DEMYSTIFYING BARRIERS TO DIGITAL FABRICATION IN ARCHITECTURE

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Abstraction

Although Digital fabrication (DFAB) has been around since 1952, it still faces low adoption rates and several challenges in the Architecture, Engineering, and Construction (AEC) industry. However, there is a lack of comprehensive research that addresses these issues. This study aims to bridge that gap by conducting a systematic literature review to identify the main categories of barriers and their subcategories for the implementation of DFAB. The review identified 16 key barriers that fall under five categories: economic, organisational, personnel, technology, and policy/regulation factors. By identifying these barriers, this research provides a foundation for future studies to examine the interrelationships among these barriers and develop strategies to overcome the barriers to DFAB implementation in architecture.

Keywords: Digital Fabrication, Barriers, Architecture, Implementation, Literature Review

1. Introduction

Digital fabrication (DFAB) refers to data-driven production, where the generated workflow and data enable numerically controlled manufacturing equipment to fabricate parts or products (Bock and Linner, 2015, Ng et al., 2021). Digital Fabrication (DFAB) is not new; its roots can be traced back to 1952 and the first creation of the numerically controlled machine tool (Gershenfeld, 2012). DFAB today has gone far beyond the applications that traditionally assist in generating planar drawings and 3D models. Experimentally, a growing number of digital tools, such as 3D printing and robotic manipulation, have enriched DFAB's practice (Agustí-Juan and Habert, 2017). DFAB capabilities can transform how buildings are designed and produced (Pawar et al., 2017).

However, in the Architectural Engineering and Construction (AEC) industry, DFAB still finds low adoption rates (Ng et al., 2022a, Ng et al., 2021) and as many challenges as opportunities (Yang, 2017, Loveridge and Coray, 2017). DFAB is a form of systemic innovation that faces many barriers to adoption (Hall et al., 2018, Katila et al., 2018). DFAB requires an integrated digital workflow of Design for Manufacture and Assembly (DfMA) (Ng et al., 2021, Tan et al., 2022). Due to the digital challenges involved, some engineering organisations are deterred from engaging in innovation in the design and manufacturing process and remain locked into established paradigms, such as the "mirroring trap" (Hall et al., 2020).

Identifying key barriers specific to the AEC industry is the basis for an in-depth study of DFAB implementation. Some studies have explored the barriers to DFAB in the manufacturing industry (Ng et al., 2022b). For example, Potstada et al. (2016) argue that the immature implementation of DFAB is due to misaligned value chains, underdevelopment of technical standards, and unclear markets. However, the AEC sector organises around projects as the basis for its main activities and is by nature different from the manufacturing industry (Tan et al., 2020, Riley and Clare-Brown, 2001). AEC projects often cover an extensive range of design disciplines with intense interdependencies. Implementing DFAB is a systematic innovation (Ng et al., 2022a). The combination of various DFAB techniques is not simply the sum of all parts (Graser et al., 2020). The bespoke nature of the architectural design and the use of multiple DFAB techniques brought about by multiple disciplines differentiate the barriers to its implementation from manufacturing. There is a need for AEC to re-examine the lessons learned from the DFAB barriers from the manufacturing industry.

Filling the gap regarding the classification of key barriers, and the relationship between them, is a pressing challenge. Some studies have proposed ways of classifying barriers in the manufacturing industry. For example, Stornelli et al. (2021) identified five categories of barriers to advanced manufacturing technologies: 1) economic barriers, 2) organisational constraints, 3) personnel-related issues, 4, technology barriers; and 5) policy and regulation barriers. This diversity is also widespread in the study of barriers in the field of construction. The widely diverse classifications show that the same barriers may contain multidimensional connotations and attributes, which is a prerequisite for their classification as different. Different perspectives of concern, such as those brought about by different purposes, can lead to differences in classification. Improving understanding of the classification of barriers can help further understand the interrelationship between various barriers, and give a more substantial answer to the research's question of *what* are barriers to DFAB? Besides, this lays the conceptual groundwork for proposing a viable exploratory classification approach to facilitate the implementation of DFAB in AEC.

