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Exploring the Implementation of Digital Fabrication in Construction: Combining System Approaches and a Revelatory Case Study from Switzerland

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Abstract: Digital fabrication is an innovative method for realizing architectural design. However, its implementation is still limited in real projects. Therefore, this research aims to explore the relationships between various implementation barriers of digital fabrication. Taking the Swiss construction industry as the empirical setting, this research comprises a mixed method of systematic review, multicriteria decision analysis, and a single revelatory case study. The systematic review identifies initial barriers to digital fabrication, the DEMATEL-ISM approach investigates barrier relationships, and the case study of the DFAB HOUSE interprets the barriers. The findings include the categorization and interpretation of 16 barriers from economic, technological, organization, personal, and policy dimensions, and reveal the unique challenges of integrating hardware-based digital fabrication technologies, involving both *physical* and *virtual* transformations. This research offers insights into how different barriers interact, impact digital fabrication implementation at project and industry levels, and guide industry stakeholders in driving innovations in digital fabrication. **DOI: 10.1061/JCEMD4.COENG-16680.** © *2025 American Society of Civil Engineers.*

Author keywords: Digital fabrication; Barriers; Construction; Implementation; Switzerland.

Introduction

Authorities in many countries around the world are taking action to address sustainability concerns, including high carbon emissions, health and safety risks, low productivity, and rising costs. Applying Industry 4.0 technologies, such as digital fabrication, to construction (also known as Construction 4.0) can contribute to solving some of these problems (Balasubramanian et al. 2021; Chang et al. 2022; Lee et al. 2021; Ng et al. 2024). Digital fabrication refers to data-driven production, in which computer generated data enables numerically controlled manufacturing equipment to fabricate parts or products (Bock and Linner 2015; Ng et al. 2021). Thus, digital fabrication primarily takes place at the manufacturing phase, emphasizing integration of advanced manufacturing tools and techniques for creating building components; while construction-related terms, such as smart construction, concern mostly the construction phase and focus on optimizing the construction process (Pan and Zhang 2023). Digital fabrication is not new; its roots can be traced back to 1952 and the first creation of a numerically controlled machine tool (Gershenfeld 2012). Digital fabrication today has gone far beyond the applications that traditionally assist in generating planar drawings and 3D models. A growing number of digital tools, such as 3D printing and robotic manipulation, have enriched digital fabrication's practice (Agustí-Juan and Habert 2017). Digital fabrication capabilities can transform how buildings are designed and produced (Pawar et al. 2017; Wang et al. 2025a).

However, in the construction industry, digital fabrication still finds low adoption rates (Ng et al. 2021), and as many challenges as opportunities (Yang 2017; Loveridge and Coray 2017). Many digital fabrication techniques originate from the manufacturing industry, and the differences between the construction and manufacturing industries introduce numerous challenges in its implementation (Vora et al. 2024; Bademosi and Issa 2021; Pradhananga et al. 2021). Digital fabrication is a form of systemic innovation that faces many barriers to adoption (Hall et al. 2018; Katila et al. 2018) and requires an integrated digital workflow of Design for Manufacture and Assembly (DfMA) (Ng et al. 2021). Some organizations 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). Although some studies revealed digital transformation faces many challenges (Trappey et al. 2024; Lee et al. 2022; Wu et al. 2021; Lee et al. 2021), there are no studies to illustrate the relationship between the specific barriers of digital fabrication in construction systematically.

Therefore, the following Research Question (RQ) arises from these contexts:

What are the barriers to the implementation of digital fabrication in construction?

Answering this question presents three Research Objectives (RO), including (1) *to identify the key barriers (RO1)*, (2) *to identify*

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the interrelationships among the key barriers (RO2), and (3) *to interpret the barriers and interrelationships in empirical settings (RO3)*. There is no previous research to date that addresses these three objectives. The answer would lay the conceptual groundwork for proposing a viable exploratory approach to facilitate the implementation of digital fabrication.

This paper is organized as follows: The section "Literature Review" reviews the literature. The section "Methodology" details the methodology. The section "Key Barriers to Digital Fabrication Implementation" presents the key barriers. The section "Interrelationships between Key Barriers" analyzes their interrelationships. Section "Implementation of Digital Fabrication in DFAB HOUSE" interprets them through the DFAB HOUSE case. The section "Discussion" discusses theoretical and practical implications, and the section "Concluding Remarks" concludes.

Literature Review

Digital Transformation and Digital Fabrication in Construction

The construction industry has seen an influx of digital-related terminology, such as digital fabrication, digital construction, and smart construction. While these terms share similarities, each has distinct focuses and technologies that differentiate them in terms of application and scope. For example, digital fabrication is a design and manufacturing workflow in which digital data is created and/or used to directly drive numerically controlled manufacturing equipment in the fabrication of part geometries and/or end products (Bock and Linner 2015; Ng et al. 2021). Digital Construction is a broader concept that encompasses the application of digital technologies across the entire construction lifecycle, from design through operation (Gharaibeh et al. 2022). Smart Construction focuses on integrating technologies like artificial intelligence (AI) to automate processes (Chen et al. 2024a) and the Internet of Things (IoT) to enhance real-time data exchange and safety within the construction environment (Wu et al. 2022). Digital fabrication not only changes traditional building manufacturing methods, enabling the construction of highly customized and complex geometries, but also breaks the limitations of conventional techniques. Additionally, it offers greater freedom in architectural design, driving breakthroughs in both aesthetics and sustainability, which distinguishes it from other concepts.

Digital Fabrication Implementation Barriers

Identifying key barriers specific to the construction industry is the basis for an in-depth study of digital fabrication implementation. Some studies have explored the barriers to digital fabrication in the manufacturing industry. For example, Potstada et al. (2015) argue that the immature implementation of digital fabrication is due to misaligned value chains, underdevelopment of technical standards, and unclear markets. However, the construction industry organizes 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). Existing studies in construction mainly focus on the challenges of adopting *hardware*, like construction automation and robotics (Cai et al. 2020; Pan and Pan 2020), and they rarely focus on the digital transformation of the processfrom design to manufacturing. Construction projects often cover an extensive range of design disciplines with intense interdependencies. Implementing digital fabrication is a systematic innovation (Ng et al. 2021). The combination of various digital fabrication techniques is not simply the sum of all parts (Graser et al. 2020). The barriers to its implementation in construction differ from manufacturing due to the bespoke nature of architectural design and the use of multiple digital fabrication techniques brought about by multiple disciplines. There is a need for the construction industry to re-examine the lessons learned from the barriers in manufacturing.

Filling the gap regarding the classification of key barriers to digital fabrication implementation, and the relationship between them, is a pressing challenge. Some studies have proposed ways of classifying such barriers in the manufacturing industry. For example, Stornelli et al. (2021) identified five categories of barriers to advanced manufacturing technologies: (1) economic barriers, (2) organizational constraints, (3) personnel-related issues, (4) technology barriers, and (5) policy and regulation barriers. Economic barriers include high capital costs, training expenses, and liquidity constraints. Organizational constraints involve issues like lack of project vision, executive resistance, and difficulties in integrating new processes. Personnel-related issues focus on employee resistance to change, fears of job loss, and skills gaps, particularly in emerging technologies. Technology barriers encompass malfunctions, integration challenges, and data security risks. Finally, policy and regulation barriers involve the absence of industry standards, insufficient government support, and intellectual property concerns. These barriers collectively complicate the successful adoption and integration of advanced manufacturing technologies in the manufacturing industry (Stornelli et al. 2021). However, the construction industry differs fundamentally from the manufacturing industry due to the project-based nature of construction. Additionally, although advanced manufacturing technologies are a key component of digital fabrication, digital fabrication also encompasses the concept of design-manufacturing integration, representing a workflow rather than solely an equipment technology. Therefore, the study by Stornelli et al. (2021) cannot be directly applied to the construction industry to reflect the implementation barriers of digital fabrication.

