Assessment Framework for 3D Concrete Printing Technology in Alignment with Construction 5.0 Criteria

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Abstract –

The transition from Construction 4.0 to Construction 5.0 signifies a new era of innovative and advanced practices in the construction industry. This study explores the integration of 3D Concrete Printing (3DCP) technology within the Construction 5.0 paradigm, emphasising its potential to transform conventional practices by aligning with core criteria of Construction 5.0 such as human-centricity, sustainability, resilience, and cost and environmental control. A systematic literature review was conducted to identify the key criteria of Construction 5.0 and determine the critical drivers of 3DCP across each criterion. For each criterion, ten critical drivers were identified that align 3DCP with Construction 5.0 principles. The study employs content analysis to rank and prioritise these drivers, ensuring a robust understanding of their significance, supported by a comprehensive framework for evaluating their alignment with Construction 5.0. Additionally, a conceptual implementation framework for 3DCP was developed, encompassing three phases: knowledge building, the adoption phase, and performance assessment. This framework aims to facilitate the practical application of 3DCP within the construction industry and provides a roadmap for industry and academia to integrate 3DCP into Construction 5.0 practices effectively.

Keywords –

construction 4.0, construction 5.0, 3D concrete printing, human centricity, sustainability, resilience, cost and environmental control

1 Introduction

The construction industry has undergone significant transformations over the years, with the advent of Construction Industry 4.0 marking a pivotal shift through Internet of Things (IoT), artificial intelligence (AI), Cloud Computing (CM), Big data Analytics (DBA), robots and Cyber Physical Systems (CPS), 3DCP, Augmented and Virtual Reality (AR/VR) and blockchain technology to enhance efficiency, automation, and data-driven decision-making [1]. Construction Industry 4.0 primarily focuses on the technological aspects of construction, emphasising automation, digitisation, and data-driven processes, but it often overlooks the human-centric elements of the industry. Despite the potential of these technologies to improve the design, management, operation, and decision-making of construction projects, the industry's ability to fully integrate them remains low [2].

In response, the Construction 5.0 paradigm is the next phase in industrial development that aims to combine the skills of human experts in partnership with efficient and precise machines to achieve production solutions that are resource efficient and preferred by clients [3]. Rather than replacing workers with machines, Construction 5.0 seeks to create a balance where smart technologies such as AI, robotics, 3DCP, Building Information Modelling (BIM), Digital Twin (DT) and IoT, empower workers to become more efficient and safer while fostering innovation [4]. This human-centred approach addresses the evolving demands of the industry, including sustainability, precision, and adaptability. Construction 5.0 builds on advancements from Construction 4.0, prioritising the collaboration between people and technology. It ensures that workers remain central to the process, using technology as a tool to enhance rather than replace their capabilities [3]. Construction 5.0 is neither a replacement nor an alternative to Construction 4.0 but rather an evolution and logical continuation. It centres around four interconnected core values: human-centricity, sustainability, resilience, and cost reduction & environmental control [1].

Among the various promising technologies and applications that Construction 5.0 supports to enhance production and deliver customised products one key technology is 3DCP, which has capacity to completely transform the conventional construction process [5]. The construction 3D Printing process involves using digital models to layer materials, such as concrete or polymers, to build structures by layering them systematically [6]. The use of this technology provides numerous benefits, including decreased labour needs, lower production expenses, increased productivity due to faster construction processes, cost savings, high efficiency, eco-friendliness, reduced waste generation, and the capability to construct intricate shapes and structures [5]. Thus, 3DCP is pivotal in advancing the construction industry towards the holistic goals of Construction 5.0.