Hence, the key Research Question (RQ) arising from these contexts is:

What are the barriers to the implementation of DFAB faced by engineering organisations?

Answering this question presents three objectives, including 1) *to identify the key barriers (RO1)*, 2) *to identify the main categories of barriers (RO2)*, and 3) *to identify the interrelationships among the key barriers (RO3)*. There is no research to address all these three objectives for DFAB in the AEC industry. There is a need for a study to systematically synthesise previous DFAB implementation cases in the AEC industry, dialogue with barrier studies in the manufacturing industry, and fill the gap in barrier studies in the AEC industry. This research aims to give an initial answer to the *RQ* by achieving *RO1* and *RO2*. The results of this research are the basis for the next research to gain further insight into these barriers for *RO3*, and the final answers to *RQ*.

2. Research Methodology

This research employs a Systematic Literature Review (SLR) to address the research gap under the above challenges. It aims to synthesise a new perspective on the implementation of advanced DFAB practice cases to construct knowledge about barriers to implementation, including key barriers and classification of barriers. SLR can document the most advanced knowledge (Lockett et al., 2006), i.e. the state-of-the-art DFAB cases, and generate new knowledge (Tranfield et al., 2003), i.e. the implementation barriers, thus providing a better explanation of the phenomenon, i.e. the implementation of DFAB.

For data collection, the research aims to understand the barriers to implementation under empirical settings rather than theoretical DFAB technical development challenges. The case study method contributes to an in-depth exploration of the implementation of DFAB. Thus, the sample was to retrieve the state-of-the-art studies of full-scale DFAB demonstrator cases. A DFAB full-scale demonstrator is a construction project that demonstrates one or several new construction technologies and results in an operational, permitted building or structure at the building scale (Graser and Hall, forthcoming). The selection of demonstrators is important because these projects have additional challenges in terms of methodology and approach when compared to more fundamental research that focuses on developing DFAB techniques. The time was limited to publications from the last ten years. English was the only language of publication considered. All literature was directly related to the AEC industry. One of the largest academic online databases, Web of Science (WoS), was used to sample the articles. Sampling was limited to refereed journal articles only, with conference papers, books, and book chapters excluded because the latter is usually classified as grey literature or does not undergo rigorous peer review (Adams et al., 2017, Clemens et al., 1995). Figure 1 shows the sampling string for querying by WoS:

Figure 1: Keyword search in the WoS database

"**digital fabrication**" (Topic) AND "**case study**" (Topic) AND
("**architecture**" OR "**construction**" OR "**building**") (Topic)
AND 2012-2022 (Year Published) AND **English** (Language)

This search returned 30 document results (November 11th, 2022). Nine articles were excluded based on the inclusion and exclusion criteria described above. The final data collection yielded a sample of 21 articles for the subsequent in-depth analysis (see Appendix). The data collection process followed theoretical saturation, rather than setting a minimum number of articles. The theoretical saturation was tested and validated by a round of snowball sampling of literature with 74 new articles. After the review of the total of 95 results, there are no new patterns emerging after the first round of snowball. Thus, the research stopped further data collection process.

For data analysis, this research adopted thematic content analysis for the returned search results. This approach is preferred over bibliometric methods that analyse large volumes of literature because it allows for more granular findings and the possibility of customised analysis. Excel and NVivo Realise 1.6.1 were used for document storage, classification and analysis. A two-step method was used.

Firstly, the content analysis aimed to group and distil through a "low hovering" over the data (Anderson, 2007). The authors read the abstracts and methodologies of the whole sample for the classification of seven categories, including:

- DFAB techniques (free code)
- Processes (if applicable, free code)
- Target improvement (free code)
- Sector (free code)
- Scale (part of building, the whole building)
- Type (experimental prototype, actual practice)
- Barriers (free code)

The research uses five categories of advanced manufacturing technology adoption barriers from the result by Stornelli et al. (2021), including 1) economic barriers, 2) organisational constraints, 3) personnel-related issues, 4, technology barriers; and 5) policy and regulation barriers, for a deductive coding. The first and the third authors implemented the coding process to barriers individually and concurrently. Finally, the thematic analysis identified and synthesised themes about barriers that emerged during the inquiry. It analysed the connotations and relationships between themes to address *RO1* and *RO2*, respectively.