In the construction industry, although studies have highlighted barriers to digital construction, such as Omari et al. (2023) analyzing barriers from the perspectives of owners, consultants, and contractors, and Chen et al. (2024b) conducting a multivariate regression analysis on barriers related to digital construction, as well as research focusing on smart construction barriers, such as Ghansah et al. (2021) exploring latent barriers inhibiting project management processes in smart construction and Hwang et al. (2022) investigating challenges in adopting smart construction and proposing effective strategies to promote adoption. However, there is a lack of attention to the design-manufacturing integration process in the entire construction industry, namely a lack of understanding and exploration of digital fabrication, because digital fabrication focuses on design–manufacturing integration and advanced manufacturing equipment, whereas digital construction is a broader concept covering the entire construction lifecycle.

To assist implementation of innovations and technologies, understanding the implementation barriers of digital fabrication is a critical gap that needs to be addressed because these barriers can hinder their unique potentials in the construction industry. Digital fabrication, with its focus on design-manufacturing integration, offers significant opportunities to influence architectural design, enabling the creation of new, highly customized building forms that were previously difficult to achieve (Schumacher 2017). It also provides a pathway to more sustainable construction by reducing material waste and allowing for more efficient use of resources (Agustí-Juan and Habert 2017; Agustí-Juan et al. 2017). The barriers to implementing digital fabrication, including economic, organizational, technological, policy, and personnel-related factors, can limit these benefits. Therefore, it is crucial to understand not only how these barriers interact but also how they are perceived and manifested in real-world projects.

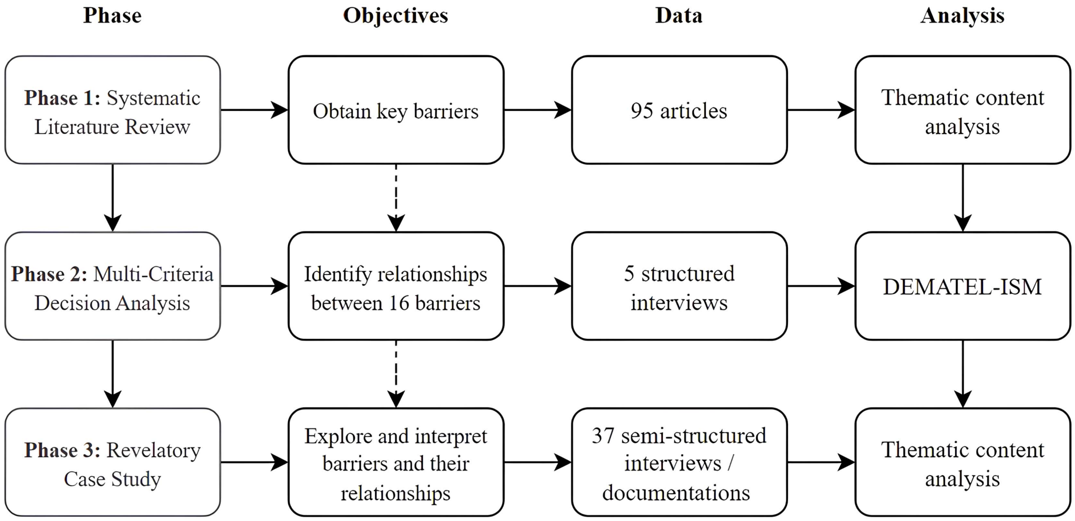

Fig. 1. Research approach and design of multicriteria case analysis.

Methodology

Research Approach and Design

Traditional multicriteria analysis methods, such as Interpretive Structural Modeling (ISM), adopt structured data sources to quantify qualitative data, thereby obtaining the weights or relationships of indicators (Dixit and Kumar 2023). ISM, having standardized steps and calculation procedures, has been widely used to explore the relationships between barriers of innovative technologies, such as Building Information Modeling (BIM) (Tan et al. 2019), and advanced manufacturing technologies (Singh and Khamba 2011). However, the drawback of ISM is that the data lacks in-depth information and focuses on factors at an abstract level, lacking empirical interpretation of these factors in real-world contexts.

Table 1. Background of interviewees

Round	Role	Experience (years)	Number
1	Business developer	10–15	1
	Innovation manager	>15	1
	Professor/Digital fabrication lead (contractor)	10–15	1
	Architect/Project manager/ Professor	>15	1
	Project, Digital planning lead (contractor)	>15	1
2	Senior researchers (e.g., professor, senior scientist, postdoc)	N/A	9
	Junior researchers (e.g., Ph.D. student/recent graduate, research assistant)	N/A	8
	Senior industry participants (>15 years' experience, e.g., SME owner, CEO/CTO, upper management)	>15	7
	Junior industry participants (<15 years' experience, e.g., project manager, site foreman)	<15	4
	Senior other (e.g., client, technician, innovation manager)	>15	4
	Junior other (e.g., client, technician, innovation manager)	<15	5

This research, therefore, proposes a new mixed method named Multi-Criteria Case Analysis (MCCA) for factor analysis related studies (see Fig. 1). Three phases of MCCA in this study include: (1) a Systematic Literature Review (SLR) method to obtain key barriers; (2) a Multi-Criteria Decision Analysis (MCDA) method to obtain the relationships between key barriers; and (3) a single revelatory case study to interpret these barriers and relationships in an empirical setting. A two-round interview with 42 interviewees was conducted (5 structured + 37 semi-structured; see Table 1). Phase 3 investigates and interprets the results derived from the first and second phases; thus, the three phases work together in a sequenced manner. MCCA aims to synthesize a new perspective on the implementation of digital fabrication to construct knowledge about barriers to implementation, including key barriers and interrelationships among barriers, and finally provide strategies to promote digital fabrication implementation.

Phase 1 Systematic Literature Review: Reasons and Procedures

This research employs a SLR to obtain an initial set of barriers. SLR documents the most advanced knowledge, such as the state-of-the-art digital fabrication cases, and generates new knowledge (Tranfield et al. 2003), like the implementation barriers. For data collection, the research aims to understand the barriers under empirical settings rather than pure technical challenges. Thus, the sample was used to retrieve state-of-the-art studies on digital fabrication implementation cases. Web of Science (WoS) was used to sample articles. Sampling was limited to refereed journal articles only. The search query is: "digital fabrication" (Topic) AND "case study" (Topic) AND ("architecture" OR "construction" OR "building") (Topic). The keyword search and screening workflow are shown in Fig. 2. This search query could affect the analysis results by focusing on practical challenges and barriers.

This search returned 30 document results (November 11, 2022). Nine articles were excluded based on the inclusion and exclusion criteria. The data collection process followed theoretical saturation, which was validated by a round of snowball sampling with 74 new articles. Because there were no new patterns emerging, the research stopped collecting further data at this point.

For data analysis, this research used a thematic content analysis, which has the advantages of allowing granular findings and the possibility of customized analysis (Anderson 2007). NVivo "**digital fabrication**" (Topic) AND "**case study**" (Topic) AND ("**architecture**" OR "**construction**" OR "**building**") (Topic)

Fig. 2. Keyword search in the WoS database.