Up to date very limited research studies have investigated the alignment of 3DCP technology with Construction 5.0 goals. Max et al. [7] examined the sustainability benefits of adopting 3DCP in the construction industry, highlighting its potential for significant material savings, reduced carbon footprints compared to traditional methods, increased automation, and addressing the current shortage of skilled labour in the sector. Himanshu et al. [8] highlighted the resilience of 3DCP structures, attributing it to enhanced customisation and faster adaptation to design changes, aligning with Construction 5.0 adaptability goals. Giovanni et al [9] explored the human-centric aspects of 3DCP, demonstrating its potential to create ergonomically safer environments by reducing manual labour. Wang et al. [10] analysed the integration of cloud manufacturing and IoT in 3DCP, highlighting its role in digitalising construction to provide reliable features, enable real-time monitoring, and improve operational efficiency, aligning with Industry 5.0 focus on technology-human collaboration. The above studies collectively underline the significance of 3DCP in fulfilling the core values of Construction 5.0, including human-centricity, sustainability, resilience, and cost reduction & environmental control. They also highlight the need for an integrated assessment framework to optimise its adoption.

A key limitation in the existing body of research is the absence of structured frameworks to evaluate how effectively 3DCP aligns with the criteria of Construction 5.0. This study seeks to fill this critical gap by developing an assessment and implementing framework that systematically evaluates 3DCP technology in alignment with Construction 5.0 criteria.

2 Research Model Development

The research methodology consists of four key steps. The first step includes a literature search. A comprehensive search was conducted across the databases including Scopus, Web of Science, and Google Scholar were utilised to retrieve peer-reviewed journal articles, conference papers, and review articles published in English since 2015. Keywords including “Industry 4.0,” “3D Concrete Printing,” “Industry 5.0,” “Construction Industry,” and “digital Construction” were used to find the articles. This ensured the inclusion of up-to-date and high-quality research addressing the study objectives.

Secondly, a systematic analysis was conducted to explore the alignment of 3DCP technology with Construction 5.0 criteria. The focus was on identifying key criteria for Construction 5.0, which broadly encompass the essential elements necessary for driving innovation, sustainability, and collaboration in modern construction practices. These criteria reflect the integration of advanced technologies with human-centric approaches to create a more adaptive and resilient construction ecosystem. This analysis provided the foundational insights necessary for developing the assessment framework.

Thirdly, a content analysis of the selected literature was conducted to identify the key drivers of 3DCP technology for each of the Construction 5.0 criteria. This is essential because the criteria of Construction 5.0 are inherently abstract and require the identification of specific drivers to enable their practical evaluation. These drivers act as measurable and actionable components that link theoretical concepts to real-world applications. By categorising and highlighting these drivers, the analysis provided valuable insights into how 3DCP technology can align with and support the overarching criteria of Construction 5.0. The findings from this analysis served as an essential foundation for the development of the proposed assessment framework.

Finally, an assessment and conceptual framework for implementing 3DCP in alignment with Construction 5.0 criteria was developed, based on identified key drivers and expert opinions from construction engineering and 3DCP specialists.

2.1 Systematic Literature Review

The systematic literature review was conducted to critically examine existing research and identify the core criteria of Construction 5.0, with a particular focus on their relevance to 3DCP technology. A summary of the systematic literature review is presented in Table 1. The four core dimensions of Construction 5.0 identified through this review are:

Human Centricity (HC): This dimension focuses on prioritising human well-being in construction by combining human ingenuity and craftsmanship with the efficiency and consistency of technology [3].

Sustainability (SU): Additive manufacturing, also known as 3D printing, is a key feature of Construction 5.0, playing a significant role in enhancing the sustainability of manufacturing processes. In Construction 5.0, additive manufacturing focuses on improving customer satisfaction by integrating added value into products and services [3].

Resilience (R): The term 'resilience' refers to the need to enhance the robustness of industrial production, enabling it to better withstand disruptions and maintain essential infrastructure during crises [1].

Cost and Environmental Efficiency (C&EE): In Construction Industry 5.0, "Cost Reduction and Environmental Control" refers to the strategic approach of minimising expenses while managing and reducing environmental impact [11].

