of C3DP and the context-dependent characteristics of its diffusion, a qualitative approach grounded in expert insight was considered appropriate for capturing institutional, technological, and socio-economic dynamics [46].

3.1. Data Collection: Semi-Structured Expert Interviews

Participants were selected using purposive sampling to ensure direct engagement with C3DP research, development, policy, or implementation [47]. The sampling strategy targeted professionals with expertise in printable materials, robotic systems, digital workflows, regulatory processes, sustainability assessment, and project deployment. This ensured that responses reflected practice-based and institutional knowledge rather than speculative opinion [48].

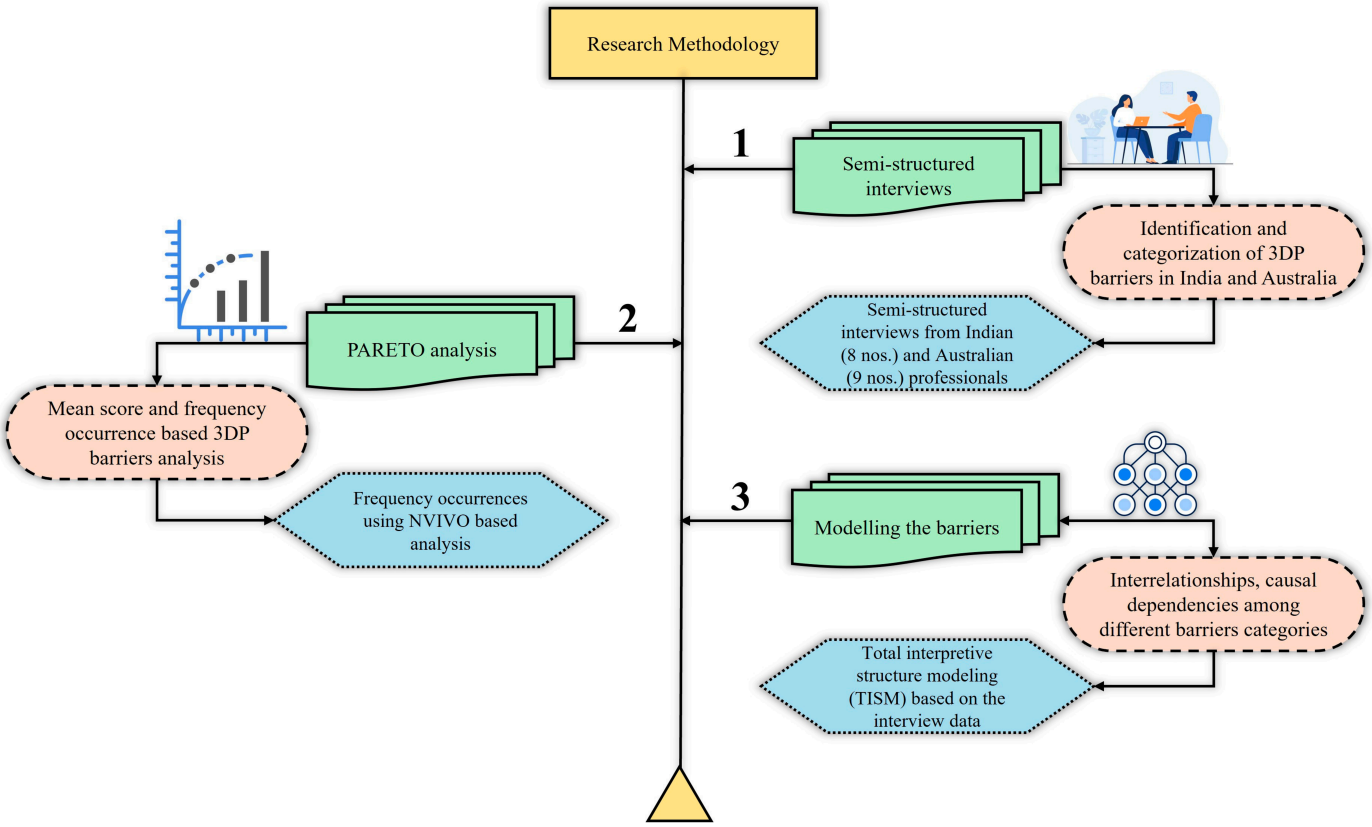


Figure 3. Research method of the study.

A total of 17 semi-structured interviews were conducted, eight in India and nine in Australia. The detailed interview protocol is mentioned in Appendix A. The sample includes representation from academia, industry, and government, enabling examination of technological, organisational, regulatory, and environmental perspectives. The sample size was appropriate for this exploratory study, as participants were selected for direct C3DP expertise across research, policy, materials, robotics, project delivery, sustainability, and regulation rather than statistical representativeness. The study prioritised analytical depth and reached thematic saturation, with no substantially new PESTEL barrier categories emerging in later interviews. Interviewees' experience in C3DP ranged from one to nine years and covered both experimental research and pilot-scale application.

Interviews were conducted via Zoom and lasted between 35 and 60 min. A flexible interview guide encouraged discussion on regulatory readiness, economic feasibility, material reliability, workforce capability, environmental considerations, and scaling constraints. The interview guide was developed from the C3DP, Construction 4.0, additive manufacturing, and PESTEL literature, then reviewed for clarity, neutrality, and alignment with the study objectives. Its semi-structured format ensured consistent theme coverage while allowing participants to provide project, policy, testing, procurement, or institutional examples. The conversational format enabled participants to articulate tacit and context-specific insights [49]. All interviews were audio-recorded, transcribed verbatim, anonymised, and processed in accordance with institutional ethics approval.

3.2. Barrier Identification and Pareto-Based Prioritisation

Interview transcripts were analysed using qualitative content analysis to systematically extract references to C3DP adoption barriers [50]. NVivo (Version 14) software facilitated coding and thematic organisation. Initial open coding captured both explicit and implicit mentions of constraints, after which codes were consolidated into higher-order

themes aligned with the PESTEL framework. The PESTEL structure was employed as an organising lens to categorise political, economic, social, technological, environmental, and legal dimensions of constraint [6]. This categorisation reflects recurring patterns observed in both the literature and interview narratives rather than an externally imposed typology.

To strengthen the reliability of the qualitative coding process, an intercoder reliability audit was conducted before applying Pareto analysis. A subset of 60 representative meaning units from the India and Australia interview transcripts was coded using the six PESTEL-based barrier categories. The main coding was compared with an independent/audit coding check, and Cohen's kappa was calculated to assess agreement. The result showed strong consistency between the two coding rounds ($\kappa = 0.900$), indicating almost perfect agreement. Any coding disagreements were reviewed and resolved before finalising the coding structure. This procedure provided additional methodological support for using frequency counts in the subsequent Pareto prioritisation. Table 1 below presents the coding reliability assessment, and Appendix B details the overall reliability audit.

Table 1. Coding reliability assessment.

Item	Description
Coding framework	PESTEL-based barrier categories
Reliability method	Intercoder reliability audit
Sample used	60 representative meaning units from India and Australia
Agreement measure	Cohen's kappa
Reliability coefficient	$\kappa = 0.900$
Interpretation	Almost perfect agreement
Disagreement resolution	Disagreements reviewed and resolved before final coding

Frequency occurrence counts were then extracted to distinguish commonly recurring systemic barriers from isolated concerns. To differentiate foundational constraints from peripheral issues, Pareto analysis was applied [51]. Pareto analysis was used not to imply causal weight, but to identify the concentration of perceived influence across expert narratives. Nevertheless, coded frequency was not treated as a direct measure of causal importance. A barrier mentioned more frequently was interpreted as more prominent within the expert narratives, but not necessarily as objectively more causal or more influential in practice than a less frequently mentioned barrier. For this reason, Pareto analysis was used only as an exploratory prioritisation technique, while TISM was used to interpret perceived structural relationships among the prioritised barriers. Barriers were ranked by frequency within each national dataset, and cumulative percentage distributions were calculated to identify the "vital few" categories accounting for the majority of references [52]. Importantly, prioritisation was conducted separately for India and Australia to preserve contextual specificity. This stage ensured that subsequent modelling focused on the most influential barrier categories rather than an undifferentiated list of themes. Tables 2 and 3 are list of interviewees from India and Australia.

Table 2. Interview participants from India.

ID	Sector	Role/Title	Discipline	3D Printing Exp. (yrs)	Focus Area	Rationale for Inclusion
IN-01	Academia	Senior lecturer	Civil engineer	8	Cementitious mix design, structural validation	R&D in C3DP materials
IN-02	Academia	Associate professor	Architect	3	Geopolymer concrete, sustainable construction	Blends design sustainability with digital fabrication
IN-03	Industry	Chief technical officer	Mechanical engineer	7	Printer automation, extrusion systems	Industry person in 3D printed housing
IN-04	Industry	Senior project engineer	Civil engineer	4	On-site construction integration	Brings execution-level project insight
IN-05	Government	Senior scientist	Materials scientist	5	Testing, durability, quality standards	Connect materials research with policy
IN-06	Industry	Director	Environmental engineer	2	Circular materials, embodied carbon reduction	Links sustainability targets with C3DP potential
IN-07	Government	Deputy director	Civil engineer	1	Building code formulation	Provides regulatory and standardisation insights
IN-08	Government	Advisor	Urban planner	2	Policy, affordable housing innovation	Policy perspective on technology adoption

Table 3. Interview participants from Australia.

ID	Sector	Role/Title	Discipline	3D Printing Exp. (yrs)	Focus Area	Rationale for Inclusion
AU-01	Academia	Senior lecturer	Civil engineer	9	C3DP materials, robotics	Researcher in C3DP
AU-02	Academia	Senior lecturer	Architect	4	BIM-design automation, parametric workflows	Academic connecting digital design with fabrication
AU-03	Industry	Innovation manager	Civil engineer	3	Construction innovation, project delivery	Manages the field deployment of C3DP pilots
AU-04	Industry	Chief executive officer	Mechanical engineer	6	Printer hardware, robotics integration	Technology innovator in 3D construction
AU-05	Government	Senior engineer	Materials engineer	5	Material R&D, testing and validation	Provides insight into national R&D and quality standards
AU-06	Government	Policy analyst	Urban planner	2	Housing policy, innovation programs	Brings a policy-level housing and innovation perspective
AU-07	Industry	Sustainability consultant	Environmental engineer	2	Life cycle assessment (LCA), green certification, embodied carbon	Sustainability benchmarking and rating systems
AU-08	Government	Standards officer	Civil engineer	1	Building codes, certification frameworks	Key link for regulatory and code readiness
AU-09	Academia	Research fellow	Structural engineer	3	BIM-AI integration, C3DP automation	Early-career researcher on digital fabrication pipelines

Validation was strengthened through four procedures. First, participant selection followed purposive criteria to ensure direct relevance to C3DP research, policy, implementation, or regulation. Second, the interview guide was reviewed internally before data collection to ensure alignment with the study objectives and PESTEL domains. Third, interview evidence was triangulated across participant groups, including academia, industry, and government. Fourth, the coded barriers and TISM relationships were checked against repeated patterns in the transcripts rather than relying on single isolated statements.

3.3. Interpretive Structural Modelling and Comparative Analysis

Following prioritisation, the shortlisted barrier categories were examined using TISM to explore directional, hierarchical, and transitive relationships among them. TISM is particularly suited to emerging technological domains where structural relationships are derived through expert reasoning, qualitative evidence, and interpretive logic rather than large statistical datasets [53,54]. In this study, TISM was used to structure expert-informed dependencies among the most influential C3DP adoption barriers, rather than to claim statistically tested causality.

The TISM process followed six steps: finalising the vital barriers separately for India and Australia; identifying pairwise relationships from coded interview evidence; developing the Structural Self-Interaction Matrix (SSIM); converting the SSIM into a binary reachability matrix; verifying transitive relationships; and conducting level partitioning to identify root-level, intermediate, and dependent barriers.

In this study, structural linkages were inferred from interview narratives in which participants described how one category influenced or reinforced another. To reduce individual expert bias, TISM relationships were included only when supported by repeated cross-interview evidence or strong domain-specific justification. These relationships were cross-checked against coded transcript evidence and compared across academic, industry, and government participants. This ensured that the hierarchy reflected recurring systemic dependencies rather than isolated anecdotes, consistent with relationship-based reasoning in additive manufacturing systems [55].

These interpretive linkages were synthesised to develop hierarchical structures distinguishing root-level drivers from intermediate and outcome-level barriers. The modelling process was applied independently to the Indian and Australian datasets to capture country-specific structural dynamics. Given the small expert sample, the TISM models are interpreted as context-sensitive, expert-informed structural representations rather than statistically generalisable national models.