Table 2. Advanced manufacturing technology implementation barriers in the manufacturing industry

Categories	Subcategory
A. Economic barriers	High cost of capital Barrier to investment justification
B. Organizational constraints	Lack of advanced manufacturing technology project vision Difficulties in buyer-supplier relationship Set-up preparation difficulties
C. Personnel-related issues	Skills development issues Employee resistance
D. Technology barriers	Shop-floor disruption Technology system issues Data security constraints
E. Policy and regulation barriers	Lack of standardization Threat to intellectual property Lack of government support Lack of information

Source: Data from Stornelli et al. (2021).

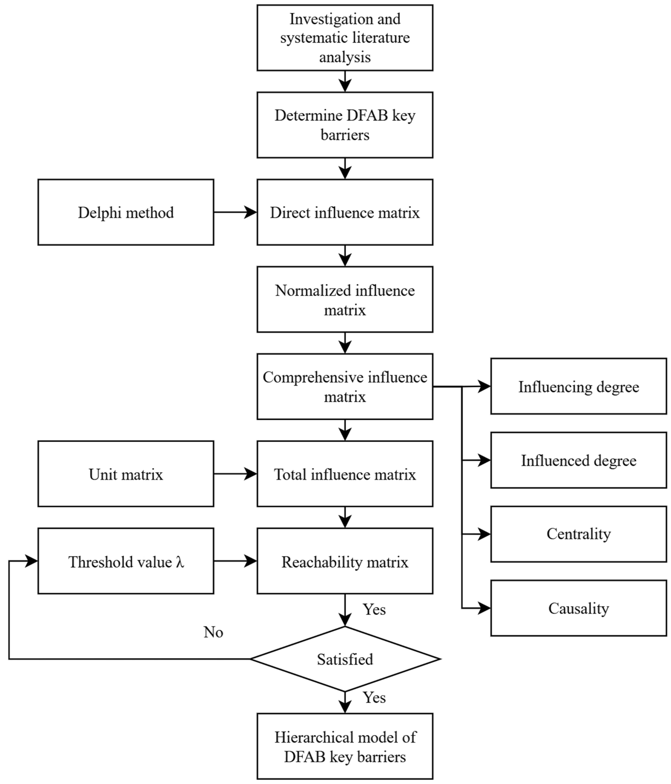

Fig. 3. Roadmap of DEMATEL-ISM (DFAB = digital fabrication).

Release 1.6.1 was 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 digital fabrication 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), and barriers (free code).

Secondly, the thematic analysis identified and synthesized themes about barriers that emerged during the inquiry by following the five categories of advanced manufacturing technology barriers identified by Stornelli et al. (2021), as shown in Table 2. Finally, 16 key barriers were identified.

Phase 2 Multi-Criteria Decision Analysis: Reasons and Procedures

MCDA is a set of techniques for explicitly evaluating multiple conflicting criteria in the decision process (Jato-Espino et al. 2014; Tan et al. 2021). Among MCDA techniques, both Decision Making Trial and Evaluation Laboratory (DEMATEL) and ISM methods have been frequently adopted to capture and explain complex relationships in various systems. Besides, DEMATEL-ISM, which has been widely used for barrier analysis as an established method (Tan et al. 2021), is a methodology used to model complex systems by analyzing the relationships and dependencies among various elements. This research used DEMATEL-ISM as the second step for exploring the digital fabrication barriers in the Swiss construction industry. Every participant interviewed had prior involvement with design for digital fabrication within Switzerland, bringing insights from the standpoint of design firms. The objective of Phase 2 was to comprehend the context of digital fabrication barriers in the Swiss construction industry, focusing on how and to what extent these barriers are interrelated. This understanding is intended to lay down a foundational context of the nation and industry for Phase 3, which explores the interaction of these barriers through the case study. In this stage, data was collected through five structured interviews, with a detailed explanation about all barriers during the interviews. The data input required for DEMATEL-ISM calculations consists of two types (0 and 1), representing whether there is an impact or not. To collect more reliable data, this research additionally used a 5-point Likert scale for the data collection, ranging from no impact to very large impact. A score of 0 indicates no impact, while 1, 2, 3, and 4 represent increasing degrees of impact. These four values are then simplified to "impact" (1) for calculation purposes. The Delphi method was employed to gather comprehensive opinions. This part of the data analysis is only to establish the relationships and framework of the five-dimension barrier categories, rather than to draw the final research conclusions. Therefore, it is sufficient to lay the foundation for further interviews and analysis in the next phase. The SPSSAU (https://spssau.com/en/index.html), a web-based platform with a graphical interface for using DEMATEL-ISM, was utilized to process the data collected from the structured interviews, such as the direct influence matrix. This platform was chosen for its ease of use, accessibility, and ability to handle commonly used decision-making models like DEMATEL-ISM. Fig. 3 shows the roadmap of this approach.

Phase 3 Revelatory Case Study: Reasons and Procedures

The case study method contributes to the in-depth exploration of the implementation of digital fabrication. The capability to bring new insights through exposure to previously inaccessible phenomena justifies the selection of a single case study (Yin 2017). Thus, a revelatory single case study is applicable to the exploration of digital fabrication implementation in its infancy. This research case sampling aims to achieve theoretical generalizability through a revelatory case. Therefore, the selection of digital fabrication case should shed empirical light on the state-of-the-art implementation of digital fabrication techniques in the Swiss construction industry.

DFAB HOUSE is a leading demonstrator of multiple digital fabrication techniques in a real building-scale setting (Graser et al. 2020). It transferred five innovative digital fabrication technologies from research to their first practical application, including the In-situ Fabricator (a/b), Mesh Mold (a/b), Smart Slab (d), Smart Dynamic Casting (c), Spatial Timber Assemblies (e), and a lightweight translucent façade (f) (see Fig. 4). It is a collaborative demonstrator of the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication. Therefore, Phase 3 identified DFAB HOUSE as the case to interpret the implementation barriers.

This study uses a qualitative data set of 37 semi-structured interviews with individuals involved in the project. These interviews sought details on the interviewees' previous experiences, their specific roles and tasks, their work methodologies, and their experiences with the project. Out of these, 36 interviews were audio-recorded, amounting to a total of 30.5 hours, and comprehensive notes were documented for each session. The group of interviewees

Fig. 4. Building parts of DFAB HOUSE. [Reprinted from Graser et al. (2021), under Creative Commons-BY-4.0 license (https://creativecommons.org/licenses/by/4.0/).]

comprised 17 technology researchers, 11 industry collaborators, and nine additional participants. This data set has also been used before to explore demonstrator of digital fabrication by using DFAB HOUSE as a case (Graser et al. 2021).

The study employs thematic content analysis (Anderson 2007). A deductive coding process was utilized to categorize textual information using thematic analysis. This process draws from the barriers outlined by Stornelli et al. (2021), who identified five primary categories of barriers to advanced manufacturing technologies. These categories serve as initial-level codes and include (1) economic barriers, (2) organizational constraints, (3) personnel-related issues, (4) technological barriers, and (5) policy and regulatory barriers. Subsequently, content analysis was applied with reference to the interrelationships of barriers identified in Phase 2 to articulate and examine the specific barrier interrelationships encountered in the DFAB HOUSE project.

Key Barriers to Digital Fabrication Implementation

This research identified 16 key barriers under five categories, as shown in Table 3, based on the systematic literature review. The most frequently occurring barrier codes are for economic and technology barriers.

