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DFAB HOUSE: implications of a building-scale demonstrator for adoption of digital fabrication in AEC

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ABSTRACT
The Architecture, Engineering and Construction (AEC) industry finds itself in an accelerating shift towards the use of more digital fabrication (DFAB) technologies. DFAB promises great advantages in AEC, but its adoption is so far lagging and there are few examples of building projects employing DFAB at scale. To facilitate DFAB adoption, we need to identify its challenges and opportunities of in the project context and understand its implications beyond project boundaries. To do this, this paper conducts a single case study on DFAB HOUSE, the first project to introduce several fundamentally new DFAB technologies to construct a fully functional building. Using Qualitative Content Analysis, we provide an overview of the challenges to consider and the strategies available to successfully adopt DFAB technologies in construction projects, establishing a socio-technical framework for DFAB adoption in AEC projects. We find that full-scale projects are an effective exploration method of DFAB in AEC, implementation at scale increases acceptance of DFAB in AEC, and projects are instrumental in establishing an emergent praxis of DFAB.

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Automation; fabrication; construction technology; technology transfer; technology management

Introduction

The Architecture, Engineering and Construction (AEC) industry finds itself in an accelerating shift towards the use of digital fabrication (DFAB) technologies. The adoption of DFAB promises great advantages such as improved resource efficiency and productivity, reduction of construction waste, and better worker safety (Bock 2015, WEF 2016, Agustí-Juan *et al.* 2018). Although the need for rapid innovation in AEC is widely recognised (Ribeirinho *et al.* 2020), there is still much resistance to adopting systemic innovations such as DFAB. As a result, the AEC industry "struggles with significant gaps between the available technology and the technology used in practice" (Singh and Holmstrom 2015).

DFAB in AEC is a domain in which technology uptake in practice proves particularly challenging. DFAB is a process where manufacturing devices are directly controlled by digital design data (Gershenfeld 2012), such as robotics or 3D printing. DFAB adoption depends on the integration of digital technologies with physical components (Meuer *et al.* 2019). For about two decades, building with digitally controlled tools has been explored in research, but few projects have reached full construction scale. To accelerate adoption, it is important to shorten time to market of new technologies (Richner *et al.* 2017), but this has been difficult for DFAB. This large gap between research feasibility and industry adoption suggests that limited DFAB adoption stems not from technology itself but from barriers to its integration into existing practice, business structures and processes (Chen *et al.* 2018), product architecture (Hall *et al.* 2020), and organizational structures (Pan and Pan 2019).

This paper seeks to understand how practitioners in AEC can overcome these challenges and capitalise on the opportunities of DFAB. Although DFAB projects remain rare, detailed research is needed on the reality of practice when DFAB technologies are implemented at scale. Here, we conduct a single-case study of the DFAB HOUSE, a seminal demonstrator project that uses a combination of six new DFAB technologies to construct a fully operational, code-compliant building,

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offering one of the first chances to study the integration of DFAB in the planning and delivery at 1:1 scale.

To learn from DFAB HOUSE, we examine how technology implementation on the project succeeded by addressing challenges related to technology, organisation, socio-cultural factors, knowledge, and perception. We summarize our findings in a socio-technical framework of DFAB adoption in AEC projects and discuss their implications for AEC practice.

Research background

Definition and fundamentals of DFAB in AEC

DFAB is defined as a fabrication or building process relying on a seamless conversion of design and engineering data into digital code to control manufacturing devices (Gershenfeld 2012). DFAB processes rely on "translation of computer generated data to physical artefact" (Dunn 2012). Through the direct transfer of digital design data to 1:1 assembly operations, DFAB combines design and construction into an integrated process (Willmann *et al.* 2016), leading to a continuous digital data chain from design to manufacturing (Bonnard *et al.* 2010, Helm *et al.* 2012). To achieve this, designers require information and knowledge about production parameters (Ng *et al.* 2020, Scheurer and Stehling 2020). This is similar to the characteristics of process and product innovation in industrial manufacturing (Nam and Tatum 1990; Scheurer and Stehling 2020).