Table 1. Systematic literature review

Author name	Articles POS	Construction 5.0 Criteria				
		HC	SU	R	C&EE	Ref
Morteza et al.	Develop a strategic roadmap outlining how Industry 5.0 achieves its sustainable development goals.	✓	✓	✓	-	[12]
Marinelli.	Explore the integration of Industry 4.0 in construction, emphasising management perspectives and the shift towards Construction 5.0	✓	✓	-	-	[13]
Praveen et al	Provides an overview of Industry 5.0, highlighting its enabling technologies, potential applications, and implementation challenges, while emphasising the importance of human-machine collaboration in advancing manufacturing solutions	✓	✓	✓	-	[14]
Huang et al.	Aims to clarify Industry 5.0 and Society 5.0, highlighting their human-centric, sustainable, and resilient visions, and aligning their development to future operations	✓	✓	✓	-	[15]
Sarioğlu	Aims to explain the shift from Industry 4.0 to Industry 5.0 and the creation of Society 5.0, focusing on human-centricity, resilience, cost and environmental efficiency, and sustainability, while introducing Consumer 5.0 to guide companies in updating marketing strategies	✓	✓	✓	✓	[16]
Humayun	Provides an overview of Industry 5.0, including its concept, applications, the role of cutting-edge technologies (CET), and the associated opportunities and challenges	✓	✓	✓	✓	[11]

3 Mapping 3DCP Drivers to Construction 5.0 Criteria

This section outlines how to identify and shortlist the key drivers of 3DCP to meet the criteria of Construction 5.0 criteria using a content analysis approach. A content analysis of more than 20 academic papers was conducted to identify and evaluate the key drivers enabling 3DCP to meet the core criteria of Construction 5.0: Human-Centricity, Sustainability, Resilience, and Cost Reduction & Environmental Control. A total of 10 drivers were identified for each criterion. Each driver was assigned a unique Code (C) to facilitate clear and structured representation throughout the analysis. The Frequency (F) of each driver's occurrence in the literature was calculated using Equation 1 to quantify its prominence [17]. This frequency evaluation identified the prominence of each driver based on its repetition mention in the literature, providing insight into its significance for aligning 3DCP with the principles of Construction 5.0.

$$\mathrm{F} = \sum \text{Driver Occurance in articles} \tag{1}$$

Next, the Significance (S) of each driver was assessed to quantify its relative importance based on its representation in the reviewed literature. Each driver was classified into one of three qualitative categories: High, Medium, or Low. This qualitative categorisation was determined by observing the emphasis placed on the driver across the reviewed studies. The category with the highest mentions was used to assign the driver's overall significance. To transform the qualitative significance into a quantitative measure for subsequent analysis a Quantitative Score (QS) is assigned to each driver (High as 5, Medium as 3, and Low as 1) and the highest frequency impact is selected for each driver following Rasul et al. [18].

$$Ls = \frac{QS \times F}{A \times N} \tag{2}$$

$$NLS = \frac{LS_{Individual}}{\sum LS} \tag{3}$$

$$CS = CS_{previous\ driver} + CS_{Current\ driver} \quad (4)$$

The literature score (LS) is calculated as outlined in Equation 2, where A is the highest possible (qualitative) score, N is the total no of papers which were considered for the identification of the challenges, frequency shows the repetition of challenges in papers. The next step was to transform this LS into a Normalised Literature Score (NLS). Normalisation is required to ensure that the data directly related to the database is considered. Further, each data field contains only one data element, which removes redundant (unnecessary) data. It is obtained by dividing each driver individual LS by the total LS (∑LS) as stated in Equation 3. After that, the Cumulative Score (CS) was then computed to provide an aggregated measure of importance. For the first driver, CS was equal to its NLS. For subsequent drivers, the CS was calculated using Equation 4. The drivers were ranked based on their LS and NLS, with the rankings providing a systematic representation of their relative importance [17]. This structured methodology ensured transparency and consistency in the identification, evaluation, and prioritisation of the key drivers for aligning 3DCP with the criteria of Construction 5.0, as presented in Table 2