The resulting models represent interpretive hierarchical configurations rather than statistically validated causal systems. By comparing the two national structures, the study identifies how institutional maturity, regulatory governance, economic incentives, and technological readiness shape distinct adoption path dependencies across developing and developed contexts. Detailed SSIMs, reachability matrices, transitivity verification, and level-partitioning tables are provided in Appendix C.

Accordingly, the TISM hierarchies should be interpreted as exploratory and context-dependent representations of perceived barrier relationships, rather than comprehensive models of national C3DP adoption ecosystems. Although the purposive sample captured expert perspectives from academia, industry, and government, it did not include all possible stakeholder groups or regional, organisational, sectoral, and procurement contexts within India and Australia. Different participant groups, project types, or sub-national settings may therefore produce additional barriers or alternative hierarchical relationships.

A limitation of TISM is that the model structure depends on expert interpretation and researcher judgement when defining directional relationships among barriers. Al-

though this study reduced subjectivity through cross-interview recurrence, stakeholder triangulation, coded evidence, and research-team review, the resulting hierarchy remains an interpretive representation of perceived dependencies. It should therefore be understood as a structured analytical model rather than an empirically validated causal system.

4. Results and Findings

4.1. Categorisation of C3DP Barriers

Following the literature review, the barriers to the adoption of C3DP were initially organised into six PESTEL-based categories. During the semi-structured interviews conducted with professionals from India (n = 8) and Australia (n = 9), the participants were asked to discuss barriers under each category. The interview transcripts were coded using NVivo, where each unique mention of a barrier was assigned a reference code. The frequency of each code across interviewees was summed to obtain the total code count, which represents the perceived prominence of the barrier. The categories were then ranked based on their mean code values after normalisation to ensure comparability (Tables 4 and 5).

Table 4. Categorization of C3DP barriers in India with codes generated from the interviewees.

ID	Barriers	Total Codes	Mean	Standard Deviation	Variance	Rank
P	Political	35				
P1	Absence of national standards, codes, or certification procedures for 3D-printed structures.	8				
P2	Fragmented and inconsistent regulatory oversight across central and state agencies.	5				
P3	Slow government approval processes and limited policy clarity on innovation adoption.	7				
P4	Lack of dedicated incentives or funding channels for experimental construction technologies.	4	5.00	2.16	4.67	2
P5	Weak inter-ministerial coordination among MoHUA, Bureau of Indian Standards (BIS), NITI Aayog, and state departments.	3				
P6	Conservative public-sector procurement practices discourage deviation from traditional methods.	6				
P7	Policy discontinuity and leadership changes affecting innovation momentum.	2				

Table 4. *Cont.*

ID	Barriers	Total Codes	Mean	Standard Deviation	Variance	Rank
E	Economic	38				
E1	High capital cost of printers, batching systems, and imported components.	8				
E2	Unclear return-on-investment (ROI) due to low utilisation rates and uncertain demand.	5				
E3	Difficulty benchmarking costs against conventional construction techniques.	7				
E4	Limited availability of affordable financing and insurance for C3DP projects.	4	4.75	2.12	4.50	4
E5	High operational costs (maintenance, calibration, power consumption).	3				
E6	Funding gaps between R&D prototypes and commercial scalability.	2				
E7	Public-housing budgets too constrained to trial new technologies.	6				
E8	Weak venture-capital pipeline beyond early-stage support.	3				
S	Social	33				
S1	Low public awareness and trust regarding the durability and safety of printed buildings.	7				
S2	Cultural preference for conventional masonry and craft-based construction.	6				
S3	Limited exposure of architects and designers to additive-fabrication workflows.	3				
S4	Lack of interdisciplinary collaboration between architects, engineers, and contractors.	6	4.71	1.60	2.57	5
S5	Weak industry-academia communication channels to disseminate successful outcomes.	4				
S6	Fear of labour displacement and resistance from skilled trade unions.	3				
S7	Scepticism among clients and developers toward experimental aesthetics or finishes.	4				

Table 4. *Cont.*

ID	Barriers	Total Codes	Mean	Standard Deviation	Variance	Rank
T	Technological	50	5.00	1.94	3.78	2
T1	Scarcity of skilled technicians and printer operators.	8				
T2	Limited data on long-term structural performance and durability in Indian climates.	5				
T3	Absence of reliable printable-mix databases and testing standards.	7				
T4	Difficulties in integrating reinforcement, utilities, and multi-material printing.	4				
T5	Complex calibration and maintenance needs under variable site conditions.	7				
T6	Inconsistent material quality and variability of local raw materials.	6				
T7	Limited interoperability between design software and printing hardware.	3				
T8	Inadequate after-sales and maintenance ecosystem for hardware suppliers.	4				
T9	Power-supply interruptions and environmental sensitivity (temperature, humidity).	2				
T10	Lack of standardised safety protocols for robotic on-site operations.	4				
En	Environmental	19	3.80	1.64	2.70	6
En1	Insufficient lifecycle and carbon-accounting data for Indian materials.	6				
En2	Lack of evidence on embodied-carbon savings compared with conventional concrete.	3				
En3	Inconsistent environmental permitting for on-site manufacturing setups.	3				
En4	Limited recycling or re-use pathways for failed or test prints.	5				
En5	Inadequate waste-management guidelines for additive-construction residues.	2				

Table 4. *Cont.*

ID	Barriers	Total Codes	Mean	Standard Deviation	Variance	Rank
L	Legal	41	5.13	1.64	2.70	1
L1	Absence of liability, warranty, and insurance frameworks for printed structures.	7				
L2	Slow code-development process despite ongoing expert committee discussions.	5				
L3	Lack of standard testing facilities accredited for AM.	6				
L4	Absence of standardised tender and procurement templates recognising 3D printing.	4				
L5	Undefined approval roles between engineers, architects, and authorities.	7				
L6	Weak enforcement of quality-assurance documentation or QA/Quality Control (QC) frameworks.	6				
L7	Limited integration of skill-development initiatives with certification programs.	3				
L8	Minimal institutional incentives for R&D collaboration or technology transfer.	3				

In the Indian context, six key categories of barriers emerged, with Legal/Institutional (mean = 5.13) and Technological (mean = 5.00) rated as the most significant constraints, followed closely by Political/Policy (mean = 5.00) and Economic (mean = 4.75) barriers. Social (mean = 4.71) and Environmental (mean = 3.80) barriers were relatively less emphasised. High coding frequencies within the Legal and Technological categories indicate that standardisation, accreditation, and certification gaps, as well as technical skill shortages and material inconsistencies, pose major impediments to scalability. The most frequently cited constraints included the absence of national codes and liability frameworks (P1, L1), scarcity of skilled operators (T1), unverified durability performance (T3), and high capital acquisition costs (E1).

In contrast, within the Australian context, the highest-ranked barrier category was Political/Policy (Mean = 6.13), reflecting a dominant concern regarding the absence of dedicated standards, slow regulatory adaptation, and fragmented approval mechanisms across states. This was followed by Technological (mean = 5.40) and Economic (mean = 5.38) barriers as significant structural challenges. Social (mean = 5.14), Legal/Institutional (mean = 5.00), and Environmental (mean = 3.80) barriers were also present but comparatively less emphasised. The most frequently cited constraints included lack of Australian standards and insurance frameworks (P1, P6, L1), uncertain business cases (E4), limited interoperability and reinforcement challenges (T2, T4), and persistent public scepticism toward printed-construction quality (S1, S2). This ranking indicates that adop-

tion constraints in Australia are less about technical readiness than risk governance and professional accountability.

Table 5. Categorization of C3DP barriers in Australia with codes generated from the interviewees.

ID	Barriers	Total Codes	Mean	Standard Deviation	Variance	Rank
P	Political	49				
P1	Absence of dedicated Australian standards or codes for 3D-printed construction.	8				
P2	Slow regulatory adaptation despite National Construction Code (NCC)'s performance-based pathway.	7				
P3	Inconsistent approval and compliance processes across state jurisdictions.	6				
P4	Limited training and awareness among certifiers, surveyors, and regulators.	5	6.13	1.55	2.41	1
P5	Bureaucratic inertia and high perceived risk around untested construction methods.	6				
P6	No established insurance or liability framework specific to C3DP.	7				
P7	Lack of explicit inclusion of AM in government tenders and procurement policies.	5				
P8	Policy lag between sustainability frameworks (e.g., Green Star, IS) and construction codes.	4				
E	Economic	43				
E1	High upfront investment in large-format printers, robotic arms, and infrastructure.	9				
E2	Dependence on imported machinery and maintenance parts increases costs.	6				
E3	Limited commercial demand beyond pilot projects.	5				
E4	Unclear business case and ROI due to a small market and inconsistent demand.	7				
E5	Shortage of investors willing to fund long payback-period innovations.	5	5.38	1.92	3.70	3
E6	Budget constraints within social-housing and public-procurement programs.	4				
E7	High operational energy costs for continuous printer operation.	3				
E8	Lack of standardised cost–benefit benchmarks for Australian conditions.	4				

Table 5. *Cont.*

ID	Barriers	Total Codes	Mean	Standard Deviation	Variance	Rank
S	Social	36	5.14	1.35	1.81	4
S1	Limited public and client awareness of printed construction reliability.	7				
S2	Aesthetic scepticism as clients are unsure about surface quality and finish.	5				
S3	Cultural preference for traditional construction methods.	6				
S4	Resistance from contractors and trades unfamiliar with digital fabrication.	6				
S5	Limited exposure of architects and design professionals to C3DP capabilities.	5				
S6	Misperception that digital fabrication is only suitable for high-end or experimental design.	4				
S7	Small creative studios struggle to access funding for prototypes or installations.	3				
T	Technological	54	5.40	1.35	1.82	2
T1	Shortage of trained printer operators and maintenance technicians.	8				
T2	Integration challenges between BIM models and print hardware/software.	6				
T3	Limited interoperability between design and robotic-control platforms.	5				
T4	Difficulty embedding reinforcement and services during printing.	6				
T5	Printer downtime risks disrupting project schedules.	5				
T6	Inadequate QA/QC standards for layer bonding and mechanical consistency.	6				
T7	Scarcity of durability and performance data for Australian materials.	5				
T8	Lack of centralized material database for printable mixes.	4				
T9	An energy-intensive process is not fully offset by renewable sources.	3				
T10	Absence of large-scale testing facilities for full-height printed walls.	6				

Table 5. *Cont.*

ID	Barriers	Total Codes	Mean	Standard Deviation	Variance	Rank
En	Environmental	19	3.80	0.84	0.70	6
En1	Unverified embodied-carbon reduction claims due to missing LCA data.	5				
En2	No Environmental-Product-Declaration benchmarks for printed concretes.	3				
En3	Supply-chain immaturity for sustainable binders and geopolymer mixes.	4				
En4	Difficulty sourcing consistent recycled aggregates nationwide.	3				
En5	Lack of frameworks linking C3DP with verified circular-economy metrics.	4				
L	Legal	35	5.00	1.83	3.33	5
L1	Lack of established warranty, insurance, and liability precedents.	8				
L2	Limited institutional readiness, as no official training or accreditation pathway for C3DP.	6				
L3	Slow institutional response in developing additive-manufacturing standards.	6				
L4	Insufficient collaboration between policymakers, certifiers, and research bodies.	5				
L5	Weak knowledge-transfer mechanisms from pilot projects to regulations.	4				
L6	Limited availability of sustainability assessors familiar with C3DP evaluation.	3				
L7	Absence of a unified national repository for printed project performance data.	3				

Although India and Australia exhibit similar PESTEL barrier categories, their structural emphasis differs. Regulatory constraints are foundational in both contexts; however, in Australia they relate primarily to standards integration and liability governance, while in India they reflect institutional capacity gaps and fragmented coordination [23,26]. Economic barriers in Australia concern scale efficiency and market continuity, whereas in India they centre on affordability and capital access [25]. Technological challenges in Australia focus on interoperability and QA, while India faces skill shortages and material variability [24]. Social resistance is more culturally embedded in India, whereas in Australia, it is performance-driven [56]. Environmental constraints remain secondary in both contexts due to limited lifecycle validation [57]. As such, Australia's barriers reflect integration within a mature regulatory ecosystem, whereas India's indicate early-stage system readiness challenges, underscoring the need for context-sensitive policy and industry interventions.

To improve transparency, standard deviation and variance were calculated for each barrier category to show whether coded references were concentrated in a few dominant sub-barriers or more evenly distributed. Higher variance, such as in India's political/policy

and economic categories, indicates stronger concentration around high-frequency barriers, while lower variance suggests a more even distribution.

4.2. Analysis of C3DP Barriers Based on Mean Index Score

The mean index score analysis was conducted to interpret the relative significance of each barrier category based on the interview participants' responses. Similar to Khan et al. [25], the mean index score provides a standardised measure to compare barrier intensity across categories and contexts. The mean index score was computed using the following Equation:

$$m_j = \frac{\sum_{j=1}^{n} F_j}{n}$$

where m_j is the mean index score of category j, F_j denotes the total code frequency of barriers belonging to that category, and n represents the number of barriers in that category.