Emerging implications of DFAB on the AEC industry

DFAB adoption is expected to widely impact AEC (WEF 2016, Ribeirinho *et al.* 2020) and increasingly replace conventional construction methods (Bock 2015). It is an essential component in the digitalisation of AEC, often referred to as *Construction 4.0* (Meuer *et al.* 2019, Forcael *et al.* 2020, Muñoz-La Rivera *et al.* 2020). The term derives from the *Industry 4.0* concept which describes "the digitization and integration of the entire value chain of the lifecycle of products" (Ghobakhloo 2020).

The potential impact of DFAB is extensive. Scholars suggest DFAB can help improve material efficiency and waste avoidance (Agustí-Juan *et al.* 2017, 2019, Mata-Falcón *et al.* 2019), reuse of materials (Kuzmenko *et al.* 2021), workplace health and safety (Keating *et al.* 2017, Garcia de Soto and Skibniewski 2020), integrative work design (Bharadwaj *et al.* 2020), and productivity (García de Soto *et al.* 2018; Fardhosseini *et al.* 2020; Hu *et al.* 2021). The implementation of DFAB will have important implications for AEC, including changes to: workforce and organisational structures, (García de Soto *et al.* 2019); integration of digital manufacturing with BIM and computational design, (Hamid *et al.* 2018); automation of construction tasks (Bock 2015, Fardhosseini *et al.* 2020, Chen *et al.* 2018); collaborative design and human-machine interaction (Vazquez and Jabi 2019); and architectural practice and education (Gramazio *et al.* 2014, Yuan *et al.* 2018).

State of the art in DFAB construction

Some DFAB processes have been used in practice (Caneparo 2014), and implementations at scale fall into three sub-domains (Kaseman and Graser 2020):

- robotic processes;
- additive manufacturing;
- specialised digitally controlled material processing technologies.

Built examples of robotically manufactured structures include pavilions by ICD (Institute for Computational Design and Construction) at the University of Stuttgart (Menges and Knippers 2020b, 2020a). Additive construction demonstrators include on-site concrete printing, for example, housing prototypes by ICON 3D and Apis Cor (Valente *et al.* 2019); 3D printed concrete prefabrication (Xu *et al.* 2020); and metal printing, for example, a footbridge by MX3D (Gardner *et al.* 2020). Specialized technologies include robotic concrete slip-forming (Lloret-Fritschi *et al.* 2019) and digitally knit tensile formwork (Popescu *et al.* 2020).

Yet, full-scale, permanent buildings that prominently feature DFAB are still rare, and examples of implementations such as Sequential Roof at ETH Zurich (Apolinarska *et al.* 2019) and the Théâtre Vidy in Lausanne (Robeller *et al.* 2017) show that technical challenges still exist (Melenbrink *et al.* 2020, Menges and Knippers 2020b).

Challenges to DFAB adoption

In addition to technical challenges, there are organisational and process barriers to DFAB adoption. DFAB for construction represents a systemic innovation, crossing the boundaries of multiple research disciplines and professions (Knippers *et al.* 2021), including architects, materials scientists, roboticists, structural engineers, manufacturers and trade contractors (Wangler et al., 2016; Willmann *et al.* 2016). Systemic innovations require collaboration across organisational boundaries for their successful implementation, and only add their full value from within a cross-organisational innovation system that allows coordination with complementary innovations (Chesbrough & Teece, 2002; Taylor & Levitt, 2004). Complementary innovations to DFAB include computational design tools (Knippers *et al*. 2021), product configurators (Cao *et al*. 2021), and Digital Twin information systems (Grieves 2015, Sacks *et al*. 2020). We adhere to this definition of systemic innovation in the context of our research, acknowledging the existence of other definitions in different contexts (Midgley and Lindhult 2017).