Table 2. Driver's identification and ranking

Drivers	C	F	S	QS	LS	LNS	CS	Rank	Ref
Human-Centricity Drivers									
Design Flexibility	H1	13	High	5	0.650	0.213	0.213	1	[6]
Enhance Precision	H2	8	High	5	0.400	0.131	0.344	2	[6]
Job Creation in New Roles	H3	8	High	5	0.400	0.131	0.475	2	[19]
Worker Fatigue Reduction	H4	3	Medium	3	0.090	0.030	0.505	8	[19]
User-Centric Design	H5	8	Medium	3	0.240	0.079	0.583	5	[19]
Worker Empowerment	H6	4	High	5	0.200	0.066	0.649	6	[20]
Smart Building Integration	H7	5	High	5	0.250	0.082	0.731	4	[21]
Community Involvement	H8	5	Medium	3	0.150	0.049	0.780	7	[21]
Human and Machine Interaction	H9	8	High	5	0.400	0.131	0.911	2	[19]
Reduced Human Error	H10	9	Medium	3	0.270	0.089	1.000	3	[20]
					∑LS = 3.05				
Sustainability Drivers									
Material Efficiency/Consumption	S1	11	High	5	0.550	0.122	0.122	3	[22]
Use of Recycled Materials	S2	13	High	5	0.650	0.144	0.266	2	[22]
Energy Efficiency in Construction	S3	7	High	5	0.350	0.078	0.344	6	[22]
Minimised Waste	S4	15	High	5	0.750	0.167	0.511	1	[23]
Reduced Water Usage	S5	5	Medium	3	0.150	0.033	0.544	8	[23]
Eco-friendly Material	S6	8	High	5	0.400	0.089	0.633	5	[24]
Circular Economy Potential	S7	8	Medium	3	0.550	0.122	0.755	3	[24]
Sustainable Supply Chain	S8	6	High	5	0.300	0.067	0.822	7	[24]
Enhance Durability	S9	10	High	5	0.500	0.111	0.933	4	[24]
Improve Thermal Comfort	S10	6	High	5	0.300	0.067	1.000	7	[24]
					∑LS = 4.5				
Resilience Drivers									
Improve Structural Integrity	R1	7	High	5	0.350	0.119	0.119	2	[25]
Reduce Chemical Hazards	R2	5	High	5	0.250	0.085	0.205	4	[26]
Reduce Ergonomic Hazards	R3	5	High	5	0.250	0.085	0.290	4	[26]
Reduce Physical Hazards	R4	6	High	5	0.300	0.102	0.392	3	[26]
Rapid Deployment	R5	6	Medium	3	0.180	0.061	0.454	5	[27]
Improve Construction Site Safety	R6	9	High	5	0.450	0.154	0.608	1	[26]
Promote Modular Construction	R7	6	High	5	0.300	0.102	0.710	3	[27]
Fire Resistance	R8	5	High	5	0.250	0.085	0.795	4	[27]
Resilience to Natural Disasters	R9	6	High	5	0.300	0.102	0.898	3	[27]
Ease of Repair	R10	6	High	5	0.300	0.102	1.000	3	[26]
					∑LS = 2.93				
Reduce Cost and Environmental Control Drivers									

Reduced Labour Cost	CE1	9	High	5	0.450	0.101	0.101	5	[28]
Increased Productivity	CE2	14	High	5	0.700	0.157	0.258	1	[28]
Reduced Construction Time	CE3	10	High	5	0.500	0.112	0.371	4	[28]
Reduce Construction Cost	CE4	12	High	5	0.600	0.135	0.506	3	[28]
Improve Air Quality	CE5	4	High	5	0.200	0.045	0.551	8	[29]
Reduced CO2 footprint	CE6	13	High	5	0.650	0.146	0.697	2	[28]
Reduced Noise Pollution	CE7	4	High	5	0.200	0.045	0.742	8	[27]
Elimination of Formwork Cost	CE8	8	High	5	0.400	0.090	0.831	6	[27]
Reduce Material Cost	CE9	8	High	5	0.400	0.090	0.921	6	[29]
Reduced Site Disturbance	CE10	7	High	5	0.350	0.101	1.000	7	[24]
					$\sum$ LS = 4.450				

4 Assessment Framework for 3DCP in Meeting the Criteria of Construction 5.0

The assessment framework for 3DCP offers a structured methodology to evaluate its alignment with the four core criteria of Construction 5.0: Human-Centricity, Sustainability, Resilience, and Cost and Environmental Control. To effectively illustrate the interconnected causal relationships among the drivers and core criteria, a causal path diagram is employed, enhancing the clarity of the framework and facilitating deeper discussions regarding the outlined causal relationships. Previous literature indicates that causal path diagrams serve as effective tools for visualizing complex processes and sequences of events. Additionally, the use of directional arrows, as suggested by Duncan (1966), elucidates the nature of influence among the various components of the framework [30]. By utilising arrows to indicate the direction of causality, the impact of each driver on its associated criterion is clearly demonstrated [31]. This approach ensures a coherent understanding of how 3DCP aligns with the core criteria of Construction 5.0 by systematically depicting the causal pathways between drivers and their associated criteria.