3. Results and Discussions

3.1 Description of the use of DFAB techniques

An initial review of the literature reveals that 3D printing and Computer Numeric Control (CNC) are the most widely used DFAB techniques from the literature sample. Although some articles suggest that combining multiple DFAB techniques can address the challenges of limitations of a single technology (Trilsbeck et al., 2019), including combinations of different models of equipment for the same type of technology and combinations of different technology types, the vast majority of articles focus solely on the use of a single DFAB technique (17 out of 21). Only a few exceptions (e.g., Graser et al. (2021)) discuss the combination of more than two DFAB techniques within one single project. In addition, most of the studies use a single case to implement and validate the proposed new or improved techniques in the action research. Only a few studies compare multiple case studies of DFAB implementation (4 out of 21) (Dahy, 2019, Graser et al., 2021, Ng et al., 2021, Agustí-Juan et al., 2017), indicating that there is still much work to be done in this area.

Current research tends to apply DFAB to simpler building types. Housing (He et al., 2021, Graser et al., 2021) and pavilions (Martínez-Rocamora et al., 2020, Kuzmenko et al., 2021, Yoshida et al., 2015, Agkathidis, 2019, Charest et al., 2019) are the main setting for the case, joined by a few other examples of sculptures and installations (Gokmen, 2022, Chiarella and Alvarado, 2015). The majority of studies still use building projects on a small scale, with only two out of twenty-one projects using DFAB in large-scale building projects (Yoshida et al., 2015, Graser et al., 2021). In other words, the majority of studies do not focus on DFAB for the building system as a whole, but rather on a single building component or system, such as panels, walls, facades, and roofs.

Based on the aforementioned findings, it is evident that further investigations are necessary to investigate a wider range of diverse DFAB techniques and to expand the research beyond the analysis of individual building components. In addition, this exploration must encompass larger-scale building initiatives and involve a comparative examination of multiple case studies. Such a comprehensive investigation can help identify additional areas where DFAB can be implemented, enhance existing techniques, and overcome the limitations of current technologies. A deeper comprehension of the barriers to the implementation of DFAB is also required to achieve these objectives.

3.2 Analysis of implementation barriers of DFAB

This research identifies 16 key barriers under five categories, as shown in Table 1. The most frequently occurring barrier codes are for economic and technology barriers.

For economic barriers, the unclear benefit of adopting the technology is another key barrier (Graser et al., 2021). There are several studies carried out to quantify the advantages of DFAB in terms of fabrication waste (Rausch et al., 2021), environment impact (Agustí-Juan et al., 2017, Kuzmenko et al., 2021), manufacturing time (Weng et al., 2021), construction cost (Martínez-Rocamora et al., 2020), etc., thus providing new evidence trying to overcome this challenge. In some specific research situations DFAB has shown advantages in these areas, however, this has not always been the case. Further investigation is required to enhance the recognition of the value of DFAB.

Most research focuses on breaking through technical barriers. Specifically, many case studies have been used to demonstrate the way in which the research proposed to overcome the technical constraints of DFAB. The constraints are manifold, such as hardware (Gomaa et al., 2021), software (Weng et al., 2021), material (Asprone et al., 2018), and process constraints (Rausch et al., 2021). These competence deficiencies are magnified in large-scale architectural projects and by the combination of multiple DFAB technologies.

From the perspective of personnel-related issues, practitioners remain sceptical about the benefits of DFAB (Graser et al., 2021). DFAB relies on capital investment in machinery, equipment and materials (Dahy, 2019). The large investment increases the risk of the project. Human error exacerbates the increased cost of consumables (Yuan et al., 2022).