Systemic innovations face great adoption challenges in AEC which suffers from fragmentation caused by competitive bidding, weak coordination between contractors, and high participant turnover between project phases (Dubois and Gadde 2002; Katila *et al*. 2018). Therefore, the organisational and social context can be as important for industry adoption of DFAB as technological feasibility (Nascimento *et al*. 2016, Pan and Pan 2019).

Research gap and research questions

To summarise, (i) DFAB has important implications for AEC, (ii) many DFAB technologies are under development, and (iii) the interdisciplinary and systemic characteristics of DFAB present barriers to its adoption in AEC.

Although much literature identifies the challenges to DFAB and other systemic innovations, little attention has been paid to the strategies developed on projects to successfully adopt DFAB. Until recently, DFAB had not yet been implemented at scale, and there were few opportunities to conduct empirical research on the topic. Thus, we focus on the following research questions:

When introducing DFAB technologies in a full-scale construction project,

I. How do we recognise and address challenges to, and seise opportunities of DFAB adoption in the project context?
II. What are the implications for DFAB adoption in AEC practice beyond project boundaries?

Case study

The case study project, DFAB HOUSE, presents an important first-time opportunity to study DFAB adoption in the context of a full-scale construction project. DFAB HOUSE is a demonstrator building by the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication, one of the world-leading research centres in DFAB for AEC. DFAB HOUSE is groundbreaking in two ways: first, it is unique for employing six fundamentally new DFAB technologies to construct all substantial parts of a multistory building; second, it is the world's first full-scale, permitted and occupied residential building constructed by means of multiple DFAB technologies. These technologies are the result of interdisciplinary research and development by the NCCR DFAB and its industry partners. The project includes research across disciplines of architecture, structural engineering, materials science, computer science, robotics and digital manufacturing. More than 40 industry partners contributed to the project, including specialist engineering firms, material and technology suppliers, and contractors (NCCR Digital Fabrication 2021).

The project site is NEST, a modular building platform operated by Empa, the Swiss Federal Laboratories for Materials Science and Technology. The NEST superstructure provides empty floor slabs as sites for independent construction projects (*Units*) aimed at accelerating market entry of new technologies, materials and building systems (Richner *et al*. 2017). DFAB HOUSE represents one such *Unit*, situated on the top-most floor slab of NEST (Figure 1).

NEST *Units* are required to be fully compliant with local building codes and an additional, stricter set of performance standards prescribed by NEST. By meeting these requirements, each DFAB technology implemented in DFAB HOUSE represents a "system prototype demonstration in operational environment" as defined on Level 7 of the Technology Readiness Level (TRL) scale (European Commission 2019). Thus, DFAB HOUSE can be described as a multi-technology demonstrator, proving the technical feasibility of new technologies not yet adopted to practice in a realistic context in preparation for broader adoption.

DFAB HOUSE demonstrates six DFAB technologies, illustrated in Figure 2. For a full description of these technologies, readers are referred to Graser *et al*. (2020).

Mesh Mould (Figure 2(a)) is a robotically welded rebar mesh combining the functions of stay-in-place formwork and reinforcement. It enables on-site, waste-free, structurally optimised concrete construction (Hack *et al*. 2020).

The In situ Fabricator (Figure 2(b)) constitutes the world's first on-site application of an autonomous,

Figure 1. NEST with DFAB HOUSE (upper left).

mobile construction robot, to fabricate the Mesh Mould rebar system (Dörfler *et al.* 2019).

Smart Dynamic Casting (Figure 2(c)) is an automated system for concrete slip forming using a reusable, actuated formwork with changing cross-section, and the first system to unify reinforcement and concreting in a single robotic process (Lloret-Fritschi *et al.* 2019).

Smart Slab (Figure 2(d)) is a pre-cast concrete ceiling slab fabricated with sand-based binder jet 3D printed formwork It combines design freedom with significantly reduced material volume (Aghaei-Meibodi *et al.* 2018).