Figure 4 illustrates the total citation frequency, number of barriers per category, and resulting mean index scores for India and Australia. For India, the highest-ranked categories were Legal (m = 5.13) and Technological (m = 5.00), closely followed by Political (m = 5.00) and Economic (m = 4.75) barriers. Social (m = 4.71) and Environmental (m = 3.80) categories received relatively lower emphasis a shown in Figure 4A. The elevated mean index scores for Legal and Technological categories underscore the significance of absent liability frameworks, lack of accreditation mechanisms, weak enforcement of QA/QC protocols, and shortages of skilled operators and validated printable-mix databases. These findings indicate that the Indian C3DP ecosystem is at a formative stage, where regulatory certainty, skill development, and standardisation infrastructure must evolve before commercial scaling can be realised.

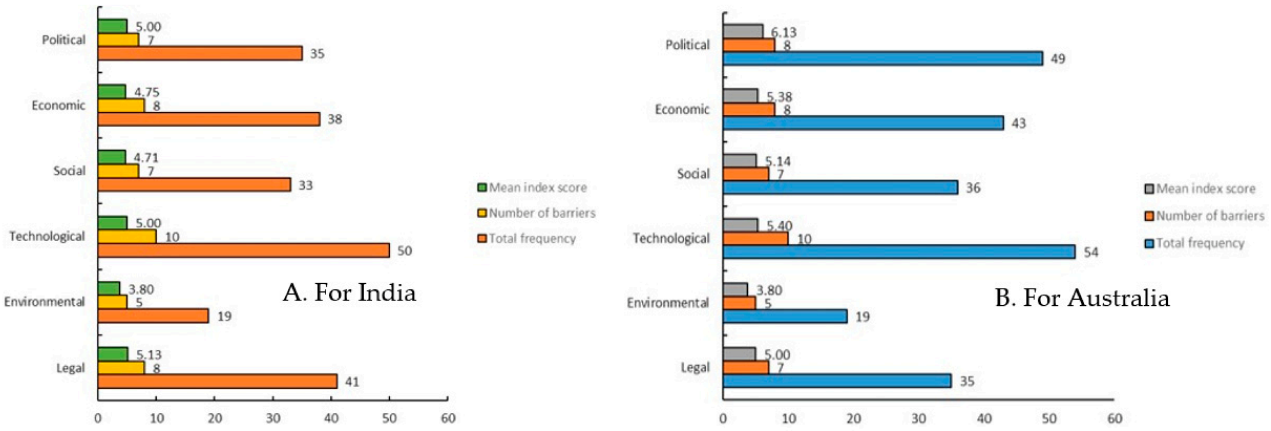


Figure 4. Mean index scores, total code frequency, and number of barriers.

In contrast, the Australian findings show a different pattern, with Political barriers exhibiting the highest mean index score (m = 6.13), followed by Technological (m = 5.40), Economic (m = 5.38), and Social (m = 5.14) barriers. Legal/Institutional (m = 5.00) and Environmental (m = 3.80) barriers scored comparatively lower as reflected in Figure 4B. The dominance of the Political/Policy category reflects the absence of dedicated codes, inconsistent state-level approval mechanisms, insurance uncertainties, and slow integration of additive construction into procurement and assessment pathways. Unlike India, where institutional readiness is still emerging, Australia's barrier structure suggests that the technical and industrial capabilities exist, but system-wide adoption is hindered by regulatory alignment and market confidence constraints.

As such, the mean index scores indicate that while Indian adoption is constrained by foundational ecosystem gaps, Australian adoption is constrained by policy harmon-

isation and market confidence. This suggests that context-specific diffusion strategies are required; India must prioritise standardisation, training pipelines, and cost-access models [26], whereas Australia must prioritise national regulatory alignment, insurer engagement, and large-scale demonstration procurement models [42].

4.3. Content Examination and Pareto Analysis of C3DP Barriers

4.3.1. Political Barriers

Political and policy-related barriers emerged as a primary gatekeeping constraint for C3DP in both India and Australia. This is consistent with the wider additive-construction literature, which repeatedly shows that standards, approval pathways, and procurement alignment are prerequisites for diffusion beyond pilots [10,58,59]. The Pareto plots (Figures 5 and 6) confirm that a small set of political constraints accounts for most of the category influence in each context, indicating that policy "readiness" shapes adoption more strongly than isolated technical feasibility [22,60].

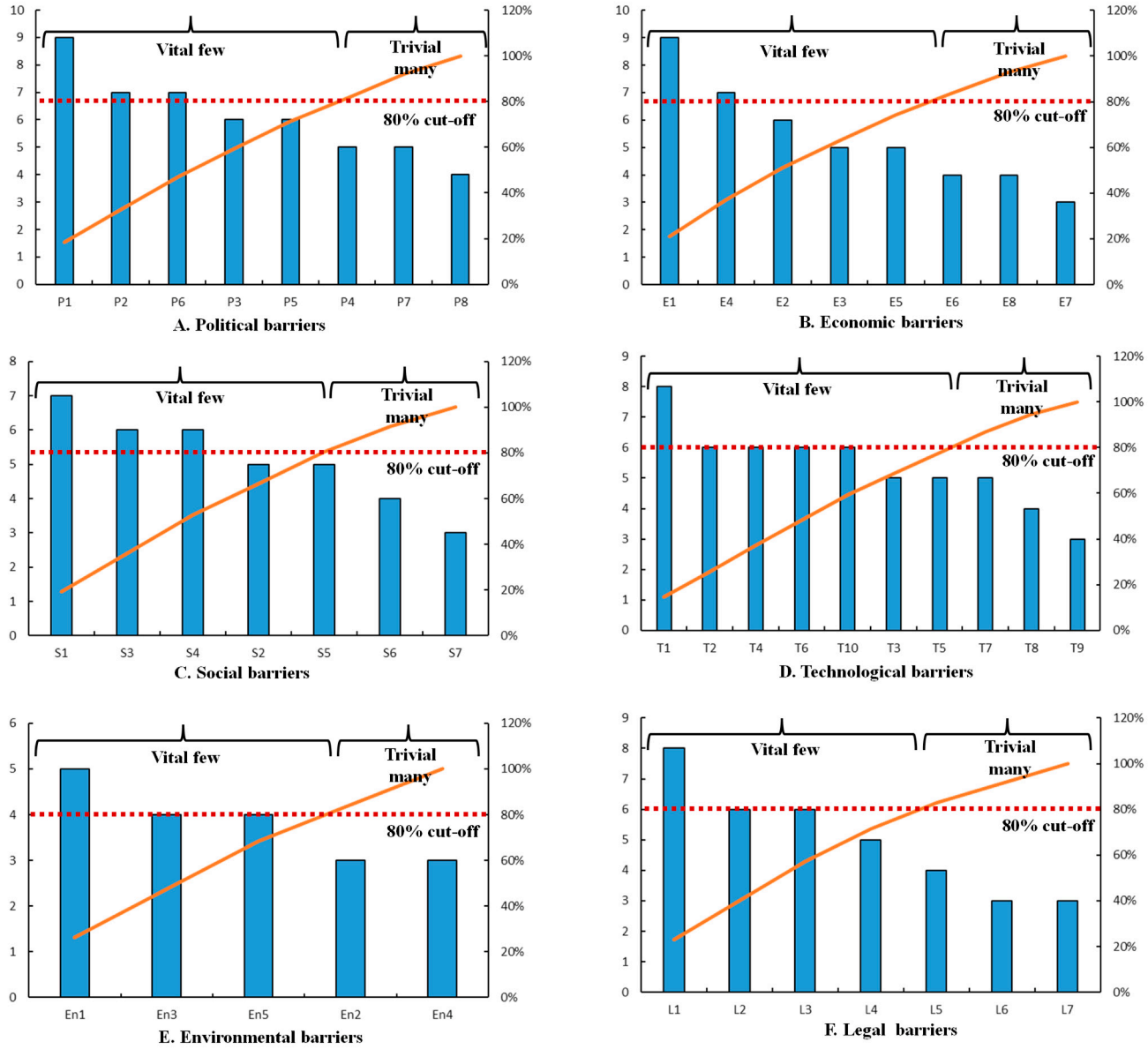


Figure 5. Pareto charts for C3DP barriers in Australia.

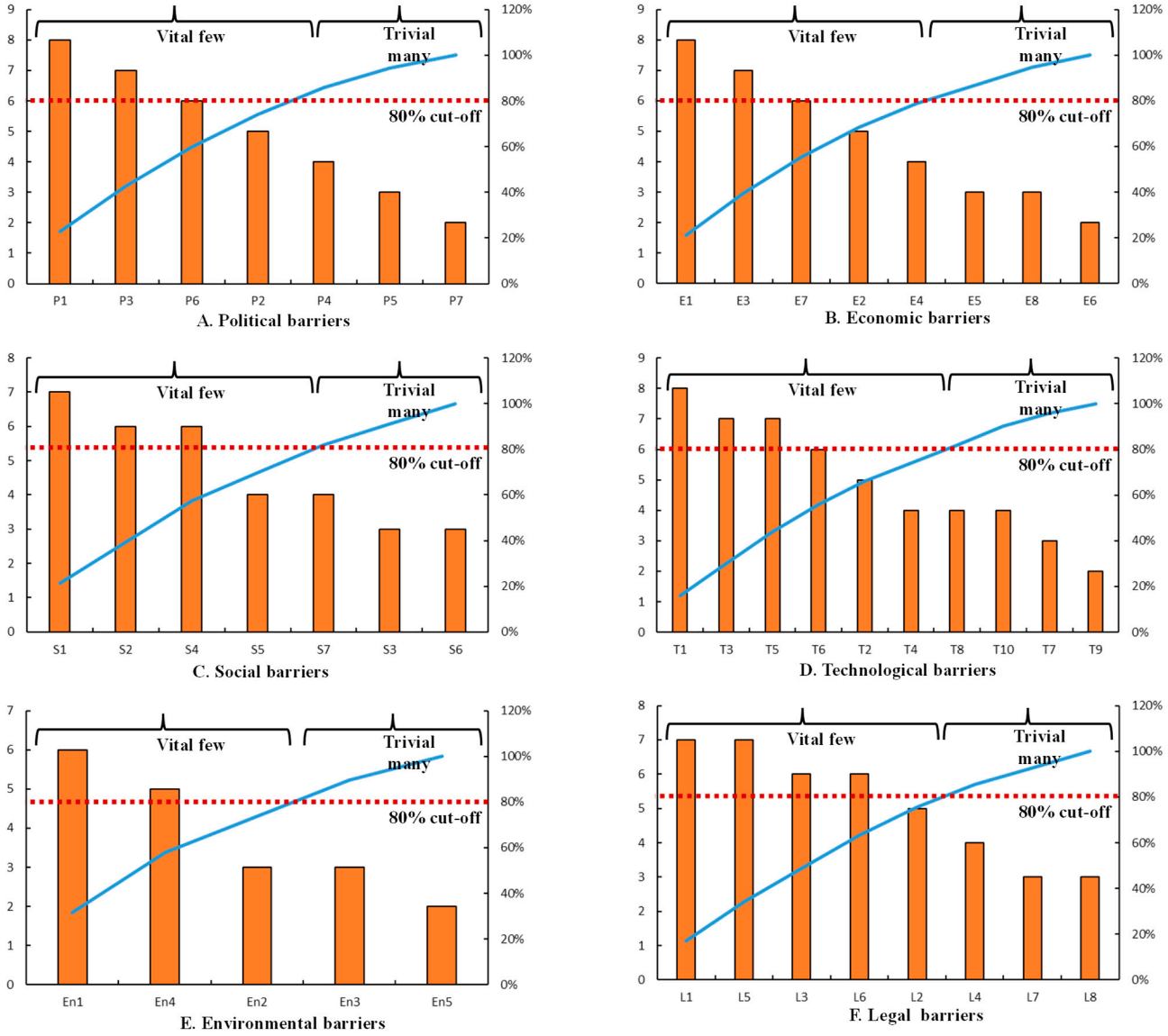


Figure 6. Pareto charts for C3DP barriers in India.

In India, the dominant political constraint is the absence of nationally codified standards and certification routes for printed structural systems (P1). Interviewees emphasised that, without BIS-type codification or a recognised municipal compliance pathway, approvals remain discretionary and project-specific. One participant captured this clearly: *"Even if the technology is ready, no authority will sign off without an IS code"* (IN-01). This institutional ambiguity interacts with slow and fragmented inter-agency coordination (P3), creating delays in clarifying "who approves what" and reinforcing conservative decision-making in public bodies, an issue also noted in broader work on barrier ecosystems in C3DP [35]. A further constraint is conservative procurement practice (P6), where tender templates embed conventional assumptions (e.g., brick masonry/RCC), leaving limited formal entry points for additive alternatives. As one respondent noted: *"If the tender document itself assumes brick masonry, how will 3D printing even enter the competition?"* (IN-04).