This also echoes the next major barrier category of policy and regulation barriers, including policy documents, data interoperability, and guidelines for human-machine interaction, etc (Graser et al., 2021). DFAB is still at a very early stage (Agustí-Juan et al., 2017, Weng et al., 2021), and comprehensive guidelines and strategies are missing (Ng et al., 2021, Graser et al., 2021), leaving its implementation without a foundation of initial knowledge and information on which to rely.

Finally, for organisational barriers including a socio-technical perspective, there are relatively few studies about the research on DFAB implementation, although there are a few notable exceptions, such as Graser et al. (2021), Ng et al. (2021) and Tan et al. (2022). This might be because most studies focus on the report of technological development rather than the building process and collaboration across the project team to implement the new technologies.

Table 1 Key implementation barriers of DFAB techniques

Categories	Main barriers	Descriptions	References
A. Economic barriers	A1. High cost of fabrication waste (e.g., material and energy)	Fabrication waste is material, energy, and resources used in digital fabrication that doesn't end up in the final product. The cost of fabrication waste varies based on factors such as material type, product design, process efficiency, and waste disposal cost.	Rausch et al. (2021), Agustí-Juan et al. (2017), Martínez-Rocamora et al. (2020), Dahy (2019), Weng et al. (2021)
	A2. High capital cost (e.g., equipment)	Buying or leasing digital fabrication equipment like 3D printers, laser cutters, and CNC machines is expensive, with ongoing expenses for maintenance, repairs, upgrades, and specialised software.	Dahy (2019), Trilsbeck et al. (2019), He et al. (2021)
	A3. High material cost	Digital fabrication materials, like resin, metal, and plastic, are costly and can increase overall expenses. Waste material generated during the process can also add to the cost if not recycled.	Martínez-Rocamora et al. (2020)
	A4. Limited investment	Small and medium-sized businesses may struggle with the cost, along with personnel training and process adaptation. Limited investment hinders research and development efforts for new materials or process innovations.	Charest et al. (2019), Martínez-Rocamora et al. (2020), Trilsbeck et al. (2019), Graser et al. (2021), Gokmen (2022)
	A5. Unclear benefit	Benefits can be hard to measure and may not be immediately obvious. Some organisations may	Agustí-Juan et al. (2017), Charest et al. (2019), Graser et al. (2021)

		not justify investment if benefits aren't clear or they lack understanding.	
B. Organisational constraints	B1. Weak coordination and collaboration	If these systems and processes are not effectively coordinated and integrated, it can lead to inefficiencies and hinder the overall effectiveness of the digital fabrication process.	Ng et al. (2021), Tan et al. (2022), Graser et al. (2021), Vazquez and Jabi (2015)
	B2. Mismatch with existing systems (e.g., tasks and processes)	Incompatible existing systems and processes can cause additional time, cost, and disruptions, and untrained or unequipped workers can lead to lower productivity.	Tan et al. (2022)
	B3. Organisational resistance to change and learn	This resistance can take many forms, such as reluctance to adopt new technologies, resistance to changes in workflow or processes, and reluctance to learn new business models. Organisations can be reluctant to change and learn due to their familiarity with traditional manufacturing methods and lack of understanding or awareness of the benefits of the new technology.	Agustí-Juan et al. (2017), Ng et al. (2021)
C. Personnel-related issues	C1. Hesitance attitude (e.g., scepticism, uncertainty and unawareness)	It may result from a lack of understanding of its benefits and integration with existing workflows. Scepticism of its capabilities and quality, the uncertainty of costs and benefits, and novelty of the technology may also contribute. Unawareness of potential uses and limitations can further impede implementation.	Ng et al. (2021), Graser et al. (2021)
	C2. Lack of competency (e.g., experience, education and skills)	Employees who lack training in digital fabrication technology can become less efficient and productive. Without the necessary experience or education to use the technology, they may miss opportunities to fully utilise it and make mistakes in the process.	Trilsbeck et al. (2019), Yuan et al. (2022), Agustí-Juan et al. (2017), Graser et al. (2021)
D. Technology barriers	D1. Hardware constraints (e.g., compatibility, reliability, and maintenance)	There may be limited availability and high cost to use digital fabrication machines, as well as limits to their reliability, precision, and production speed. In some cases, the size and capacity of these machines may also be a constraint, limiting the scale of production.	Trilsbeck et al. (2019), Kuzmenko et al. (2021), Vazquez and Jabi (2015), Asprone et al. (2018)
	D2. Software constraints (e.g., compatibility, reliability, and user-friendliness)	Outdated or unsupported software can cause compatibility issues with other systems, leading to operational problems and inefficiencies. In addition, software that is not user-friendly or does not meet the needs of the organisation can make it difficult for employees to use digital fabrication technology effectively.	Nathansohn et al. (2020), Weng et al. (2021), He et al. (2021)
	D3. Material constraints (e.g., availability and suitability)	There are limitations to the types of available materials, properties (e.g., strength, durability, and flexibility), and the need for specialised equipment and expertise.	Martínez-Rocamora et al. (2020), Dahy (2019), Trilsbeck et al. (2019), Kuzmenko et al. (2021), Gomaa et al. (2021), Asprone et al. (2018)
	D4. Process constraints (e.g., compatibility,	Compatibility issues can arise when software, hardware, or materials do not work together. Insufficient speed or production volume can compromise efficiency. The technology can	Rausch et al. (2021), Martínez-Rocamora et al. (2020), Weng et al. (2021), Yuan et al.