Spatial Timber Assemblies (Figure 2(e)) is a robotic prefabrication process for timber modules. Collaborating robot arms fabricate and assemble structurally performant, material-efficient structures (Thoma *et al.* 2019, Adel 2020).

Lightweight Translucent Façade (Figure 2(f)) is a membrane facade with aerogel insulating filling integrated with *Spatial Timber Assemblies*. It combines freedom of shape with high thermal performance, daylighting and weight reduction (Graser *et al.* 2021).

Research methodology

By demonstrating multiple new DFAB technologies at full construction scale, DFAB HOUSE represents an unusually rich and complex case to study DFAB in the real-life context of a construction project. It can be considered a rare source of insight into an emerging subject that is still lacking larger, quantifiable datasets (Yin 2014). Therefore, this research uses a single case study approach as "an opportunity to describe the process by which a complex phenomenon unfolds" (Taylor *et al.* 2011).

Data collection

Primary data were collected through a total of 37 semi-structured interviews with project participants, Participant questions included information about background experiences, roles and responsibilities, work processes, and project experience. 36 interviews were recorded (total time 30.5 hours) and notes were taken on all interviews. The sample includes 17 technology researchers (e.g., principal investigators (PIs), PhD and postdoctoral researchers, scientific assistants), 11 industry partners (e.g., managers, engineering and construction specialists and executing site personnel), and 9 other participants (e.g., planners, technicians, client's representatives, and R&D managers). Interviewees were selected based on the authors' knowledge of the project, following the principle of purposeful sampling which aims to "obtain cases deemed information-rich for the purposes of study" (Sandelowski 2000). Interviewee selection was guided by their active role in the development and application of DFAB or in decision-making on the project.

Figure 2. Building parts of DFAB HOUSE and associated DFAB applications: Mesh Mould (a), In Situ Fabricator (b), Smart Dynamic Casting (c), Smart Slab (d), Spatial Timber Assemblies (e), Lightweight Translucent Façade (f).

Data were collected until theoretical saturation was reached (Strauss and Corbin 1990).

The first author was himself involved in the project management of DFAB HOUSE. First-hand knowledge of the project was an important asset for this research as the project organization was dynamic, decentralized and characterized by informal collaboration. These factors would have made access difficult to researchers without prior knowledge of the project. A trade-off to this access is a greater risk that personal biases can affect the research process (Dainty 2008). To mitigate this risk, the two co-authors were kept external to the project to provide an outsider perspective (Gioia *et al.* 2013) and to challenge the first author towards increased reflexivity regarding research design and data analysis.

Data analysis

This research uses Qualitative Content Analysis, a method of qualitative data analysis deemed appropriate for examining a nascent field (Mayring 2014, Kuckartz 2019). The focus of the method is on developing a category system to describe and explicate