For economic barriers, the unclear benefit of adopting the technology is a key barrier (Graser et al. 2021). There are several studies carried out to quantify the advantages of digital fabrication 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 digital fabrication 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 digital fabrication.

For organizational barriers, including a socio-technical perspective, there are relatively few studies about the research on digital fabrication 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 reporting on technological development rather than the building process and collaboration across the project team to implement new technologies.

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 digital fabrication. The constraints are manifold, such as hardware (Gomaa et al. 2021), software (Weng et al. 2021),

Table 3. Digital fabrication implementation barriers from the literature review

Categories	Main barriers	References
A. Economic barriers	A1. High cost of fabrication waste (e.g., material and energy)	Rausch et al. (2021), Agustí-Juan et al. (2017), Martínez-Rocamora et al. (2020), Dahy (2019), and Weng et al. (2021)
	A2. High capital cost (e.g., equipment)	Dahy (2019), Trilsbeck et al. (2019), and He et al. (2021)
	A3. High material cost	Martínez-Rocamora et al. (2020)
	A4. Limited investment	Charest et al. (2019), Martínez-Rocamora et al. (2020), Trilsbeck et al. (2019), Graser et al. (2021), and Gokmen (2022)
	A5. Unclear benefit	Agustí-Juan et al. (2017), Charest et al. (2019), and Graser et al. (2021)
B. Organizational constraints	B1. Weak coordination and collaboration	Ng et al. (2021), Tan et al. (2022), Graser et al. (2021), and Vazquez and Jabi (2015)
	B2. Mismatch with existing systems (e.g., tasks and processes)	Tan et al. (2022)
	B3. Organizational resistance to change and learn	Agustí-Juan et al. (2017) and Ng et al. (2021)
C. Personnel-related issues	C1. Hesitance attitude (e.g., skepticism, uncertainty, and unawareness)	Ng et al. (2021) and Graser et al. (2021)
	C2. Lack of competency (e.g., experience, education, and skills)	Trilsbeck et al. (2019), Yuan et al. (2022), Agustí-Juan et al. (2017), and Graser et al. (2021)
D. Technology barriers	D1. Hardware constraints (e.g., compatibility, reliability, and maintenance)	Trilsbeck et al. (2019), Kuzmenko et al. (2021), Vazquez and Jabi (2015), and Asprone et al. (2018)
	D2. Software constraints (e.g., compatibility, reliability, and user-friendliness)	Nathansohn et al. (2020), Weng et al. (2021), and He et al. (2021)
	D3. Material constraints (e.g., availability and suitability)	Martínez-Rocamora et al. (2020), Dahy (2019), Trilsbeck et al. (2019), Kuzmenko et al. (2021), Gomaa et al. (2021), and Asprone et al. (2018)
	D4. Process constraints (e.g., compatibility, efficiency, and scalability)	Rausch et al. (2021), Martínez-Rocamora et al. (2020), Weng et al. (2021), Yuan et al. (2022), Graser et al. (2021), Kuzmenko et al. (2021), Gomaa et al. (2021), Trilsbeck et al. (2019), Agkathidis (2019), Gokmen (2022), and Charest et al. (2019)
E. Policy and regulation barriers	E1. Lack of laws and regulations	Graser et al. (2021) and Kuzmenko et al. (2021)
	E2. Lack of standards and codes	Graser et al. (2021), Gokmen (2022), Martínez-Rocamora et al. (2020), and 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 digital fabrication technologies.

From the perspective of personnel-related issues, practitioners remain skeptical about the benefits of digital fabrication (Graser et al. 2021). Digital fabrication 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). Digital fabrication 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.

Interrelationships between Key Barriers

Decision Making Trial and Evaluation Laboratory Analysis

In this step, the DEMATEL method was used to investigate the cause-and-effect relationship among the identified 16 barriers that are relevant to the implementation of digital fabrication in the Swiss construction industry. This method involves specialists evaluating the barriers using a scale from 0 to 4, reflecting the extent of influence one barrier impacts on others. The scale provides enough gradation to distinguish varying levels of influence between barriers, with 0 indicating no influence and 4 indicating the strongest possible influence, according to the 5-point Likert scale. Based on the expert evaluations, a pair-wise comparison relationship is formulated, as shown in Fig. 5. Among all economic barriers, A1 has, in general, relatively weak relationships with most other barriers; A4 and A5 have relatively medium relationships with other barriers. Among all organizational constraints, B2 has the most relationships with other barriers; this is followed by B3. Among personnel-related issues, C1 has stronger relationships with many other barriers than C2. Among the technology barriers, D4 has relatively strong relationships while the other three have comparatively weak relationships. The two barriers under the category of policy and regulation barriers have weak relationships among others.

In DEMATEL analysis, the centrality-causality diagram (as shown in Fig. 6) serves as a graphical instrument for the visualization and explication of the causal relationships among various barriers within a system. By integrating the detailed explanations of the factors into the diagram, decision-makers are facilitated in identifying: (1) which barriers exert the most substantial impact on the system (high centrality); and (2) which barriers are principal

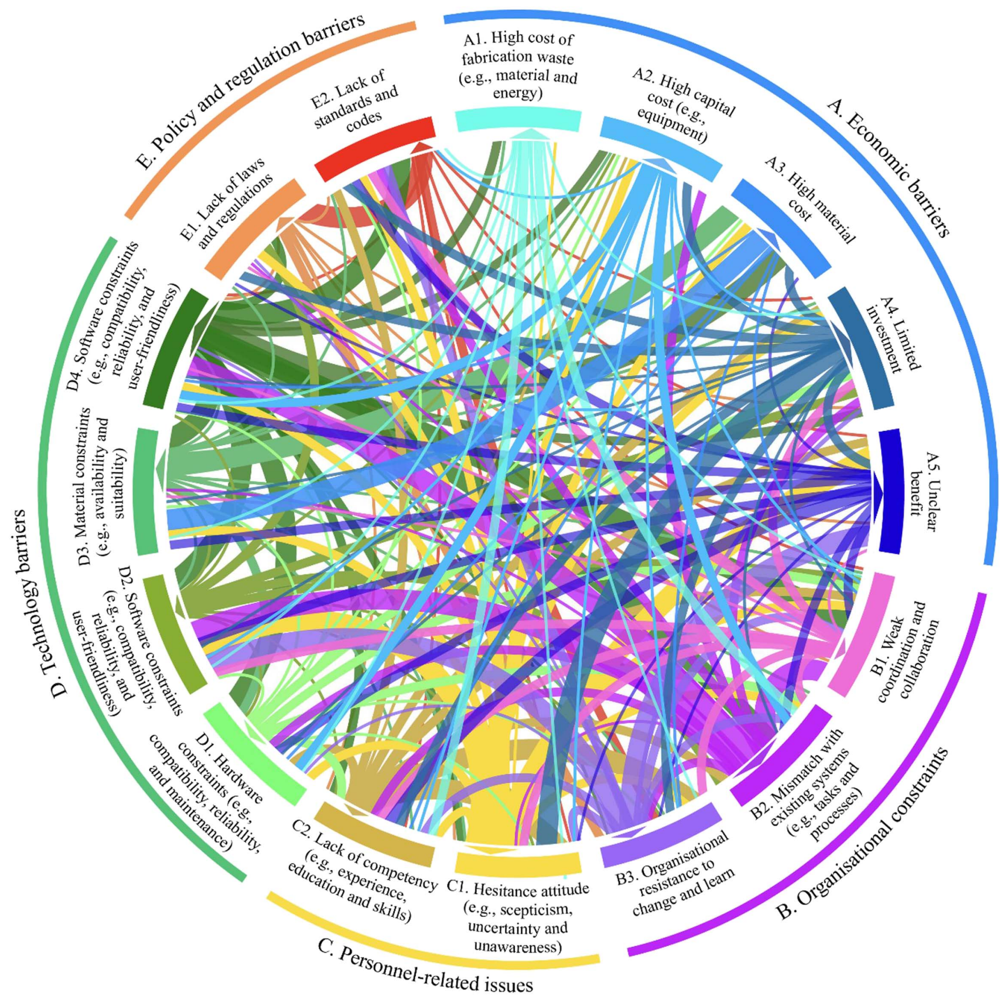

Fig. 5. Relation matrix between the identified 16 barriers.