	efficiency, and scalability)	also face scalability challenges for larger and more complex structures or if it is too costly to scale up.	(2022), Graser et al. (2021), Kuzmenko et al. (2021), Gomaa et al. (2021), Trilsbeck et al. (2019), Agkathidis (2019), Gokmen (2022), Charest et al. (2019)
E. Policy and regulation barriers	E1. Lack of laws and regulations	The existing regulatory environment creates uncertainty, limits innovation, causes a lack of standardisation, and leads to intellectual property disputes. Without clear legal frameworks and guidelines, organisations and individuals hesitate to invest in digital fabrication and struggle to protect their intellectual property.	Graser et al. (2021), Kuzmenko et al. (2021)
	E2. Lack of standards and codes	The absence of widely-accepted and enforced technical standards and codes makes it difficult for machines from different manufacturers to work together, ensure consistent quality, and ensure safe use. It also creates uncertainty for new players in the market.	Graser et al. (2021), Gokmen (2022), Martínez-Rocamora et al. (2020), Weng et al. (2021)

4. Conclusions

This research investigates the implementation of DFAB in architecture through a SLR. The review suggests that the majority of studies focus on a single DFAB technique, with only a few exploring the combination of multiple techniques. Additionally, current research mainly applies DFAB to simpler building types, with a focus on individual building components rather than the building system as a whole. This research extends the existing understanding of advanced manufacturing technology adoption in terms of its barrier categorises by Stornelli et al. (2021) to a specific area, namely DFAB techniques in architecture. There are 16 key barriers under five categories, including 1) economic barriers, 2) organisational constraints, 3) personnel-related issues, 4, technology barriers; and 5) policy and regulation barriers.

As for the limitation, the research finds that it can only get a set of initial barriers to the implementation of DFAB through the literature review. As the question of implementation barriers is a social-technical issue rather than a purely technical issue, the answer to the research question would be a context-based answer. There are large differences in the level of industrialisation and robotisation between countries. Key barrier factors, and the relationship between barrier factors, can vary depending on the country and region. Although the findings of this study cannot conclusively answer the research questions posed, the significance of this study lies in the field of literature and in understanding the progress of development and associated barriers to DFAB implementation. These preliminary findings can be used as a basis for the next step of barrier investigation and validation in specific country scenarios.