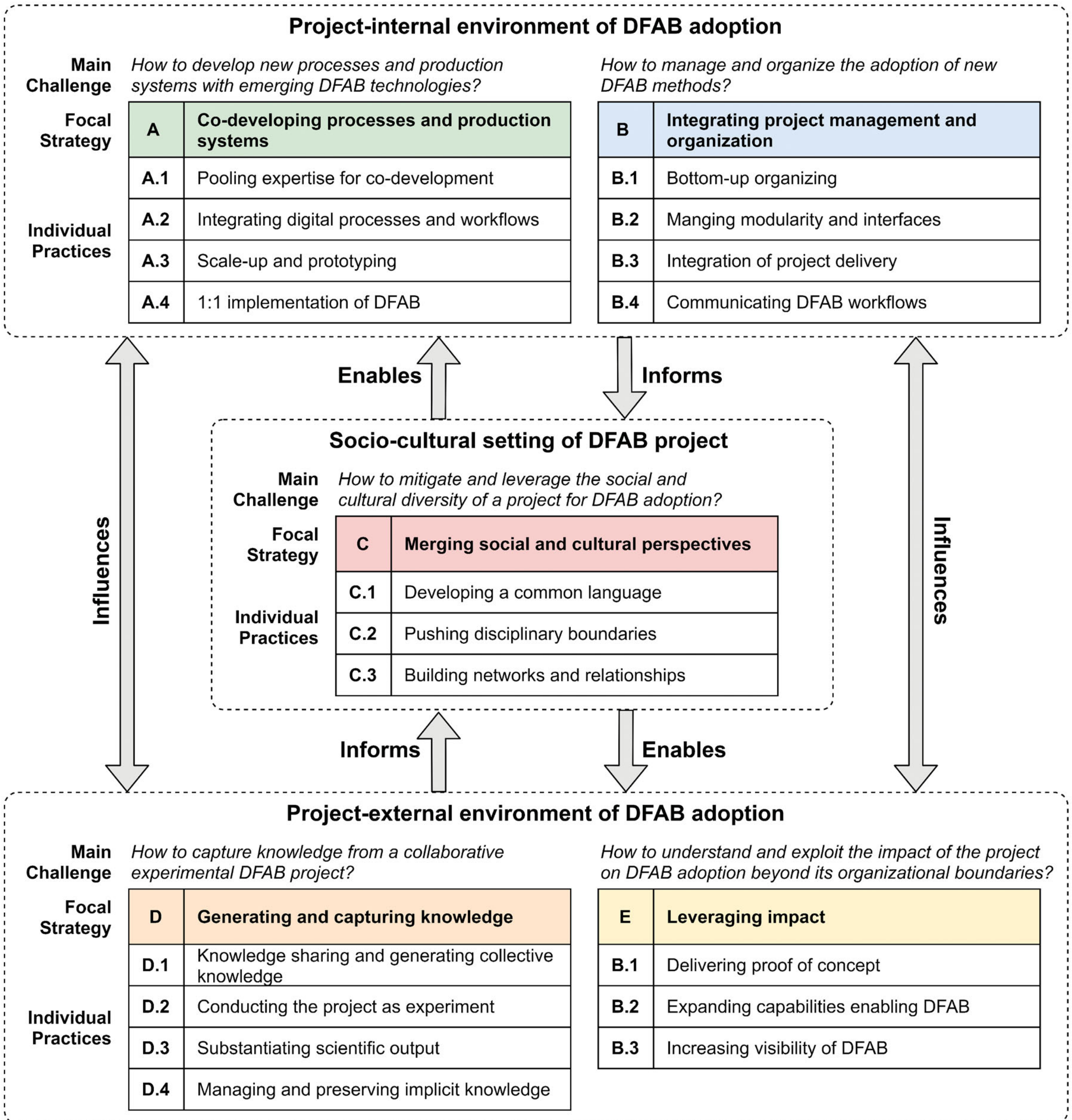

Figure 3. Socio-technical framework of DFAB adoption in AEC projects.

qualitative data from a research-led perspective (Eisenhardt 1989; Kuckartz 2019). There are two main variants: deductive, i.e., driven by pre-existing literature or theory; or inductive, i.e., derived from the content of the data itself. For this study we chose the specific technique of Inductive Category Development, a summarising approach deriving categories from the entire collected data. The aim is understanding "without bias owing to the preconceptions of the researcher" (Mayring 2014). This approach is similar to the "open coding" process in Grounded Theory (Strauss and Corbin 1990) but relies less on interpretative transformation and theory-building, allowing researchers to "stay closer to their data" (Sandelowski 2000). This makes it a more suitable methodology for case research conducted with prior knowledge of the object of study. The text analysis software MAXQDA was used to perform the analysis.

In a second step, we performed a Strengths – Weaknesses – Opportunities – Threats (SWOT) analysis (Helms and Nixon 2010) of each of the main categories that resulted from Qualitative Content Analysis. SWOT analysis is recognised as one of the most extensively used techniques of strategic planning (Glaister

Table 1. Main Challenges, Focus Areas and Focal Strategies for DFAB adoption on projects.