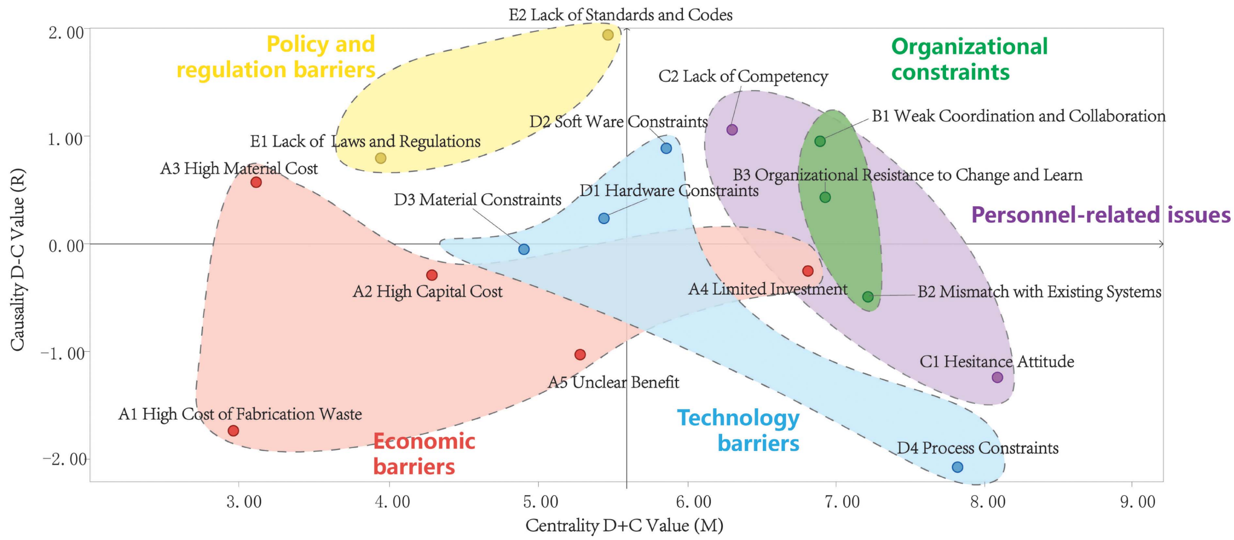

Fig. 6. Centrality-causality diagram.

causes and which are primary effects (positive or negative causality). This diagram is constructed on the foundation of two principal metrics: Centrality and Causality.

The centrality of a factor denotes its overarching significance within the entirety of the system. A factor with elevated centrality possesses substantial influence within the system. In the diagram, the horizontal axis (X-axis) represents this value, positioning factors based on their overall importance and influence in the system. By contrast, the causality of a factor indicates whether it predominantly acts as a cause or as an effect within the system. Should the causality of a factor be a positive value, it is primarily a cause; conversely, if it is a negative value, then it is chiefly an effect. The vertical axis (Y-axis) in the diagram describes this dimension, placing factors above or below the zero-line based on whether they are causes or effects.

With these indicators, barriers are plotted within the diagram, with their specific positions indicating their centrality and causality. For instance, a barrier such as "B1 Weak coordination and collaboration" or "B3 Organizational resistance to change and learn" that appears in the upper rightmost part of the diagram signifies a high centrality and a positive causality, denoting it as a significant cause within the system with substantial influence. Conversely, a barrier such as "A1 High cost of fabrication waste" located in the lower left quadrant would have low centrality and negative causality, implying it is less influential and predominantly an effect.

The DEMATEL analysis also generated the influence-dependency diagram (see Fig. 7) predicated on the following two principal metrics: Influence (R): The degree of influence denotes the aggregate impact a factor has on other factors. This is typically ascertained by calculating the sum of the rows (R) for the factor, which represents the cumulative impact that this factor has on all other factors; and Dependency (C): The degree of dependency reflects the overall extent to which a factor is influenced by other factors. This is determined by computing the sum of the columns (C) for the factor, signifying the total influence all other factors have on this factor.

- Quadrant I includes A4, B1, B2, B3, C1, and D4, which are characterized by high influence and high dependency. They are critical components of the system, but their state may be unstable because any changes can induce alterations throughout the system.
- Quadrant II includes A5, which has a relatively high influence but low dependency. These are primarily driver factors or causes that influence other factors.

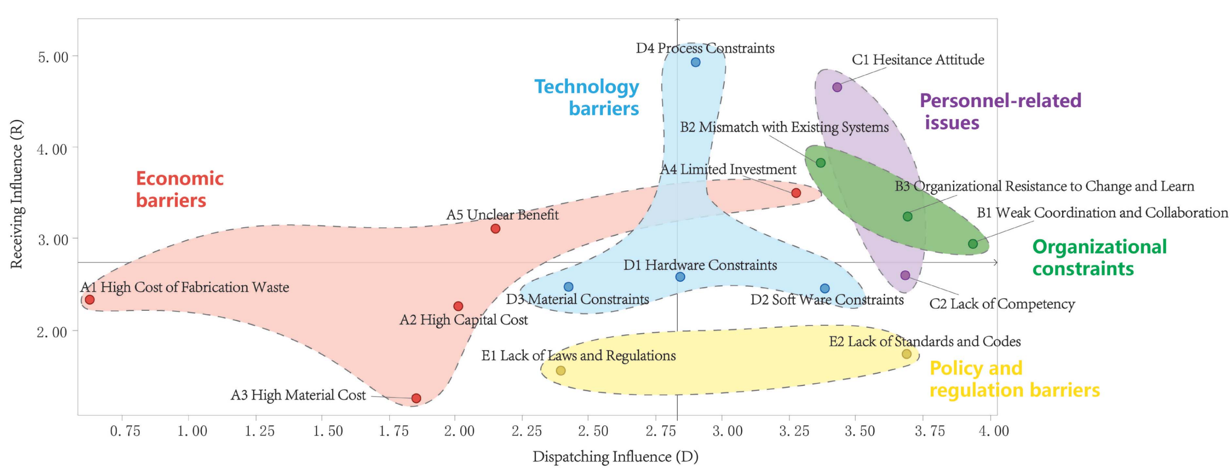

Fig. 7. Influence-dependency diagram.

- Quadrant III includes A1, A2, A3, D3, and E1, with low influence and low dependency. Their role in the system is comparatively minor.
- Quadrant IV includes C2, D1, D2, and E2, which are low in influence but high in dependency. These are predominantly influenced by other factors and represent outcomes or effects.