Future research will further identify and classify the potential barriers within an empirical setting to get an in-depth understanding to DFAB implementation. It will therefore need to focus more on specific contexts, such as country contexts, in terms of the difficulty of DFAB implementation. By comparing the barriers to DFAB implementation in different country contexts, it is expected that a more comprehensive and essential framework will be provided to enhance the strategies for DFAB implementation. In addition, more research is needed to investigate a broader range of diverse DFAB techniques and larger-scale building initiatives to overcome the limitations of current DFAB implementation.

Acknowledgement

This research was supported by the National Centre of Competence in Research (NCCR) Digital Fabrication, funded by the Swiss National Science Foundation.

Appendix - 1

No.	Title
1	Topology Optimization of Architectural Panels to Minimize Waste during Fabrication: Algorithms for Panel Unfolding and Nesting
2	Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall
3	Parametric Programming of 3D Printed Curved Walls for Cost-Efficient
4	A Collaborative Approach to Digital Fabrication: A Case Study for the Design and Production of Concrete 'Pop-up' Structures
5	3D printing system for earth-based construction: Case study of cob
6	Assessing environmental impact of digital fabrication and reuse of constructive systems
7	Architecture-Scale Human-Assisted Additive Manufacturing
8	3D printing of reinforced concrete elements: Technology and design approach
9	Digital fabrication, BIM and early contractor involvement in design in construction projects: a comparative case study
10	DFAB HOUSE: implications of a building-scale demonstrator for adoption of digital fabrication in AEC
11	Design for disassembly: Using temporary fabrication for land politics in the Negev
12	Dark Matter Garden: A case study in algorithmic modelling and digital fabrication of complex steel structures
13	Computation and Optimization of Structural Leaf Venation Patterns for Digital Fabrication
14	BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study
15	PATCHWORK GRIDSHELLS: USING MODULARITY TO FACILITATE PREFABRICATION AND SIMPLIFY CONSTRUCTION
16	Natural Fibre-Reinforced Polymer Composites (NFRP) Fabricated from Lignocellulosic Fibres for Future Sustainable Architectural Applications, Case Studies: Segmented-Shell Construction, Acoustic Panels, and Furniture
17	Meeting in the middle: Hybrid clay three-dimensional fabrication processes for bio-reef structures
18	Folded Compositions in Architecture: Spatial Properties and Materials
19	Feasibility study of large-scale mass customization 3D printing framework system with a case study on Nanjing Happy Valley East Gate
20	Extracting BIM Information for Lattice Toolpath Planning in Digital Concrete Printing with Developed Dynamo Script: A Case Study
21	Environmental assessment of multi-functional building elements constructed with digital fabrication techniques
22	A framework for generating and evaluating façade designs using a multi-agent system approach
23	A methodology for transferring principles of plant movements to elastic systems in architecture
24	A procedural framework for design to fabrication
25	A triangular grid generation and optimization framework for the design of free-form gridshells
26	Automatic generation of fabrication drawings for façade mullions and transoms through BIM models
27	Computational design of a nature-inspired architectural structure using the concepts of self-similar and random fractals
28	Connecting architecture and engineering through structural topology optimization
29	Deployable scissor arch for transitional shelters
30	Design to fabrication method of thin shell structures based on a friction-fit connection system
31	Exterior prefabricated panelized walls platform optimization
32	Façade form-finding with swarm intelligence
33	Form finding of nexorades using the translations method
34	Friction magazine: The upcycling of manufacture for structural design
35	Machine learning for architectural design: Practices and infrastructure
36	Morphogenesis of surfaces with planar lines of curvature and application to architectural design
37	Ornamental Discretisation of Freeform Surfaces Developing digital tools to integrate design rationalisation with the form finding process
38	Parametric design to minimize the embodied GHG emissions in a ZEB
39	Parametric modelling and evolutionary optimization for cost-optimal and low-carbon design of high-rise reinforced concrete buildings
40	Simulation-based evolutionary optimization for energy-efficient layout plan design of high-rise residential buildings