In Australia, the same standards gap (P1) appears, but it manifests less as "absence of governance" and more as integration and accountability within an already mature compliance ecosystem. While performance-based provisions can theoretically accommodate novel systems, interviewees stressed that certifiers and regulators remain cautious when standards and precedents are incomplete, an issue frequently reported in the adoption

literature as a mainstreaming bottleneck [60]. One interviewee explained this as institutional risk aversion: *"The technology is moving faster than the compliance apparatus; no one wants to take personal responsibility for approving something unfamiliar"* (AU-08). In parallel, insurance-linked risk governance acts as a political-institutional filter because unclear risk allocation suppresses approvals and procurement confidence. As described by an industry participant: *"If insurers don't know how to quantify risk, the project stalls right there"* (AU-03). This aligns with recent standardisation-focused discussions that identify formal guidance, verification protocols, and compliance language as essential enablers for additive construction at scale [61].

As such, Figures 5 and 6 indicate that political barriers in both contexts converge around standards and approval legitimacy but diverge in their underlying mechanisms: India is constrained by institutional capacity and coordination gaps, whereas Australia is constrained by conservative regulatory integration and professional accountability. In both countries, the political "vital few" barriers act upstream of market confidence and project pipeline formation, supporting the view that diffusion depends on governance alignment as much as technology maturity [34,59].

4.3.2. Economic Barriers

Economic constraints constitute one of the most decisive categories shaping the feasibility and scalability of C3DP in both India and Australia. The Pareto results (Figures 5 and 6) show that although several financial concerns were identified, three barriers in each country account for the majority of economic influence. Consistent with the broader additive construction literature, high capital intensity, cost uncertainty, and unclear return on investment frequently limit the transition from experimental to commercial deployment [10,59,60].

In India, the dominant economic barrier is the high upfront capital cost of large-scale printer systems and supporting infrastructure (E1). Interviewees highlighted that most advanced hardware components are imported, increasing acquisition, maintenance, and spare-part dependency. One industry respondent stated, *"Even well-established contractors hesitate because the cost of one printer equals multiple traditional project start-ups"* (IN-03). This capital sensitivity is amplified by India's highly competitive, price-driven procurement culture, where the lowest initial bid typically prevails over lifecycle efficiency considerations. The second critical barrier is the absence of reliable cost benchmarking frameworks (E3). Additive construction does not align neatly with traditional square-foot pricing models, making it difficult for clients to evaluate value equivalence. As one academic participant explained, *"Clients want a single rate per square foot, but additive processes don't behave in those linear pricing models"* (IN-01). This uncertainty reinforces risk aversion in early-stage adoption, a phenomenon widely noted in the innovation cost-uncertainty literature [62]. A third influential constraint relates to rigid public-sector housing budgets (E7), which leave minimal fiscal space for pilot premiums or experimentation. As articulated by a policy advisor, *"The housing programs are financially stretched; there is no room for experimental cost premiums, even if they reduce time"* (IN-08).

In Australia, while high initial investment cost (E1) also ranks among the vital few, its interpretation differs. The issue is less about affordability and more about market continuity and scale efficiency. Interviewees stressed that equipment investment becomes viable only if a stable project pipeline exists. One CEO remarked, *"The equipment is financeable, but it only makes business sense if a stable pipeline exists. Right now, it's pilot-to-pilot, not programmatic work"* (AU-04). This links closely with uncertainty in return on investment due to inconsistent demand (E4). Demonstration projects generate visibility but do not guarantee repeatability, which investors require to justify capital exposure. As noted by an innovation manager,

"We deliver singular projects successfully, but we can't yet guarantee continuity, and continuity is what investors look for" (AU-03). A further barrier concerns investor reluctance toward long payback-period technologies (E5), particularly where risk-sharing mechanisms are underdeveloped. As one sustainability consultant observed, *"Investors support technologies when risk is shared, and markets are visible, C3DP hasn't reached that threshold yet"* (AU-07).

Comparatively, both contexts identify capital intensity as central, but the structural drivers diverge. In India, economic barriers are embedded in cost-sensitive demand environments, procurement rigidity, and limited financing mechanisms for innovation. In Australia, barriers stem from scale economics, investor confidence, and the absence of sustained project pipelines. Figures 5 and 6, therefore, suggest that India requires policy-backed financial instruments and benchmarking frameworks to de-risk early adoption, whereas Australia requires demand consolidation and structured procurement continuity to justify long-term capital deployment [63]. These findings align with international studies arguing that additive construction becomes economically viable only when supported by predictable market signals and structured innovation finance models [62].

4.3.3. Social Barriers

Social barriers influence how C3DP is perceived, trusted, and professionally legitimised within the construction ecosystem. The Pareto analysis (Figures 5 and 6) indicates that a limited cluster of perception-related and professional-culture barriers accounts for most of the social resistance in both countries. This aligns with the broader additive construction literature, which emphasises that technological acceptance depends not only on performance but also on perceived reliability, craftsmanship norms, and professional identity alignment [1,15].

In India, the most influential social barrier is limited public awareness and trust in the durability and safety of printed structures (S1). Interviewees repeatedly stressed that end-users associate structural permanence with conventional masonry and reinforced concrete. One participant stated, *"People want something that looks proven and permanent"* (IN-02). The absence of long-term reference buildings intensifies this credibility gap. Another industry respondent observed, *"People want to see a printed building that has survived monsoon, heat, and time. Until then, it's seen as experimental"* (IN-03). Such trust deficits are consistent with findings that emerging construction technologies face cultural inertia where established materials are equated with structural legitimacy [26].

A second vital social barrier in India relates to a deep-rooted preference for traditional, labour-intensive construction systems (S2). Masonry and site-based craftsmanship are culturally embedded and linked to employment structures. As one government scientist reflected, *"Brick-and-mortar has cultural legitimacy here; it signals solidity"* (IN-05). This cultural attachment slows behavioural transition even where technical feasibility exists. Additionally, limited interdisciplinary literacy between architects, engineers, and contractors (S4) constrains design-for-print workflows. As expressed by an academic participant, *"Most architects design first and ask the printer to follow, but printing requires design to adapt"* (IN-01). This highlights a socio-technical gap between digital modelling capacity and fabrication-oriented thinking.

In Australia, while limited public familiarity (S1) also ranks among the vital few, the underlying concern differs. Rather than durability under climatic conditions, scepticism centres on finish quality, aesthetic expectations, and performance assurance. One architect noted, *"Clients accept the idea quickly, but the moment they see surface texture, they question quality"* (AU-02). Thus, acceptance is conditioned by perceived alignment with established residential quality standards. A second influential barrier concerns professional risk culture (S3). Builders and project managers are accustomed to predictable liability frameworks

associated with traditional systems. As one innovation manager stated, *"Builders know exactly how to manage risk in blockwork and formwork; new methods introduce unknown liability"* (AU-03). This reflects institutional conservatism frequently discussed in innovation diffusion research within regulated industries [64].

A third shared constraint involves limited fabrication literacy despite digital proficiency (S4). Although Australia has strong BIM penetration, interviewees identified a gap between parametric modelling skills and robotic construction knowledge. As one research fellow remarked, *"We produce graduates who can model anything, but few know what a printer can or cannot physically do"* (AU-09). This reinforces evidence from additive construction studies that workforce upskilling must extend beyond software literacy toward integrated design–fabrication competencies [56].

Comparatively, Figures 5 and 6 reveal that social barriers in India are shaped by cultural trust, craft identity, and public legitimacy, whereas in Australia they are shaped by performance expectations, aesthetic norms, and professional liability culture. In both contexts, however, visible demonstration projects, interdisciplinary education reform, and evidence-based communication strategies are essential to reshape perceptions. The findings confirm that C3DP adoption involves both technical change and socio-cultural transformation in construction practice [11,12].

4.3.4. Technological Barriers

Technological barriers constitute the operational core of C3DP adoption challenges, influencing reliability, repeatability, and scalability of printed construction systems. Pareto analysis (Figures 5 and 6) indicates that although numerous technical issues were mentioned, a small subset accounts for the majority of technological influence in each context. Consistent with additive construction research, technical feasibility in laboratory settings does not automatically translate into site-level robustness, particularly where material behaviour, reinforcement integration, and workflow interoperability remain unresolved [43,65].

In India, the most influential technological barrier is the shortage of skilled operators and technicians capable of managing the combined demands of material rheology, robotic calibration, and on-site troubleshooting (T1). Interviewees emphasised that operating a construction printer requires hybrid expertise not commonly available within conventional contractor teams. One participant remarked, *"You can't simply retrain a mason to run a printer overnight; this is a different skill ecosystem"* (IN-03). This shortage slows project replication and reinforces dependence on specialised research teams.

A second high-impact barrier concerns the absence of regionally validated printable-mix databases and standardised testing procedures (T3). Material variability across Indian climatic zones significantly affects extrusion consistency and interlayer bonding. As noted by one academic expert, *"You need to tweak the mix every time you change a city; there is no national printable-mix guideline to start from"* (IN-01). This leads to repeated trial-and-error cycles, increasing time and cost uncertainty. Closely related is the instability of printer calibration and field performance (T5), particularly under high temperature and humidity conditions. One materials scientist observed, *"A printer that works perfectly in a controlled lab behaves unpredictably on a construction site in peak Indian summer"* (IN-05). These constraints illustrate that climatic exposure, supply-chain variability, and absence of performance benchmarks collectively limit technological standardisation, an issue highlighted in the broader C3DP literature [41,66].

In Australia, technological barriers reflect a more integration-oriented challenge. While skilled operator shortages (T1) also appear, the nature of the gap differs; interviewees noted that trained robotics professionals are often drawn to higher-paying sectors such as mining

and aerospace, reducing talent retention within construction. As one industry leader explained, *"We lose trained operators to mining within months; they get paid double"* (AU-04).

Interoperability between BIM-based design systems and printer hardware (T2) emerged as a second dominant barrier. Although digital modelling capabilities are strong, translation into executable toolpaths requires manual adjustment and specialist oversight. As one research fellow stated, *"We design parametrically, but the translation to G-code still needs refinement; that's where errors creep in"* (AU-09). This underscores the need for seamless digital-to-physical integration pipelines, a recurrent theme in advanced additive construction studies [60].

A further critical barrier involves the absence of standardised QA/QC frameworks for layer bonding, reinforcement embedding, and structural consistency (T6). While printed elements may demonstrate adequate compressive strength in laboratory tests, there remains no widely accepted protocol for certifying printed assemblies under industry-recognised performance language. As noted by a senior materials engineer, *"We can print strong walls, but we cannot yet certify them in the same language the industry understands"* (AU-05). This reflects the broader observation that additive construction requires not only mechanical performance but also codified verification metrics to gain professional trust [8].

Importantly, interview evidence also emphasised that scaling C3DP demands system-level optimisation rather than isolated printer innovation. Participants highlighted that productivity gains depend on harmonising material rheology, extrusion speed, reinforcement strategy, and digital control architecture within an integrated workflow. Without this alignment, printing remains technically feasible but commercially fragile. The technological challenge, therefore, lies less in "whether it can print" and more in "whether it can print consistently, predictably, and certifiably" across varied project conditions [67].

Comparatively, Figures 5 and 6 indicate that India's technological barriers are driven by skill development gaps, material variability, and climatic adaptation challenges, whereas Australia's barriers centre on integration maturity, interoperability, and formalised quality verification. In both contexts, technological readiness is intertwined with institutional and professional acceptance; operational robustness must be demonstrable before regulatory confidence and market scaling can occur [25].

4.3.5. Environmental Barriers

Environmental considerations are frequently cited as a primary justification for C3DP adoption; however, the Pareto analysis (Figures 5 and 6) indicates that sustainability remains a constrained rather than fully operational driver in both contexts. While additive construction is often associated with reduced formwork waste and material optimisation, interview evidence suggests that environmental claims currently outpace verified data and certification mechanisms [57]. This observation aligns with recent scholarship cautioning that C3DP's environmental advantages depend heavily on binder composition, LCA transparency, and supply-chain maturity rather than the printing process alone [9].

In India, the most influential environmental barrier is the absence of robust, standardised embodied-carbon and lifecycle datasets for printable materials (En1). Several interviewees stressed that although supplementary cementitious materials such as fly ash and slag are available, there is no nationally harmonised methodology to quantify carbon savings relative to conventional reinforced concrete [68]. One academic participant remarked, *"We speak about sustainability benefits, but unless we can show the numbers, these claims don't translate into decisions"* (IN-02). Without comparable LCA benchmarks, sustainability narratives remain aspirational rather than policy-enabling.