Interpretive Structural Modelling (ISM) Analysis

In the context of implementing digital fabrication in the Swiss construction industry, the ISM analysis in Fig. 8 categorizes barriers into several levels, with direct, intermediate, and underlying factors:

- Level 6 and Level 5 (Direct Factors): These are the most immediate barriers faced when implementing digital fabrication. At Level 6, A1 represents the "High cost of fabrication waste" such as materials and energy, while C1 represents "Hesitance attitude" characterized by skepticism, uncertainty, and unawareness. Level 5, "A4 Limited investment," would typically contain factors that have a direct impact on the adoption of digital fabrication but are not as immediate or as tangible as those at Level 6.
- Level 4 and Level 3 (Intermediate Factors): These factors serve as a bridge between the foundational issues and the direct barriers. At Level 4, A5 represents "Unclear benefit," which directly affects the perception and decision-making process of stakeholders. Level 3 includes a mix of specific constraints such as A3 "High material cost"; B2 "Mismatch with existing systems"; and various hardware, software, material, and process constraints (D1, D2, D3, and D4). These factors indicate challenges that are more tactical and need to be addressed to facilitate the practical aspects of digital fabrication implementation.
- Level 2 and Level 1 (Underlying Factors): These represent the foundational challenges that must be addressed to support digital fabrication implementation. Level 2 includes A2 "High capital cost" related to equipment investment and E1 "Lack of laws and regulations," which can create systemic barriers to innovation. Level 1 highlights B1 "Weak coordination and collaboration"; B3 "Organizational resistance to change and learn"; C2 "Lack of competency" in terms of experience, education, and skills; and E2 "Lack of standards and codes," which are deep-rooted factors that influence the organizational and regulatory readiness for digital fabrication.

Implementation of Digital Fabrication in DFAB HOUSE

Economic Barriers in DFAB HOUSE

DFAB HOUSE, as a single revelatory case, is then used to interpret these barriers. Economic barriers in the context of DFAB HOUSE include four subcategories: (1) investment risks; (2) partnership costs; (3) dissemination challenges; and (4) research-commercialization dilemma. Investment risks include "indefinite exploration" without implemented results and the lack of measurable return on research and development (R&D), which hinders further investment, emphasized by the uncertainty associated with digital fabrication technologies, as one interviewee reflected:

> It's not easy to find money for this kind of work … But the return on the investment is 5 or 10 years from now. Or not even sure if there is any [return on investment].

In addition, there are also concerns about the resources required to establish and maintain industry partnerships and the risks to projects due to the loss of industry partners. For example, one interviewee mentioned:

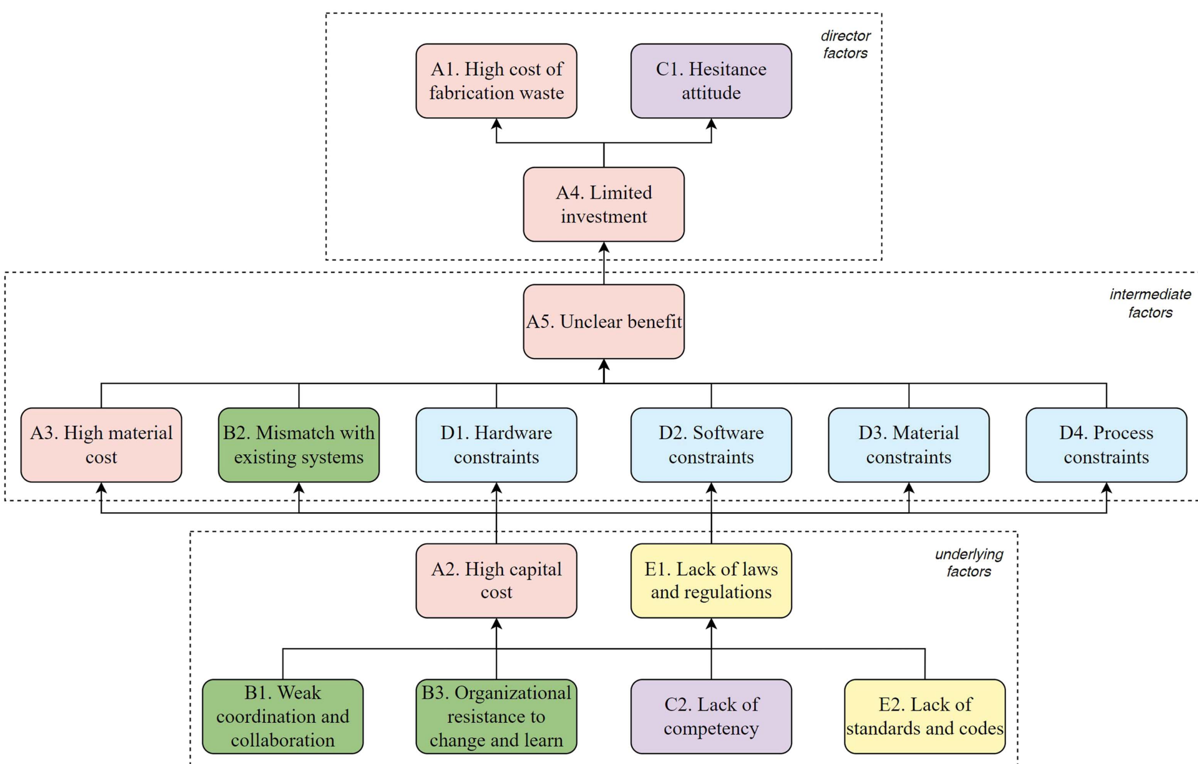

Fig. 8. Interpretive Structural Modelling (ISM) for digital fabrication barriers.

> The industry would like immediate things that could actually be sold tomorrow. And often we then have ideas and innovation objects that have a lot of potential and then take longer to enter the market

This quotation also shows there are barriers to securing the resources required for dissemination. Besides, a research-commercialization dilemma exists, which reflects the challenge of balancing innovative ideas' excitement with their practical risks. For example, one interviewee mentioned:

> If someone comes to me and says, hey, this would be a great topic with potential ... Then I say what are the risks ... I realized someone brings something to me that is associated with risks

These economic barriers were not isolated; they impacted organizational constraints, manifesting as a reluctance to fully commit to the necessary partnerships and collaborative frameworks needed to drive the project forward. The promise of digital fabrication technologies was, thus, counterbalanced by the risk-averse nature of the investment landscape.

Organizational Constraints in DFAB HOUSE

The main organizational challenges in the DFAB HOUSE project can be grouped into two key areas. First, the project faced difficulties in combining the flexible, evolving parametric research approach with the more rigid, traditional organizational workflows. This mismatch caused time-consuming efforts to align both approaches. Second, teamwork across different disciplines was another significant challenge. Coordinating the various dependencies and independent tasks between teams working on digital fabrication proved difficult, especially because the project involved many participants with different goals, making it hard to find solutions that worked for everyone. Many interviewees expressed their concerns about communication and integration issues:

> I believe [the challenge is] communication. Because for us, construction site practitioners working with researchers, the language and processes are two different worlds coming together.

> In the beginning, it was very difficult because we didn't have the terminology; we couldn't really communicate well.

Communication within the organization between various teams became a critical issue. The integration of digital fabrication processes called for a reconfiguration of roles and a departure from traditional construction methods, which in turn necessitated a shift in organizational culture and practices.