Human-Centricity is a fundamental pillar of Construction 5.0, and the framework addresses this through ten drivers (H1 to H10) that collectively prioritise the well-being, engagement, and empowerment of individuals involved in construction processes. Drivers such as worker fatigue reduction, enhanced precision, and user-centric design underscore the technology’s ability to create safer and more inclusive construction environments. The integration of smart technologies and the reduction of human error further emphasise how 3DCP fosters a human-centred approach to construction.

The criterion of Sustainability is addressed by 10 drivers (S1 to S10) that focus on minimising environmental impact and maximising resource efficiency. Drivers such as material optimisation, waste reduction, and the use of recycled materials collectively reduce the environmental footprint of construction activities. Furthermore, the adoption of eco-friendly materials and circular economy principles aligns C3DP with global sustainability goals, ensuring long-term environmental benefits.

Resilience, another critical criterion, is supported by ten drivers (R1 to R10) that enhance the adaptability, durability, and reliability of 3D printed structures. Rapid deployment capabilities improved structural integrity, and resilience to natural disasters are key features that make 3DCP a transformative technology in dynamic and high-risk environments. These drivers collectively ensure that 3DCP contributes to robust and future-proof construction practices.

Finally, Cost and Environmental Control is comprehensively addressed through ten drivers (CE1 to CE10) that focus on reducing costs while maintaining environmental sustainability. Drivers such as reduced labour costs, faster construction timelines, and the elimination of formwork illustrate how 3DCP achieves cost efficiency. Simultaneously, the reduction of carbon emissions, noise pollution, and improvements in indoor environmental quality demonstrate its alignment with environmental control objectives. By addressing both economic and ecological efficiencies, 3DCP aligns with Construction 5.0 emphasis on sustainable and cost-effective practices.

This assessment framework, as depicted in Figure 1 provides a clear and logical structure to evaluate 3DCP technology to meet Construction 5.0 criteria. The causal path diagram serves as a critical tool for visualising these relationships, facilitating a comprehensive understanding of how 3DCP drivers influence the achievement of each criterion. This structured approach not only underscores the transformative potential of 3DCP but also serves as a basis for further research and practical implementation in advancing construction practices.

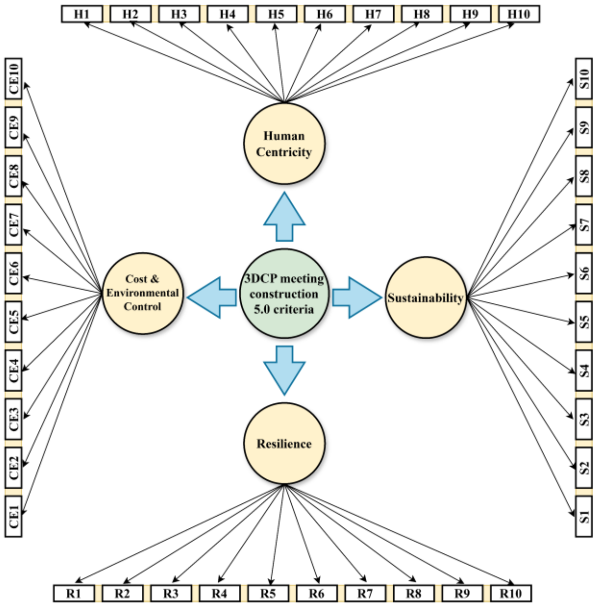

Figure 1. 3DCP assessment framework for Construction 5.0

5 Implementation Framework For 3DCP in Construction Industry

A conceptual framework for implementing a 3DCP in Construction Industry 5.0 was made using an assessment framework and expert opinions of construction engineering and 3DCP specialists, as shown in Figure 2. This conceptual framework comprised three phases: “Knowledge Building Phase”, “Implementation phase”, and “Evaluation Phase”.