A second significant barrier relates to the lack of structured recycling pathways for failed prints, surplus mixes, or experimental prototypes (En4). Additive processes may

reduce formwork waste, yet rejected printed components often revert to conventional disposal routes. As one environmental engineer noted, "Waste reduction is possible, but we still do not have circular loops defined for trial materials" (IN-06). This highlights the gap between theoretical circular economy (CE) potential and implemented recovery systems.

Additionally, inconsistent environmental permitting procedures for on-site printing setups (En3) were cited as slowing pilot deployment. In regions with strict local environmental compliance rules, mobile batching and printing installations require approvals not explicitly designed for additive workflows. This reinforces findings in the literature that regulatory adaptation is critical for enabling low-carbon innovation pathways [18].

In Australia, environmental barriers manifest differently. The dominant issue is not resource availability but verification alignment. Interviewees emphasised that sustainability claims must be supported by Environmental Product Declarations, formal LCA comparisons, and compatibility with Green Star or Infrastructure Sustainability (IS) rating systems (En1). As one sustainability consultant observed, *"If we cannot produce certified LCA comparisons, sustainability arguments fail during procurement"* (AU-07). Thus, unlike India, where proof generation is limited, Australia requires proof standardisation within existing compliance frameworks.

A second barrier concerns the immaturity of supply chains for low-carbon printable binders (En3). While geopolymer and alkali-activated systems are technically feasible, they remain largely confined to research pilots rather than widely distributed commercial production. As noted by one industry participant, *"Low-carbon mixes exist, but scaling supply beyond pilot batches is the real challenge"* (AU-04). This supply-chain limitation constrains the environmental differentiation of C3DP from conventional concrete systems.

A further issue involves the absence of a formalised CE framework tailored to AM in construction (En5). Interviewees highlighted that although printing can theoretically optimize material deposition, there is no established mechanism to audit or reward these efficiencies within sustainability rating tools. One participant reflected, *"The process might be efficient, but unless the certification system recognises it, the market does not value it"* (AU-05).

Across both contexts, experts subtly underscored that environmental performance is fundamentally linked to material science rather than merely fabrication technique. In particular, the rheological requirements of printable mixes often necessitate higher binder content, which may offset claimed carbon reductions unless alternative binders are systematically integrated. As one participant explained, *"Printing precision alone does not guarantee lower emissions; the binder chemistry determines that"* (AU-04). This observation reinforces recent studies arguing that sustainable C3DP depends on low-carbon binder innovation and transparent performance verification [38,69].

Comparatively, Figures 5 and 6 demonstrate that India's environmental barrier landscape is dominated by the need to generate credible carbon and circularity data under conditions of material variability, whereas Australia's barriers stem from the need to formalise and certify environmental proof within established sustainability frameworks. In essence, India must build empirical datasets, while Australia must institutionalise those datasets into recognised rating and procurement systems. In both cases, environmental performance will only become a decisive adoption driver when quantifiable, standardized, and certifiable metrics align AM practice with national decarbonization objectives [39].

4.3.6. Legal Barriers

Legal barriers represent one of the most decisive constraints on the transition of C3DP from pilot experimentation to mainstream construction practice. While technical feasibility can be progressively improved through research and training, printed buildings cannot scale without clear liability allocation, certification pathways, and regulatory recognition [7].

The Pareto analysis (Figures 5 and 6) shows that a limited number of legal factors account for most institutional hesitation in both India and Australia. This finding is consistent with prior research indicating that additive construction technologies often advance faster than regulatory frameworks designed for conventional reinforced concrete systems [19].

In India, the most influential legal barrier is the absence of defined liability, warranty, and insurance models for printed structures (L1). Interviewees described a persistent accountability vacuum, where project participants remain uncertain about who bears responsibility for structural performance if printed elements fail. As one senior government advisor explained, *"Everyone agrees the technology is promising, but no one wants to sign the stability certificate yet"* (IN-05). This uncertainty discourages formal project approvals and increases perceived professional risk.

A second critical barrier concerns ambiguity in approval authority roles across architects, structural engineers, and municipal bodies (L5). Printed construction does not fit neatly within established approval templates, leading to case-by-case negotiations. One policymaker observed, *"Printed buildings don't sit clearly under any existing code category, so every project becomes a negotiation"* (IN-07). Such fragmentation slows adoption and reinforces bureaucratic conservatism.

The third vital constraint is the lack of accredited testing facilities and certification protocols specifically tailored to printed assemblies (L3). Although material testing laboratories exist, there are no nationally standardised procedures for certifying layered deposition systems as integrated structural elements. As noted by an industry participant, *"We can test cubes, but we don't yet have protocols to certify a printed wall as a system"* (IN-03). Without assembly-level validation frameworks, institutional confidence remains limited.

In Australia, the leading legal constraint similarly relates to insurance and warranty uncertainty (L1), but it is embedded within a more mature compliance culture. Interviewees repeatedly highlighted that without insurer acceptance, commercial projects stall irrespective of technical readiness. As one innovation manager stated, *"If insurers cannot quantify the risk, the conversation stops immediately"* (AU-03).

A second influential barrier is the absence of nationally recognised accreditation pathways for C3DP operators and certifiers (L2). Professional accountability within Australia's construction industry is closely tied to licensure and documented competence. As expressed by a senior industry leader, *"If the operator isn't formally accredited, liability becomes a negotiation rather than a rule"* (AU-04). This emphasis on formal competence reflects Australia's structured risk-governance environment [67].

The third vital barrier involves the slow development of standards specific to printed construction (L3). Although the NCC permits performance-based solutions, interviewees noted that regulators and certifiers remain cautious in applying this flexibility to layered deposition systems. One standards officer remarked, *"The code allows innovation, but practitioners need clearer guidance on how to demonstrate compliance"* (AU-08). This gap between regulatory allowance and practical interpretability limits mainstream uptake.

Comparatively, Figures 5 and 6 illustrate that legal barriers in both contexts revolve around accountability, certification, and risk governance, yet their institutional expression differs. In India, the challenge lies in clarifying authority structures and formalising approval procedures within a fragmented regulatory environment. In Australia, the emphasis is on codifying competence, aligning with insurer requirements, and embedding C3DP within established compliance language.

Across both countries, interviewees consistently indicated that legal readiness progresses more slowly than technological capability. As one participant succinctly noted, *"Technology can move in months; regulation moves in years"* (AU-05). The findings therefore confirm that mainstream adoption of C3DP depends not only on material innovation or

digital integration but on structured liability frameworks, recognised certification protocols, and regulator familiarity supported by demonstrable evidence [16,57]. Until these institutional mechanisms mature, C3DP is likely to remain concentrated within demonstration projects rather than fully embedded within national construction markets.

4.4. Theorizing the Hierarchical Structure and Path Dependencies of the Vital Barriers

While the Pareto analysis identified the vital few barriers within each PESTEL category, it does not reveal how these barriers interact structurally or which categories act as root drivers of systemic inertia. To address this limitation, TISM was employed to explicate the hierarchical ordering and transitive linkages among the barrier categories for India and Australia. Figures 7 and 8 present the total interpretive structural models for the two contexts. These models reveal that although similar categories are involved, the directionality, intensity, and systemic anchoring of barriers differ substantially across the two national ecosystems. This systems-oriented interpretation is consistent with recent C3DP scholarship arguing that adoption constraints are rarely independent; instead, they co-evolve through institutional legitimacy, market continuity, and verification capacity, which collectively shape diffusion trajectories [19,35].

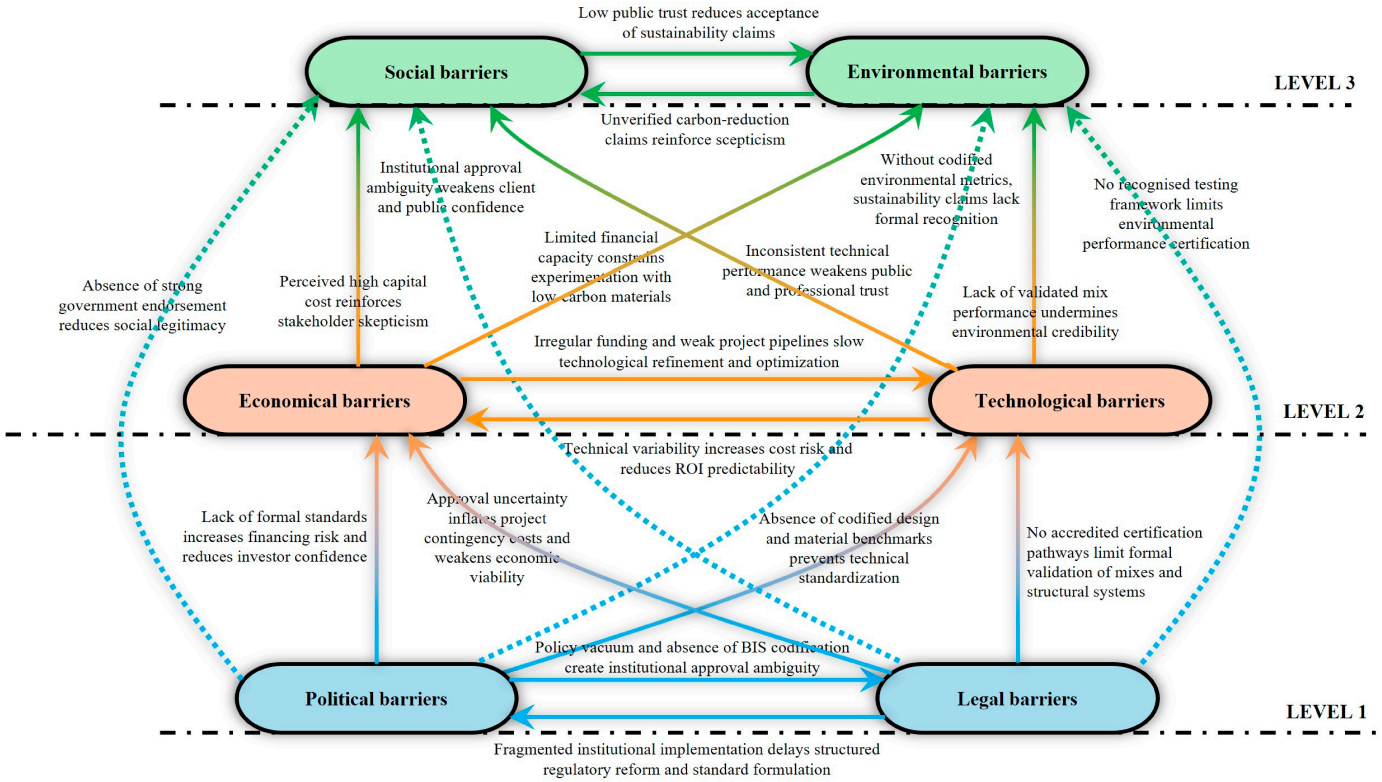


Figure 7. TISM for barriers to C3DP in India.