Personnel-Related Issues in DFAB HOUSE

The DFAB HOUSE project encountered challenges at the personnel level due to (1) the participants' lack of experience and (2) resistance to change. On the complexity and challenges for academic teams, one interviewee mentioned:

> An academic agenda of a PhD researcher means focusing on your work concentrating. While this project involved basically the opposite skills.

In addition, due to the lack of experience, participants needed time to find their place in the R&D process. For example, one interviewee mentioned:

> In the beginning, it was a little bit of a mix between who thinks the role is to design, who thinks the role is to calculate or whose role is to do the fabrication ... But it was like a dynamic process and that people step by step found their specific roles in the collaborative effort.

Secondly, the resistance to change hinders digital fabrication implementation. One interviewee talked about the need for an open mindset:

> It often starts, I think, with somebody having the feeling that they need to change ... It's a feeling of unease that's maybe a negative feeling really but that is compelling people to reach out and try new things.

Participants' different attitudes towards tasks, collaboration, and new technologies may reflect different interests of individuals, which also hinders digital fabrication implementation. One interviewee mentioned:

> There obviously has been frictions between people and groups ... But ... I think [it is because of] personal interests.

The personnel-related and technological barriers were deeply interconnected because the DFAB HOUSE project's success relied on the team's ability to manage and adapt to the novel demands of digital fabrication. Technological challenges such as scaling up prototypes to full-scale building projects required not just innovative solutions but also a workforce adept at navigating the new landscape of digital fabrication.

Technology Barriers in DFAB HOUSE

Technologically, the project faces the challenges of (1) scaling up from laboratory experiments to viable full-scale construction and (2) the absence of a solidified demonstrator implementation methodology for large-scale digital fabrication. One interviewee described the challenge of implementing the digital fabrication techniques:

> The big difference was indeed that it had to really work in an architectural context ... It became a kind of compromise between design wishes and possibilities in fabrication.

This interviewee also discussed the significant challenges faced in scaling up the technology from a conceptual or laboratory scale to a practical, full-scale architectural application:

> What I really learned was how complicated it was to make a very simple flexible form. That the system has many more constraints than I had ever imagined.

Many interviewees highlighted the challenges posed by the absence of an established demonstrator methodology for implementing large-scale digital fabrication projects. The demonstrator like DFAB HOUSE can show the real problems in terms of scaling these digital fabrication technologies. One interviewee mentioned:

> Having these demonstrator projects as DFAB HOUSE, I think is a huge enabler for really finding out where the problems are.

Policy and Regulation Barriers in DFAB HOUSE

Policy and regulation barriers highlight the conflicts between innovative digital fabrication applications and existing building standards, codes, and regulations. For example, one interviewee mentioned:

> The final structure had to be compliant with the building code and it had to be safe obviously ... We had to actually make very specific contracts regarding risk and liability.

Interviewees also highlighted the challenges of implementing cutting-edge digital fabrication technologies in an industry that is not yet fully prepared or educated, placing an extra burden on the project team for education and knowledge transfer.

> We had other difficulties ... the industry is not educated yet for these things, you will be the one responsible to show them how to open the 3D file, how to make a section.

Also, interviewees showed the dual nature of the project's challenges: balancing regulatory flexibility in certain design areas while also managing the risks and consequences of decision-making under time pressure.

> We did have many constraints in terms of building code ... Sometimes you make wrong choices because you're under time pressure.

The interviewee specifically noted how the relative flexibility in building codes of façade elements allowed for some creative freedom. However, this flexibility also introduced challenges because decisions had to be made quickly, leading to less-than-ideal outcomes. In DFAB HOUSE, building codes and safety approvals were not fully ready for the digital fabrication technologies being used most effectively. Many aspects of the project were heavily influenced by regulatory constraints, whether due to existing codes or the absence of specific regulations.

Discussion

Theoretical and Methodological Implications

This study engages in a dialogue with and seeks to supplement two categories of existing knowledge. The first category pertains to the barriers in the implementation of advanced manufacturing technology within the manufacturing sector, while the second relates to the barriers encountered in the digital transformation of the construction industry, primarily centered around BIM.

Construction is inherently project-based and location-bound, contrasting with manufacturing's emphasis on standardized mass production in a factory setting for widespread distribution (Tan et al. 2020). The implementation of digital fabrication in construction encounters unique barriers that are not as prevalent in manufacturing due to specific industry challenges. Economic barriers are more pronounced due to the larger scale of construction projects, capital costs, and the costs associated with on-site implementation. Organizational constraints in construction are heightened by the diversity of stakeholders and the extended duration of projects, as opposed to the more controlled environments found in manufacturing. Personnel-related issues in construction revolve around the need for on-site skill adaptation and safety training, which differ from manufacturing's focus on machine operation and IT competencies. Policy and regulation barriers in construction are more complex, with building codes and compliance playing a significant role. Technological barriers in construction involve the challenge of integrating digital fabrication into existing building processes, which are more site-specific and variable compared to the standardized processes in manufacturing facilities. Therefore, while both industries confront barriers related to economics, organization, personnel, technology, policy, and regulation, the context and expression of these barriers differ substantially due to the intrinsic characteristics of each sector.

The second significant theoretical contribution of this study is the advancement of research and understanding of the barriers to digital transformation in the construction industry. Although the implementation of digital fabrication can rely on BIM collaboration (Ng et al. 2021), the barriers encountered are markedly different from those identified in previous studies. For instance, Tan et al. (2019) initiated a broad discussion about the barriers to implementing BIM in prefabricated construction. While digital fabrication also encompasses BIM and prefabrication, the barriers it presents and their interrelations do not entirely align with the conclusions drawn in their paper. This is because digital fabrication represents not only a *virtual* and *soft* transformation in processes and organizational forms but also a *physical* shift in production methods, relying on advanced manufacturing equipment such as 3D printers and robotics, which are not typically encompassed by traditional BIM implementation. Most BIM research has focused more on the implementation of software and the transformation of organizational models (Ahn et al. 2016; Vass and Gustavsson 2017; Miettinen and Paavola 2014; Wang et al. 2025b), without exploring the adoption of hardware equipment. The implementation of digital fabrication, however, represents a digital transformation process that layers both software and hardware (Graser et al. 2021). This hardware-based digital transformation process introduces a set of challenges to the construction industry that are distinct from those associated with traditional BIM. For example, while Tan et al. (2019) noted that economic factors were not as significant a barrier in prefabricated construction with BIM, this study reveals that economic barriers have a substantial impact on the implementation of digital fabrication due to the considerable initial investments required not only in equipment but also in technological development. Consequently, the barriers to implementing digital fabrication are more complex compared to those faced during BIM implementation.

Regarding the methodology, this research presents a methodological combination of DEMATEL-ISM with a single revelatory case study (i.e., MCCA), which represents an approach in review studies and factor analysis research. This integration bridges the gap between broad systematic insights and detailed context-specific understanding and pioneers a methodology that offers both breadth and depth, potentially setting a precedent for future studies. The integration of DEMATEL-ISM, rooted in positivism (Brugha 2003) and revelatory case studies aligned with interpretivism (Yin 2017), presents a philosophical divergence between objective quantification and qualitative understanding. However, when successfully integrated, this combination has the potential to offer a comprehensive insight—capturing both the systemic interrelationships and the intricate, context-specific nuances of a phenomenon.