5.1 Phase 1: Knowledge Building Phase

The Knowledge Development stage emphasises the need for stakeholder awareness and capacity building through partnerships with professional organisations, academic institutions, and industry bodies. By incorporating 3DCP into training programmes, educational curriculum, and industry case studies, this stage facilitates the dissemination of reliable information and best practices.

5.2 Phase 2: Adoption Phase

The Adoption Phase operationalises the framework through decision making and implementation strategies that address critical barriers, such as high initial costs and a lack of technical expertise. Financial incentives, including subsidies, tax exemptions, and expedited approvals, are positioned as enablers for adoption, and industry stakeholders can use these mechanisms to encourage investment in 3DCP technologies.

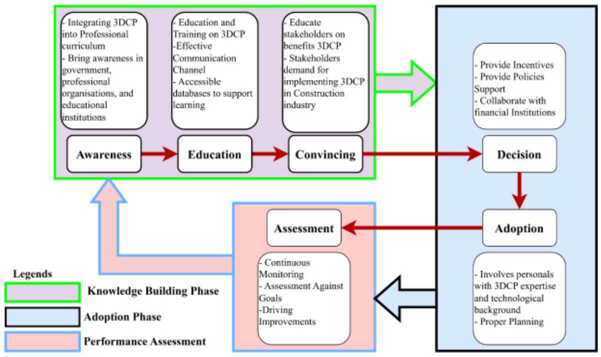

Figure 2. Implementation framework for 3DCP in the construction industry

5.3 Phase 3: Performance Assessment

The Performance Assessment stage provides a mechanism for continuous evaluation and improvement. By monitoring and assessing projects against Construction 5.0 objectives, this stage ensures compliance with human-centric, sustainable, and resilient construction goals.

This framework provides a structured, scalable, and impact-driven approach to integrating 3D concrete printing into Construction 5.0. It enables industry stakeholders to overcome barriers to adoption while delivering sustainable and efficient construction solutions. For academia, it offers a robust foundation for research, collaboration, and knowledge dissemination, advancing the discourse on next-generation construction technologies. By fostering a symbiotic relationship between research and practice, this framework has the potential to catalyse transformative advancements in the built environment, addressing global challenges in sustainability, resilience, human-centric development, and cost and environmental control.

6 Conclusion

This research highlights the transformative role of 3DCP technology in achieving the goals of Construction 5.0. By aligning with the core pillars of Construction 5.0, including human centricity, sustainability, resilience, and cost and environmental control, 3DCP has proven to be a pivotal innovation in modern construction practices. To evaluate the contribution of 3DCP to these objectives, an assessment framework was developed, systematically identifying and prioritising critical drivers across the four dimensions. This framework provided a robust mechanism to quantify the alignment of 3DCP with Construction 5.0 principles, enabling the identification of actionable insights and key performance indicators. By integrating measurable factors, such as design flexibility, material efficiency, and resilience to natural disasters, the assessment framework establishes a foundation for benchmarking the adoption of 3DCP against Construction 5.0 goals.

In addition to the assessment framework, this research proposed a conceptual implementation framework designed to operationalise the findings and facilitate the practical application of 3DCP within the construction sector. The implementation framework is structured into three phases: knowledge building, adoption, and performance assessment. The knowledge-building phase focuses on raising awareness among stakeholders, promoting capacity development, and establishing partnerships with academic institutions and industry bodies. The adoption phase addresses challenges such as high costs and limited expertise, advocating for strategies like financial incentives and multidisciplinary collaboration. Lastly, the performance assessment phase ensures ongoing evaluation and iterative improvement, aligning implementation efforts with the objectives of Construction 5.0.

Future work will focus on integrating insights from grey literature with empirical validation through surveys and case studies to enhance the practical applicability and robustness of the proposed framework, allowing for a more comprehensive understanding of its real-world implications. These efforts will provide additional insights into the applicability of 3DCP across diverse construction scenarios, ensuring that it remains a transformative technology in the industry. Furthermore, this iterative process will facilitate continuous refinement of the framework, strengthening its role in bridging theoretical principles with practical applications.

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