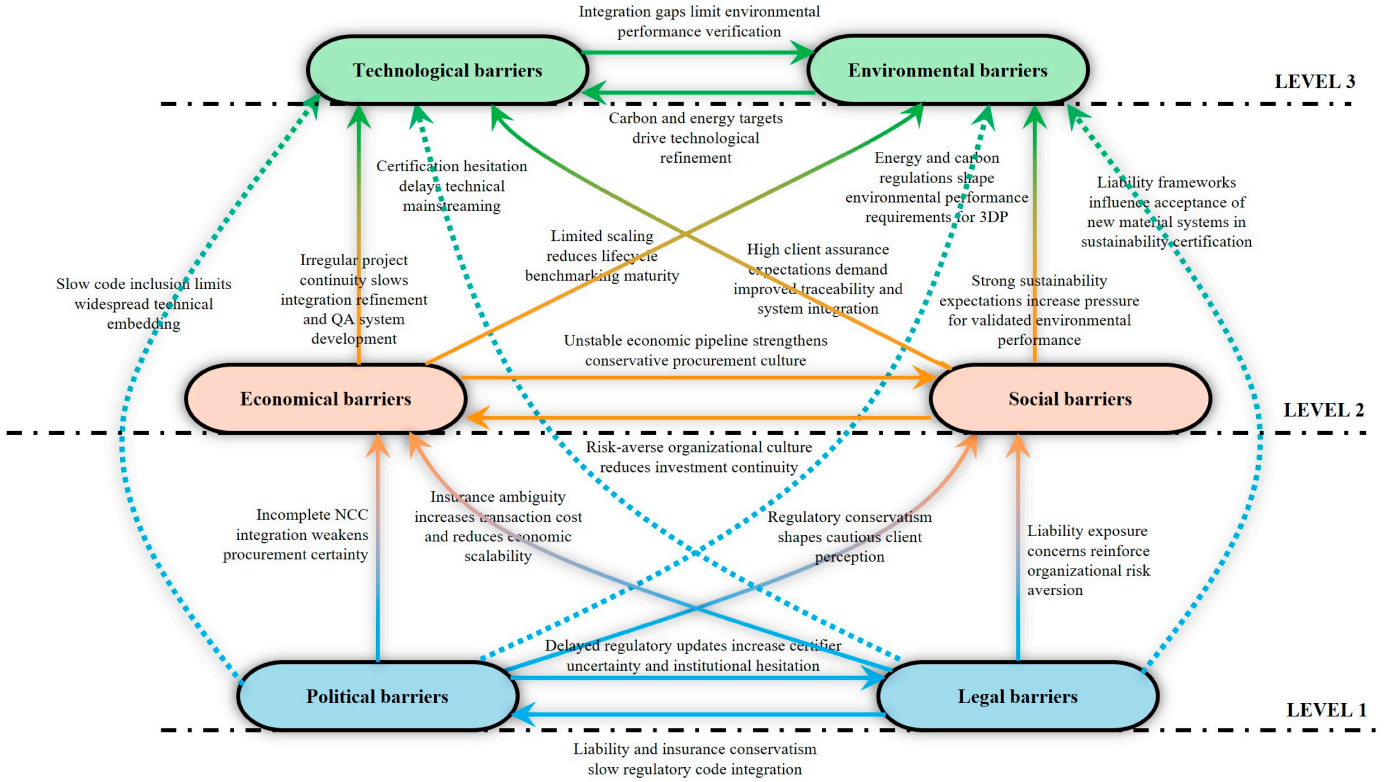


Figure 8. TISM for barriers to C3DP in Australia.

4.4.1. India: Institutional Fragmentation and Cascading Legitimacy Deficits

Figure 7 illustrates that, in India, political (P) and legal (L) barriers occupy the foundational layer of the structural hierarchy. This positioning reflects consistent interview evidence indicating that the absence of BIS codification, unclear approval pathways, and fragmented institutional responsibility constitute the primary impediments to mainstream adoption (IN-01; IN-07; IN-03). Participants emphasised that without formalised design codes and accredited certification routes, printed structures remain dependent on discretionary approvals rather than routinised compliance. This institutional ambiguity directly shapes economic behaviour by inflating perceived risk and discouraging capital investment in printers and associated infrastructure (IN-01; IN-08). Relatedly, interviewees stressed that interim guidance (for instance, provisional standards and testing notes) could function as a critical bridge from pilots to wider implementation (IN-02; IN-05), reinforcing the argument that early-stage codification is central to stabilising adoption pathways.

The model demonstrates strong bottom-middle linkages. Regulatory absence constrains the economic (E) domain by weakening financing confidence and limiting procurement continuity, particularly when financiers and public agencies cannot rely on codified benchmarks for approval and liability allocation (IN-01; IN-08; IN-03). Simultaneously, the lack of codified technical benchmarks constrains technological (T) maturation, as firms lack validated frameworks for mix standardisation, reinforcement integration, and QA (IN-01; IN-03). This aligns with broader C3DP reviews showing that the credibility of printed systems depends heavily on validated performance data, standardised procedures, and repeatable QA methods rather than isolated demonstrations [62].

Within the middle layer, economic and technological barriers reinforce one another. Limited project continuity restricts opportunities for iterative technical refinement, while technological inconsistency increases cost contingencies and reduces return-on-investment predictability. Several participants highlighted that without stable pipelines, it is difficult to build confidence in mix consistency and long-term performance across varied sites

and climatic conditions (IN-01; IN-03). This capability-cost feedback loop helps explain why pilot projects do not automatically translate into systemic diffusion, echoing recent modelling work that positions interdependencies among adoption barriers as a principal reason for slow transition from experimentation to normalisation [10,62].

At the top of the hierarchy, social (S) and environmental (Env) barriers emerge as dependent outcomes shaped by lower-layer constraints. Technical inconsistency weakens public and professional trust, while high capital costs reinforce scepticism toward technology's practicality (IN-02; IN-03). Environmental credibility similarly depends on technical validation and institutional recognition. Without standardised lifecycle benchmarks and validated low-carbon material pathways, sustainability claims remain aspirational rather than certifiable. As IN-06 noted, the carbon-reduction potential of geopolymer or alternative binders cannot be formally recognised without institutional endorsement and testing consistency, and interviewees repeatedly linked sustainability credibility to nationally accepted testing/certification infrastructures (IN-01; IN-02; IN-06). This interpretation is consistent with sustainability assessment studies showing that large-scale C3DP environmental outcomes vary substantially by material system and verification approach, underscoring the importance of credible assessment frameworks [57].

Importantly, Figure 7 also shows direct bottom-top linkages. In India, government endorsement functions as a legitimacy signal. The absence of policy clarity reduces social acceptance regardless of technical feasibility, particularly in risk-averse construction decision environments (IN-02; IN-07). Similarly, environmental benchmarking requires codified metrics; without regulatory integration, environmental performance cannot be formally institutionalized. The resulting transitive structure suggests that institutional ambiguity generates economic hesitation, which constrains technological advancement, reinforces social scepticism, and ultimately leads to weak environmental validation [1,22]. This hierarchical path dependency suggests that technological refinement alone cannot unlock mainstream adoption in India. Regulatory codification and coordinated institutional validation mechanisms represent the principal leverage points for systemic transition, particularly through interim standards, national testing capacity, and shared data infrastructures (IN-01; IN-02; IN-03; IN-05).

4.4.2. Australia: Risk Governance, Procurement Inertia, and Integration Bottlenecks

In contrast, Figure 8 reveals a structurally different configuration for Australia. Although political (P) and legal (L) barriers again occupy the foundational layer, their character differs markedly. Rather than regulatory absence, the interviews highlight regulatory conservatism and liability governance as dominant anchors (AU-01; AU-03; AU-08). Certifier hesitation, insurance ambiguity, and the gradual integration of additive construction into the NCC shape the risk landscape within which firms operate, and participants noted that insurers and certifiers depend heavily on codified references to benchmark risk (AU-01; AU-05). This reflects broader observations in the C3DP literature that mature markets often require formalised standards and accepted verification regimes to translate technical capability into routinised adoption [19].

The bottom-middle linkages indicate that liability and compliance uncertainty translate into procurement caution and organisational risk aversion. When insurers cannot confidently price risk and certifiers require exceptional documentation, transaction costs increase, and project pipelines remain irregular [23]. This weakens the economic continuity necessary for scaling and reinforces conservative decision-making cultures among contractors and clients (AU-03; AU-04). The middle-layer interaction therefore manifests as a procurement inertia loop: unstable economic returns reinforce cautious organizational behaviour, which further limits investment continuity. This "lock-in" dynamic aligns with

recent barrier-interrelationship modelling that emphasises transitive reinforcement among institutional, market, and organisational constraints in C3DP adoption [35].

Unlike India, the upper layer in Australia consists of technological (T) and environmental (Env) barriers. Here, technology is not constrained by fundamental readiness gaps but by integration maturity. Interviewees emphasized challenges related to reinforcement embedding, envelope continuity, service integration, and quality traceability systems (AU-01; AU-03), and AU-04 noted that technical feasibility is no longer the main question; scaling depends on whether integration and verification can be normalized into conventional delivery practices. These integration challenges directly shape environmental performance, such as building energy compliance, durability expectations, and embodied carbon reporting depending on holistic system integration [13,18]. This also resonates with review evidence that sustainable performance claims in C3DP depend on robust material optimization, consistent process control, and credible assessment practices [20].

Conversely, environmental performance requirements exert upward pressure on technological refinement. Australia's energy efficiency codes, lifecycle assessment frameworks, and emerging embodied carbon targets require validated integration solutions. Thus, a bidirectional performance loop exists between T and Env at the scaling stage. As stricter carbon and energy benchmarks emerge, firms must refine material optimisation, precision control, and digital traceability to demonstrate compliance (AU-08; AU-01). This is aligned with the sustainability-focused literature highlighting how environmental assessment pressures can drive technical iteration and verification maturity in additive construction pathways [19].

Direct bottom-top linkages further illustrate that regulatory integration and liability clarity directly affect technological mainstreaming and environmental certification. Delayed NCC inclusion limits standardized detailing, while insurance frameworks influence whether innovative material systems can be recognized within sustainability certification processes (AU-05; AU-03). The transitive structure in Australia indicates that liability conservatism produces procurement inertia, which constrains integration refinement, intensifies environmental benchmarking pressures, and ultimately drives further technological evolution. Unlike India, where institutional absence drives stagnation, Australia exhibits institutional maturity coupled with risk governance conservatism. The bottleneck is not initial feasibility but system-level integration within an established compliance ecosystem.

4.4.3. Comparative Structural Insights

A comparative reading of Figures 7 and 8 reveals two distinct systemic logics. In India, the root constraint is institutional formation; in Australia, it is institutional conservatism. India's upper-layer barriers (S and Env) represent legitimacy deficits emerging from lower-layer uncertainty. Australia's upper-layer barriers (T and Env) reflect integration maturity challenges within a regulated environment. These findings reinforce socio-technical transition theory, which posits that technology diffusion depends not solely on innovation attributes but on alignment between regulatory regimes, market incentives, and socio-cultural legitimacy [16]. They also echo the recent C3DP literature showing that ecosystem coordination and verification capacity are decisive for shifting from pilots to routinised implementation [56,66].

In both contexts, technological capability alone is insufficient to enable mainstream adoption; however, the strategic intervention points differ, with India requiring regulatory codification and institutional capacity building, while Australia requires liability clarification and procurement reform to facilitate integration scaling. By theorising these hierarchical and transitive relationships, this study advances the understanding of C3DP adoption from a list-based barrier perspective to a structured systemic interpretation.

5. Discussion

This study critically examined the systemic barriers influencing C3DP adoption in India and Australia. Rather than treating obstacles as isolated constraints, the findings reveal a layered socio-technical configuration in which institutional readiness, market logic, technological robustness, and cultural legitimacy co-evolve. In line with socio-technical transition theory [16], C3DP diffusion is shaped less by hardware capability and more by the alignment of regulatory structures, professional norms, and economic incentives.

However, the India-Australia distinction should be interpreted as an analytical comparison of dominant adoption patterns rather than as a claim of internal uniformity. Within both countries, C3DP readiness may vary across states, cities, client types, firm capabilities, procurement routes, regulatory authorities, and project sectors. For example, technology-oriented firms, research-led pilot projects, or public-sector innovation programmes may show higher readiness than conventional contractors or cost-sensitive housing projects. Similarly, state-level approval cultures, local material availability, and organisational risk appetite may influence adoption differently within the same national context. Therefore, the comparison highlights broad institutional tendencies identified from the expert data, while recognising that sub-national and organisational diversity may produce alternative adoption pathways.

5.1. Institutional Readiness as the Primary Gatekeeper

Across both contexts, regulatory and legal uncertainty function as a structural bottleneck. While performance-based codes theoretically enable innovation, the absence of explicit standards, accreditation pathways, and insurer-recognised certification frameworks constrains mainstream adoption. This reflects the "institutional lag" identified in construction automation research [10,35].

However, the study shows that institutional lag is not uniform. In India, fragmentation across regulatory bodies generates ambiguity of authority, slowing approval scaling beyond pilot projects [26]. In Australia, regulatory coherence exists, yet strong liability and insurance cultures create heightened risk sensitivity [23]. This distinction advances the literature by demonstrating that regulatory maturity does not eliminate adoption barriers; rather, it transforms their nature, from coordination deficits to accountability thresholds.

Theoretically, this reinforces the proposition that innovation adoption in construction is mediated by governance architecture, not merely technical capability. Managerially, it suggests that policymakers must prioritise structured certification pathways and insurer engagement before scaling pilot programs. Without institutional endorsement, technological validation alone is insufficient to unlock market confidence.

The TISM results therefore show that governance barriers act as systemic drivers rather than isolated constraints. When standards, certification pathways, and liability frameworks remain unclear, technical evidence is less likely to translate into certifier confidence, procurement approval, or market acceptance.

5.2. Economic Viability as a Function of Market Structure

Economic feasibility emerged as conditional on utilisation continuity rather than capital cost alone. Consistent with automation research [68], the viability of large-scale C3DP equipment depends on stable project pipelines. However, the study reveals structural divergence in both contexts.

In India, price-sensitive procurement systems and entrenched low-cost masonry markets limit cost competitiveness. Economic barriers are demand-driven and affordability-centred. In Australia, high labour costs theoretically favour automation, yet investor

caution and inconsistent project flow inhibit capital commitment. Thus, the constraint is investment logic rather than affordability.