Practical Implications and Proposed Strategies

Practical Implications

Economic factors play a decisive and dominant role in the implementation of digital fabrication, yet their specific manifestations vary greatly between the two sets of analyses. The form they take can differ depending on the maturity level of digital fabrication technologies. For instance, in the case of the DFAB HOUSE, many digital fabrication technologies were developed concurrently with the project's progress, rather than utilizing pre-existing and established mature technologies. Therefore, in this particular case, many economic factors are related to R&D. For those digital fabrication projects that employ mature technologies, economic barriers may more commonly stem from the initial costs of equipment purchase and investment. Additionally, there are minor differences in technological barriers, although they are generally consistent. While limitations related to hardware, software, materials, and processes also occurred in the DFAB HOUSE project, this project, being a demonstrative R&D initiative, aimed to break through many existing technological constraints to develop new technological paradigms. Hence, some technological limitations are not accidental but anticipated and addressed during the process. In the DFAB HOUSE project, the primary technological barriers stemmed from scaling laboratory R&D and prototypes to real-world projects.

The other three barrier factors—organizational, personal, and policy—show a high degree of consistency between the two analyses. There is evidence that these aspects represent more foundational barriers. In contrast, technological and economic factors often act as intermediary and direct factors, thus varying with the specific context of the scenario. This aligns with the conclusions drawn from both the DEMATEL-ISM method and the DFAB HOUSE case study.

Strategies to Promote Digital Fabrication in Practice

These findings offer insights about how to implement digital fabrication that are applicable in Switzerland but may also be generalized to other countries. This study recommends four-level, multitiered strategies to promote the implementation of digital fabrication on the individual, project, organizational, and industry levels (see Fig. 9). On the individual level, it involves investing in education and training programs that impart the necessary technical and implementation skills (Song 2020). For example, specialized workshops on digital fabrication tools, such as 3D printers, could be offered to provide hands-on experience. Additionally, the work design should allow for flexibility, giving individuals the autonomy to explore how best to apply digital fabrication technologies to their specific tasks (Kahlert and Grote 2022). On the project level, it is important to integrate the consideration of using digital fabrication into the early planning and design phases. This could involve the use of integrated project delivery methods, as well as the development of prototype demonstrator implementation methodologies and project management strategies that are specifically for digital fabrication (Graser et al. 2021). For instance, initiating pilot prototypes to test the viability of digital fabrication technologies in early phases could help identify and resolve potential issues before full-scale implementation. On the organizational level, organizations need to develop strategic partnerships with technology providers, research institutions, and other stakeholders to facilitate business model innovation, cultivate collective expertise, and drive technological advancements (Walzer et al. 2023). For example, shared access to fabrication facilities could be used to reduce capital costs. On the industry level, policymakers should research suitable standards, codes, and regulations that support the safe and effective implementation of digital fabrication (Ng et al. 2023).

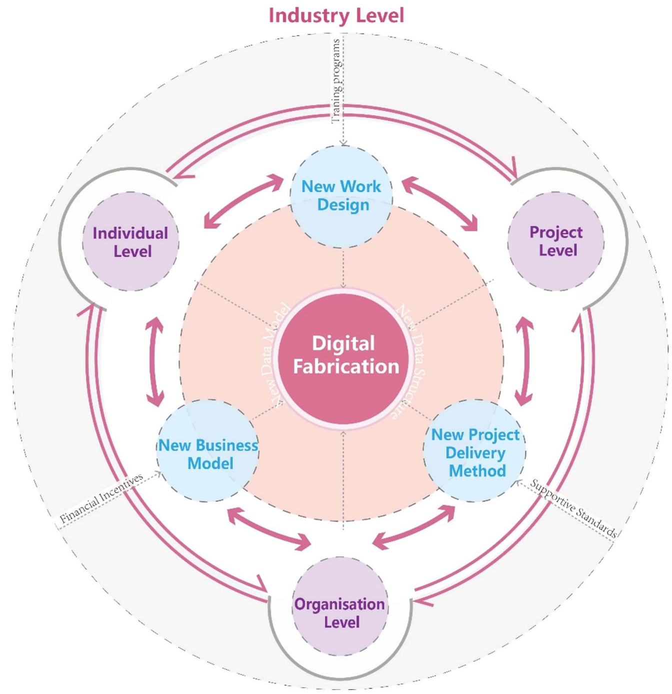

Fig. 9. Strategies to promote digital fabrication.

Concluding Remarks

This study presents the multifaceted barriers to the implementation of digital fabrication in the Swiss construction industry. Five main categories of digital fabrication implementation barriers have been identified. The research highlights the key role of economic factors as both a driving force and a barrier in the adoption of digital fabrication embodying a high-risk, high-return paradigm, with their impact varying significantly depending on the maturity of the technology and the nature of the project. The DFAB HOUSE case study highlights how economic considerations impact R&D in projects that are at the cutting edge of technological innovation. The study also reveals that while technological, organizational, personal, and policy barriers present consistent challenges across the industry, their specific manifestations and the strategies to overcome them must be contextually adapted.

Furthermore, the research has contributed to theoretical discourse by distinguishing the barriers associated with digital fabrication from those of traditional BIM implementation, emphasizing the unique challenges posed by the physical aspects of digital transformation in fabrication. It also offers a comprehensive view that captures both systemic interrelationships and detailed, context-specific insights.

To effectively advance the practice of digital fabrication, this research recommends a four-level multitiered approach, ranging from individual, project, and organization, to industry. On the individual level, fostering an innovative environment through education and flexible work design is key to empowering professionals with the skills for digital fabrication. Project success should focus on the early integration of digital fabrication into planning and design, using collaborative methods and management strategies to streamline implementation. Organizations play a critical role by cultivating a culture of change and innovation, allocating resources to pilot projects, and forming strategic alliances to enhance technological capabilities. On the industry level, supportive policies and standards, coupled with incentives and public research investments, are vital for creating an ecosystem for digital fabrication adoption.

In practice, the insights from this study can inform the development of strategies to deal with the complexity of digital fabrication implementation. By recognizing the varied nature of barriers and the importance of context, industry stakeholders can better prepare for and invest in the future of construction, driving innovation while managing the risks and challenges. Future research can continue to explore these barriers in diverse contexts, expand stakeholder perspectives, and develop methodologies that can be standardized across the industry to foster the development and adoption of digital fabrication in construction. In addition, the proposed MCCA

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research method could be widely adopted in future review studies and factor analysis research.

The research has some limitations that indicate future research directions. For example, this search query focuses on case studies that may influence the analysis outcomes by emphasizing real-world barriers through demonstrator implementation, while potentially excluding broader theoretical or technical insights not captured through case studies. Besides, the research primarily focused on the perspectives of design professionals, and did not include insights from construction professionals. This could mean that certain barriers from the on-site perspective, such as challenges in field conflicts or constructability issues, might not have been fully captured and discussed in the scope of this study. One limitation of the DEMATEL-ISM method is that it relies on expert judgment. Additionally, the use of a single revelatory case study in Phase 3 may limit the transferability of the findings to other contexts or industries. Future research could expand by incorporating the perspectives of construction professionals to provide a different view of the barriers in digital fabrication. Additionally, exploring multiple case studies across different industries could help enhance the transferability and applicability of the findings.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

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Author Contributions

Tan Tan: Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft. Konrad Graser: Data curation; Investigation; Methodology; Resources; Validation; Writing – review and editing. Alexander N. Walzer: Data curation; Investigation; Resources; Validation; Writing – review and editing. Ming Shan Ng: Validation; Visualization; Writing – review and editing. Daniel Hall: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing – review and editing.

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