41	GA based design automation and optimization of earthquake resisting CFS structures in a BIM environment
42	Building rethought – 3D concrete printing in building practice
43	Design and System Considerations for Construction-Scale Concrete Additive Manufacturing in Remote Environments via Robotic Arm Deposition
44	Design of a 3D printed concrete bridge by testing
45	Design of a post-disaster shelter through soft computing
46	Evaluating The Visibility of Building Syrian Refugee Shelters by 3D Printing Technology in Jordan
47	Modular Structure Construction Progress Scenario: A Case Study of an Emergency Hospital to Address the COVID-19 Pandemic
48	NEST HiLo: Investigating lightweight construction and adaptive energy systems
49	Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell
50	Testing and initial verification of the world's first metal 3D printed bridge
51	The hive a human and robot collaborative building process
52	Tree-Structure Canopy: A case study in design and fabrication of complex steel structures using digital tools
53	Jammed architectural structures: towards large-scale reversible construction
54	Development of the construction processes for reinforced additively constructed concrete
55	Particle-bed 3D printing in concrete construction – Possibilities and challenges
56	Robotic timber construction — Expanding additive fabrication to new dimensions
57	Seismic Performance of F3D Free-Form Structures Using Small-Scale Shaking Table Tests
58	Structural Optimization through Biomimetic-Inspired Material-Specific Application of Plant-Based Natural Fiber-Reinforced Polymer Composites (NFRP) for Future Sustainable Lightweight Architecture
59	An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction
60	An Off-Site Construction Digital Twin Assessment Framework Using Wood Panelized Construction as a Case Study
61	BIM-based graph data model for automatic generative design of modular buildings
62	Development of Variable Residential Buildings with 3D-Printed Walls
63	Environmental Footprint and Economics of a Full-Scale 3D-Printed House
64	Extrusion-Based Additive Manufacturing of Concrete Products: Revolutionizing and Remodeling the Construction Industry
65	Implications of Construction 4 0 to the workforce and organizational structures
66	Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study
67	Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall
68	Supply-chain transparency within industrialized construction projects
69	NEST – A platform for the acceleration of innovation in buildings
70	Toward site-specific and self-sufficient robotic fabrication on architectural scales
71	Life cycle assessment of integrated additive–subtractive concrete 3D printing
72	A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study
73	BIM-Based Digital Fabrication Process for a Free-Form Building Project in South Korea
74	Productivity Analysis of Documentation Based on 3D Model in Plant Facility Construction Project
75	‘Materials as a Design Tool’ Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios
76	Environmental assessment of large-scale 3D printing in construction A comparative study between cob and concrete
77	Environmental design guidelines for digital fabrication
78	Construction site layout planning using multi-objective artificial bee colony algorithm with Levy flights
79	Modelling curved-layered printing paths for fabricating large-scale construction components
80	A Simple Framework for the Cost–Benefit Analysis of Single-Task Construction Robots Based on a Case Study of a Cable-Driven Facade Installation Robot
81	In-Situ Fabrication Mobile Robotic Units on Construction Sites
82	Three cooperative robotic fabrication methods for the scaffold-free construction of a masonry arch
83	A framework for computer-aided design and manufacturing of habitat structures for cavity-dependent animals

84	Augmented bricklaying - Human–machine interaction for in situ assembly of complex brickwork using object-aware augmented reality
85	Automated robotic fabrication for temporary architecture rethinking plastics
86	Experimental research on transition from scale 3D printing to full-size printing in construction
87	How 3D printing technology changes the rules of the game Insights from the construction sector
88	Integrative computational design and construction rethinking architecture digitally
89	Large-scale 3D printing of ultra-high performance concrete—A new processing route for architects and builders
90	Mobile robotic fabrication beyond factory conditions Case study Mesh Mould wall of the DFAB HOUSE
91	Ontology-based manufacturability analysis automation for industrialized construction
92	Perspectives on a bim-integrated software platform for robotic construction through contour crafting
93	Reality is interface: Two motion capture case studies of human–machine collaboration in high-skill domains
94	Structural stay-in-place formwork for robotic in situ fabrication of non-standard concrete structures a real scale architectural demonstrator
95	Topology optimization for 3D concrete printing with various manufacturing constraints

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