This comparative insight contributes theoretically by distinguishing between "cost-constrained markets" and "confidence-constrained markets" in construction innovation diffusion. Managerially, India requires policy-backed incentives, cost benchmarking tools, and integration into public housing procurement, whereas Australia requires pipeline consolidation, risk-sharing procurement models, and clearer return-on-investment signalling mechanisms.

5.3. Technological Integration Beyond Capability

The findings confirm global advancements in printable materials, robotic control, and digital modelling [69]. However, technological maturity is unevenly distributed. In India, challenges centre on environmental variability, raw-material inconsistency, and site-level robustness. In Australia, the constraint lies in digital interoperability and performance-verifiable QA/QC frameworks.

This divergence highlights an important theoretical implication: technological readiness must be understood as context-embedded rather than universally scalable. Additive construction systems interact with climatic conditions, supply-chain stability, and certification language. Consequently, C3DP is not a plug-and-play innovation but an ecosystem-dependent technology.

For practitioners, this implies that investment should prioritise localisation strategies in developing contexts and verification frameworks in developed contexts. The transition challenge is therefore not printing accuracy alone, but the integration of materials science, digital workflows, and compliance validation into a coherent production system.

5.4. Cultural Legitimacy and Professional Identity

The study also demonstrates that social acceptance is structurally linked to professional identity and public perception. In India, resistance is rooted in cultural permanence associated with masonry; in Australia, scepticism is linked to liability culture and finish expectations. These findings align with research showing that construction innovation disrupts deeply embedded craft narratives [41]. Critically, the results suggest that demonstration projects function not only as technical proof but as symbolic artefacts that reshape legitimacy. Adoption therefore requires narrative transformation alongside engineering validation.

5.5. A Systemic Adoption Architecture

Synthesising these insights, C3DP adoption emerges as a coordinated transition challenge rather than a discrete technical upgrade. Regulatory uncertainty amplifies investor hesitation; market caution sustains social scepticism; limited social legitimacy slows procurement reform. This feedback loop reflects socio-technical transition dynamics [16].

Theoretical implications of the study include:

- Advancing a comparative, context-sensitive model of additive construction diffusion.
- Demonstrating that institutional maturity alters, rather than removes, innovation barriers.
- Positioning C3DP adoption as an ecosystem configuration problem rather than a single-domain constraint.

Managerial implications include:

- Prioritizing standards development and insurer collaboration as first-order interventions.
- Aligning procurement frameworks with additive construction logic.
- Establishing interdisciplinary training linking digital design, materials engineering, and robotic fabrication.

- Deploying strategically located demonstrator projects to shift market perception and regulatory familiarity.

As such, the findings suggest that successful C3DP diffusion requires synchronised shifts across governance, markets, technology, and culture.

5.6. Analytical Interpretation of Dominant Barriers and Implementation Implications

Building on the descriptive results and TISM hierarchies, this subsection explains why particular barriers emerge as dominant and how these findings extend the previous C3DP adoption literature. The dominance of institutional and governance barriers can be explained by the assurance-dependent nature of construction innovation. Unlike many manufacturing applications, C3DP outputs must satisfy building approval, structural safety, durability, insurance, procurement, and public-trust requirements before they can be adopted at scale. This aligns with previous C3DP studies [10,34,45], who identify standardisation, certification, material validation, and regulatory acceptance as recurring barriers to large-scale implementation.

These findings also connect with socio-technical transition theory, particularly Geels' [16] argument that emerging technologies diffuse only when technological capability aligns with regulatory regimes, markets, users, and institutional structures. Similarly, innovation diffusion theory helps explain why perceived relative advantage, compatibility, trialability, and observability remain limited when standards, QA/QC procedures, and certifier confidence are underdeveloped [43]. From an institutional theory perspective [43], legitimacy, regulatory recognition, and professional acceptance are necessary before C3DP can move from experimental pilots to routine industry practice.

For future C3DP implementation, this suggests that strategies should not focus only on printer capability, robotic precision, or printable materials. Technical developments are necessary, but they are insufficient without parallel development of assurance infrastructure. Priority should therefore be given to interim standards, certifier-recognised QA/QC protocols, validated material datasets, insurance engagement, pilot procurement pathways, and structured workforce certification. This is consistent with the implementation concerns highlighted by previous studies [22,26,51].

5.7. Prioritised Intervention Pathways for India and Australia

Based on the vital barriers identified through Pareto analysis and the hierarchical dependencies revealed through TISM, this study proposes a set of prioritised intervention pathways for India and Australia. These actions are derived explicitly and implicitly from the interview narratives, where participants repeatedly emphasised the need for standards, certification pathways, public demonstration projects, targeted skill development, locally validated materials, procurement reform, and risk-governance mechanisms. The proposed interventions are not statistically tested policy prescriptions; rather, they are expert-informed pathways for breaking the institutional and technical path dependencies identified in the study. Table 6 presents the prioritised intervention pathways for C3DP adoption in India and Australia.

Table 6. Prioritised intervention pathways for C3DP adoption in India and Australia.

Priority	India: Key Path Dependency	Prioritised Intervention	Australia: Key Path Dependency	Prioritised Intervention
1	Absence of dedicated national C3DP codes and fragmented approval processes	Develop interim BIS guidelines for C3DP materials, design validation, structural testing, and approval pathways (IN-01, IN-05, IN-07).	NCC ambiguity and case-by-case certification	Develop an interim ABCB/Standards Australia technical handbook or NCC appendix for C3DP performance solutions (AU-05, AU-08, AU-01).
2	Limited institutional coordination across government, academia, and industry	Establish a national C3DP taskforce involving BIS, MoHUA, CPWD, CBRI, academia, and industry (IN-07, IN-08, IN-03).	Fragmented risk governance between certifiers, insurers, clients, and regulators	Establish a regulatory–insurance–certifier working group to define liability allocation and insurability criteria (AU-08, AU-06, AU-03).
3	Limited large-scale evidence beyond pilots	Fund public demonstration projects in affordable housing, disaster-resilient shelters, sanitation units, and public infrastructure (IN-08, IN-04, IN-03).	Procurement conservatism and low public-sector demand	Introduce public procurement pilots or innovation quotas for low-risk C3DP applications, such as amenities, retaining walls, drainage units, and public furniture (AU-06, AU-03, AU-04).
4	Skill shortages in robotics, extrusion control, mix design, and site operation	Introduce C3DP modules in civil engineering, architecture, ITI, and polytechnic training programmes, supported by hands-on certification (IN-03, IN-04, IN-01, IN-02).	Shortage of hybrid skills in robotics, concrete technology, BIM, and digital quality assurance	Develop TAFE/university micro-credentials for C3DP operator training, digital QA, and performance-based compliance documentation (AU-01, AU-02, AU-04, AU-09).
5	Material variability and lack of regionally validated printable mixes	Create regional testing centres for printable materials, including locally available sand, fly ash, slag, calcined clay, and other supplementary cementitious materials (IN-01, IN-02, IN-05, IN-06).	Limited locally validated material datasets for Australian climates	Expand university–industry testing of printable mixes under Australian climatic, fire, durability, and acoustic performance requirements (AU-01, AU-05, AU-07, AU-09).
6	High capital cost and weak financing confidence	Provide soft loans, tax incentives, or innovation grants for local printer manufacturing, material testing, and pilot deployment (IN-03, IN-06, IN-08).	High capital cost and uncertain return on investment	Support shared printing hubs, collaborative testbeds, and government-backed demonstration funding to improve utilisation and reduce risk exposure (AU-03, AU-04, AU-06).

Table 6. *Cont.*

Priority	India: Key Path Dependency	Prioritised Intervention	Australia: Key Path Dependency	Prioritised Intervention
7	Public and client scepticism regarding durability and acceptability	Use certified demonstration projects and public awareness programmes to build trust in structural performance and long-term durability (IN-05, IN-07, IN-08).	Certifier, client, and insurer hesitation	Use digital QA records, sensor-based monitoring, and BIM-linked as-built documentation to increase confidence in printed elements (AU-02, AU-08, AU-09, AU-05).

The proposed pathways reflect the different maturity conditions of the two ecosystems. For India, the immediate priority is to move from fragmented experimentation toward coordinated regulatory formation, skill development, and locally validated material systems. For Australia, the priority is not basic technology awareness, but the creation of risk-governance mechanisms that allow certifiers, insurers, procurers, and clients to accept C3DP within a performance-based compliance environment. In both contexts, public demonstration projects are essential because they convert technical feasibility into institutional confidence and market legitimacy.

5.8. Conceptualising C3DP Adoption Within Construction 4.0 Transitions

The findings suggest that C3DP adoption should be understood as part of the wider Construction 4.0 transition rather than as the diffusion of a single fabrication technology. C3DP integrates robotics, digital modelling, material science, automation, sensor-based quality assurance, and data-driven workflows; therefore, adoption depends not only on printer capability or material performance, but also on institutional readiness in approval, procurement, certification, insurance, workforce training, and project delivery systems [9,60].

From a socio-technical transition perspective, C3DP becomes constrained when technological capability advances faster than the surrounding regulatory, professional, and market systems [16]. This explains why technically successful pilots do not automatically lead to routine adoption. In both India and Australia, standards, certification pathways, liability frameworks, procurement practices, and workforce capabilities must evolve alongside material and robotic performance [22,23,34].

The comparative findings also show different institutional conditions. India's challenge is mainly institutional formation, involving codes, testing infrastructure, skill ecosystems, and coordinated policy mechanisms [20,26]. Australia's challenge is closer to institutional adaptation, where mature approval, insurance, and procurement systems require stronger evidence before accepting non-conventional construction methods. Thus, C3DP adoption depends on four interacting layers: technological capability, institutional legitimacy, market and procurement readiness, and social-professional acceptance. C3DP can move from pilot experimentation to mainstream Construction 4.0 practice only when these layers are aligned.

6. Conclusions

This study examined the barriers influencing C3DP adoption in India and Australia through 17 semi-structured expert interviews, content coding, Pareto prioritisation, and TISM. The findings show that C3DP adoption is not constrained by isolated technical

limitations alone but by a concentrated set of institutional, economic, technological, social, environmental, and legal barriers. Across both countries, the absence of dedicated standards, certification pathways, liability clarity, and insurer-recognised approval mechanisms emerged as central constraints. These barriers limit the transition of C3DP from pilot demonstrations to routine industry practice. The comparative findings show that India and Australia face different adoption challenges. In India, the key issue is institutional formation, including fragmented regulation, limited codification, material variability, skill shortages, and cost-sensitive procurement. In Australia, the challenge is institutional adaptation, where mature but risk-averse systems of certification, insurance, procurement, and compliance slow the acceptance of non-conventional construction methods. Therefore, C3DP adoption depends not only on technological readiness but also on socio-technical alignment among regulation, market confidence, professional capability, and public trust. The study provides several practical recommendations. In India, policymakers should prioritise interim BIS-based guidance for C3DP materials, design validation, structural testing, and approval pathways. Public agencies should support demonstration projects in affordable housing, public infrastructure, sanitation units, and disaster-resilient shelters. Industry adoption can be further supported through regional material testing centres, local printer manufacturing, and structured training programmes for engineers, architects, technicians, and site supervisors. In Australia, the priority is to integrate C3DP into the existing performance-based regulatory environment through interim ABCB or Standards Australia guidance, clearer NCC-based performance solution pathways, insurer-recognised testing protocols, and public procurement pilots. For industry, BIM-linked digital QA/QC records, validated material datasets, and hybrid workflows combining C3DP with modular, precast, or prefabricated systems can improve confidence and scalability. The industrial applicability of the study lies in identifying where adoption risk is concentrated and which upstream barriers must be addressed first. Contractors, technology providers, regulators, certifiers, insurers, and public clients can use the findings to prioritise standards development, risk allocation, pilot procurement, workforce training, and performance validation before attempting large-scale deployment. This study has limitations. The findings are based on 17 expert interviews across two countries and should therefore be interpreted as analytically generalisable rather than statistically generalisable. The expert sample provides analytical depth across relevant stakeholder groups but does not capture the full diversity of regional, organisational, sectoral, and procurement conditions within India or Australia. Therefore, the findings should be interpreted as exploratory and analytically generalisable rather than as comprehensive national generalisations. Although variance, standard deviation, and coding reliability were added to improve methodological transparency, the analysis remains based on coded qualitative frequencies. Also, Pareto analysis helped identify frequently emphasised barriers; coded frequency does not necessarily equate to causal importance. The results therefore indicate perceived prominence within the interview data rather than measured causal weight. The TISM models represent expert-informed structural interpretations and do not empirically test causal relationships. Adoption conditions may also vary across states, cities, project types, procurement systems, and stakeholder groups. Future research should test the proposed barrier relationships and intervention pathways through larger surveys, Delphi studies, longitudinal case studies, pilot-project evaluations, and cross-country comparative research. As such, the study concludes that scaling C3DP requires more than proving that the technology works. It requires coordinated institutional, regulatory, commercial, and professional systems that can support its transition from experimental innovation to mainstream Construction 4.0 practice.

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Institutional Review Board Statement: Ethical review and approval were waived for this study by the Institutional Committee, as per the Australian NHMRC National Statement (classified as "negligible risk") and the Indian ICMR National Ethical Guidelines 2017 (classified as "less than minimal risk"). This waiver is applicable because the study is based on a secondary analysis of completely de-identified data from 17 semi-structured expert interviews conducted across Australia and India, ensuring no personal identifiers were accessible to the researchers.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors Mohammad Arqam and Joeri Tuijn were employed by the company Ignition Chamber. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Appendix A. Semi-Structured Interview Protocol

Purpose of the interview

To identify drivers, barriers, enablers, and institutional conditions influencing the adoption of Construction 3D Printing in India and Australia.

Opening questions

1. Could you briefly describe your professional role and your involvement with C3DP or related digital construction technologies?
2. How would you describe the current maturity of C3DP adoption in your country or sector?

Drivers of C3DP adoption

3. What are the main factors encouraging interest in C3DP?
4. Are these drivers mainly technological, economic, environmental, policy-related, or market-driven?
5. Can you provide examples from projects, policy initiatives, research programmes, or industry trials?

Barriers to C3DP adoption

6. What are the most significant barriers preventing wider adoption of C3DP?
7. Are there specific political, policy, or regulatory barriers?
8. What economic or financial barriers affect adoption?
9. What social, workforce, cultural, or professional barriers are evident?
10. What technological barriers exist, such as material performance, printer reliability, layer bonding, reinforcement, quality assurance, or digital integration?
11. What environmental or sustainability-related barriers affect adoption?
12. What legal, certification, liability, insurance, or approval-related barriers affect implementation?

Interrelationships among barriers

13. Do some barriers influence or reinforce other barriers?
14. Which barriers do you consider root causes, and which are more likely to be downstream consequences?
15. Can you provide examples of how one barrier, such as the absence of standards, affects finance, procurement, technical validation, or public trust?

Enablers and intervention pathways

16. What actions could accelerate C3DP adoption in your country or sector?
17. What role should government, industry, universities, certifiers, insurers, and training institutions play?
18. What types of pilot projects, standards, procurement reforms, or training programmes would be most useful?

Comparative and future outlook

19. How does your country compare with other international contexts in C3DP adoption?
20. Where do you see C3DP adoption in the next five to ten years?

Closing question

21. Is there anything else you think is important for understanding C3DP adoption barriers or future pathways?

Appendix B. Coding Reliability Assessment for C3DP Barriers

Table A1. Reliability summary.

Item	Value	Notes
Coding framework	PESTEL barrier categories	Political, Economic, Social, Technological, Environmental, Legal
Source material	India and Australia interview transcripts	60 meaning units selected across the 17 interviews
Reliability method	Intercoder reliability audit	Main coding compared against independent/audit coding
Number of coded units	60	10 units per category
Observed agreement	0.91	55 agreements out of 60 units
Expected agreement	0.16	Expected agreement by chance
Cohen's kappa	0.90	Interpretation: almost perfect agreement
Disagreement resolution	Discussion-based reconciliation	Disagreements were reviewed before finalising the PESTEL coding framework

Table A2. Audit coding matrix.

Serial Number	Participant	Representative Coded Extract	Main Code	Audit Code	Decision
1	IN-01	Lack of clear national roadmap and no dedicated 3DCP code	Political	Political	Agree
2	IN-02	Need for a national 3DCP Innovation Mission under DST or MoHUA	Political	Political	Agree
3	IN-03	Regulatory vacuum requires each authority to be convinced separately	Political	Political	Agree
4	IN-04	No standard tendering clause for 3D printing in public construction	Political	Political	Agree
5	IN-07	Municipal approval requires conventional IS code references	Political	Legal	Disagree; resolved after coder discussion
6	AU-01	Interim standards from ABCB or Standards Australia would help	Political	Political	Agree
7	AU-03	NCC does not yet cover 3D-printed elements	Political	Political	Agree
8	AU-05	Each printed structure requires a Performance Solution pathway	Political	Political	Agree
9	AU-08	Procurement rigidity excludes additive methods from tenders	Political	Political	Agree
10	AU-08	Cross-agency collaboration is needed to align housing innovation policy	Political	Political	Agree
11	IN-01	High upfront investment means small builders cannot justify printer purchase	Economic	Economic	Agree
12	IN-02	Funding committees often question whether robotics fits housing priorities	Economic	Economic	Agree
13	IN-03	Importing sensors, servos and control boards increases machinery cost	Economic	Economic	Agree
14	IN-04	Prototype-scale printing remains 20 to 25 percent higher in cost	Economic	Political	Disagree; resolved after coder discussion
15	IN-06	Public housing budgets are too constrained for unproven technologies	Economic	Economic	Agree

Table A2. *Cont.*

Serial Number	Participant	Representative Coded Extract	Main Code	Audit Code	Decision
16	AU-01	Printing remains more expensive than blockwork after logistics and amortisation	Economic	Economic	Agree
17	AU-03	Large-format printer costs create a major commitment for mid-tier contractors	Economic	Economic	Agree
18	AU-04	Capital costs remain high and utilisation rates are low	Economic	Economic	Agree
19	AU-08	Funding approval needs proven cost-effectiveness	Economic	Economic	Agree
20	AU-03	Local components reduce printer costs and improve commercial feasibility	Economic	Economic	Agree
21	IN-01	Automation is sometimes viewed as a threat to construction employment	Social	Social	Agree
22	IN-01	People equate conventional concrete blocks with solidity	Social	Social	Agree
23	IN-02	Robots and code-based design feel alien to some colleagues	Social	Economic	Disagree; resolved after coder discussion
24	IN-03	Workers initially react with curiosity and suspicion	Social	Social	Agree
25	IN-04	Labour unions question whether automation will cut jobs	Social	Social	Agree
26	AU-01	Public often misunderstands 3D printing as pressing a button overnight	Social	Social	Agree
27	AU-02	Some clients view the layered printed texture as unfinished	Social	Social	Agree
28	AU-04	Unions initially saw automation as a threat	Social	Social	Agree
29	AU-07	Design-craft integration shapes cultural acceptance	Social	Social	Agree
30	AU-08	Residents ask whether printed homes will last or be safe in bushfire	Social	Social	Agree
31	IN-01	Variable sand gradations, humidity and temperature affect mix consistency	Technological	Technological	Agree

Table A2. *Cont.*

Serial Number	Participant	Representative Coded Extract	Main Code	Audit Code	Decision
32	IN-01	Small labs lack rheology equipment for printability parameters	Technological	Technological	Agree
33	IN-02	Geopolymer setting time is difficult to control for extrusion	Technological	Technological	Agree
34	IN-03	Nozzle clogging, power stability and sand gradation can make or break a print	Technological	Technological	Agree
35	IN-04	Architectural drawings must be converted into G-code geometry	Technological	Technological	Agree
36	AU-01	Real-time LiDAR feedback adjusts layer geometry mid-print	Technological	Technological	Agree
37	AU-03	Sensor logs track extrusion rate, layer geometry and curing conditions	Technological	Technological	Agree
38	AU-04	Layer adhesion and dimensional accuracy need new QA metrics	Technological	Environmental	Disagree; resolved after coder discussion
39	AU-06	Testing protocols do not capture inter-layer bonding or anisotropy	Technological	Technological	Agree
40	AU-06	Temperature and humidity swings change setting time dramatically	Technological	Technological	Agree
41	IN-01	High OPC content in current mixes raises sustainability concerns	Environmental	Environmental	Agree
42	IN-02	Geopolymer mixes can reduce CO_2 emissions compared with OPC systems	Environmental	Environmental	Agree
43	IN-03	Fly-ash-rich mixes reduce embodied carbon compared with OPC mortar	Environmental	Environmental	Agree
44	IN-04	Low-clinker binders and recycled aggregates align with ESG reporting	Environmental	Environmental	Agree
45	IN-06	Circular materials and embodied carbon reduction influence adoption	Environmental	Environmental	Agree
46	AU-01	LCA studies show waste and embodied-carbon reductions	Environmental	Environmental	Agree
47	AU-02	Topology optimisation places material only where structurally needed	Environmental	Environmental	Agree

Table A2. *Cont.*

Serial Number	Participant	Representative Coded Extract	Main Code	Audit Code	Decision
48	AU-03	Cement replacement mixes and recycled glass fines support circularity	Environmental	Environmental	Agree
49	AU-04	Eliminating formwork timber is a carbon benefit	Environmental	Environmental	Agree
50	AU-08	Demolished concrete can be recycled into printable mixes	Environmental	Environmental	Agree
51	IN-01	Without certification, government departments cannot easily approve structures	Legal	Legal	Agree
52	IN-02	Architects hesitate because no design codes or approval frameworks exist	Legal	Technological	Disagree; resolved after coder discussion
53	IN-03	Insurance is difficult because underwriters do not understand printed walls	Legal	Legal	Agree
54	IN-04	Engineers remain cautious until BIS formalises durability criteria	Legal	Legal	Agree
55	IN-05	National testing facilities are required for validated material certification	Legal	Legal	Agree
56	AU-01	Risk allocation in contracts is unclear when robotic systems are involved	Legal	Legal	Agree
57	AU-03	Underwriters do not know how to price risk for printed walls	Legal	Legal	Agree
58	AU-05	Certifiers hesitate because liability rests on unproven methods	Legal	Legal	Agree
59	AU-05	Insurers rely on codes and need codified references	Legal	Legal	Agree
60	AU-08	Certified methods are required before public agencies can adopt printed housing	Legal	Legal	Agree

Table A3. Confusion matrix.

Main Code/Audit Code	Political	Economic	Social	Technological	Environmental	Legal
Political	9	0	0	0	0	1
Economic	1	9	0	0	0	0
Social	0	1	9	0	0	0
Technological	0	0	0	9	1	0
Environmental	0	0	0	0	10	0
Legal	0	0	0	1	0	9
Total audit-coded	10	10	9	10	11	10
Cohen's kappa	0.900					

Appendix C. TISM Procedure, Matrices and Level Partitioning

Table A4. SSIM symbols and conversion rules.

Symbol	Meaning
V	Barrier *i* influences barrier *j*
A	Barrier *j* influences barrier *i*
X	Barriers *i* and *j* influence each other
O	No direct relationship identified
SSIM symbol	**Binary conversion rule**
V	(i, j) = 1 and (j, i) = 0
A	(i, j) = 0 and (j, i) = 1
X	(i, j) = 1 and (j, i) = 1
O	(i, j) = 0 and (j, i) = 0

Table A5. Structural self-interaction matrix for India.

Barrier	P	E	S	T	Env	L
P	–	V	V	V	V	X
E		–	V	X	V	A
S			–	A	X	A
T				–	V	A
Env					–	A
L						–

Table A6. Initial reachability matrix for India.

Barrier	P	E	S	T	Env	L
P	1	1	1	1	1	1
E	0	1	1	1	1	0
S	0	0	1	0	1	0
T	0	1	1	1	1	0
Env	0	0	1	0	1	0
L	1	1	1	1	1	1

Table A7. Final reachability matrix for India after transitivity.

Barrier	P	E	S	T	Env	L	Driving Power
P	1	1	1	1	1	1	6
E	0	1	1	1	1	0	4
S	0	0	1	0	1	0	2
T	0	1	1	1	1	0	4
Env	0	0	1	0	1	0	2
L	1	1	1	1	1	1	6
Dependence power	2	4	6	4	6	2	

Table A8. Structural self-interaction matrix for Australia.

Barrier	P	E	S	T	Env	L
P	–	V	V	V	V	X
E		–	X	V	V	A
S			–	V	V	A
T				–	X	A
Env					–	A
L						–

Table A9. Initial reachability matrix for Australia.

Barrier	P	E	S	T	Env	L
P	1	1	1	1	1	1
E	0	1	1	1	1	0
S	0	1	1	1	1	0
T	0	0	0	1	1	0
Env	0	0	0	1	1	0
L	1	1	1	1	1	1

Table A10. Final reachability matrix for Australia after transitivity.

Barrier	P	E	S	T	Env	L	Driving Power
P	1	1	1	1	1	1	6
E	0	1	1	1	1	0	4
S	0	1	1	1	1	0	4
T	0	0	0	1	1	0	2
Env	0	0	0	1	1	0	2
L	1	1	1	1	1	1	6
Dependence power	2	5	5	6	6	2	

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