	Main Challenges	Focus Area	Focal Strategies
A	*How to develop new processes and production systems with emerging DFAB technologies?*	Technology	Co-developing processes and production systems
B	*How to manage and organise the adoption of new DFAB methods?*	Organisation	Integrating project management and organisation
C	*How to mitigate and leverage the social and cultural diversity of a project for DFAB adoption?*	Socio-cultural setting	Merging social and cultural perspectives
D	*How to capture knowledge from a collaborative experimental DFAB project?*	Knowledge	Generating and capturing knowledge
E	*How to understand and exploit the impact of the project on DFAB adoption beyond its organisational boundaries?*	Perception and pay-off	Leveraging impact

and Richard Falshaw 1999). Using SWOT analysis, we develop an early perspective on the strengths and weaknesses and the future opportunities and threats of the DFAB adoption strategies found in the case data.

Data validation

To meet the burden of proof in case study research, this study uses five strategies to achieve validation (Taylor *et al.* 2011, Yin 2014). First, good practice in qualitative research requires employing multiple data sources for triangulation (Cho and Lee 2014). Therefore, project protocols covering research, coordination and client meetings, permit submissions and yearly scientific reports were reviewed. Using data produced at different project stages helped control for various types of biases in the interviews, for example, hindsight and social desirability bias. Second, the author team was chosen up-front with different disciplinary backgrounds and affiliations to include a plurality of views and limit social determinants such as groupthink and conformity pressures. Third, the three authors conducted a coder conference to control for inter-coder reliability. Three interviews were first coded independently by each of the authors using the first author's proposed code system, allowing each to make amendments, take notes privately and report their initial stance at the beginning of the conference. This was followed up by an open discussion with focus on logical, unanimous resolution of disagreements regarding the categories and the coding. This strategy served to enhance internal consistency and the accuracy of the code system. Fourth, the findings were discussed with a group of interviewees for communicative validation to control for construct validity. Fifth, we included direct case data quotes to validate the constructs described in the findings, thus "letting the data speak for itself" (Taylor *et al.* 2011).

The authors used these strategies to proactively and consciously control for biases in the analysis. Nevertheless, we acknowledge that some biases likely still exist in the qualitative, single-case research approach taken in this study.

Research findings

Challenges and strategies of DFAB adoption

From the analysis, five Main Challenges emerged with respect to the implementation of DFAB, each related to a different Focus Area. Corresponding to these Main Challenges, we identified five Focal Strategies subsuming the individual actions reported by the project participants to address these challenges (Table 1). For each Main Challenge, we then identified a set of individual practices, or courses-of-action, pursued by the actors in the project organisation to facilitate DFAB adoption.

Synopsis of findings

The following synopsis presents the results of the Qualitative Content Analysis for each of the five Main Challenges, Focus Areas, and Focal Strategies identified, followed by a SWOT analysis of each Focal Strategy, referencing the results detailed in the descriptive analysis (Table 2(A–D)).

A Co-developing processes and production systems

Main Challenge A, *How to develop new processes and production systems with emerging DFAB technologies*, was addressed by four practices.

A.1 Pooling expertise for co-development. An important step at the outset was pooling expertise from both research and practice to assemble teams of experts. Research teams formed across groups with

Table 2A. SWOT analysis of co-developing DFAB processes and production systems.

Strengths	Weaknesses
• Pooling complementary expertise of diverse stakeholders (A.1) • Embedding analysis and feedback data in production data (A.2) • Concurrent development of technology, design, and implementation process (A.3) • Integration across research projects and specific design tasks (A.4)	• Digital workflow integration lagging behind technical possibilities (A.2) • Unexpected complexity in upscaling (A.3) • Time-consuming trial and error approach (A.3) • Lack of researcher experience with scale, complexity and time pressure (A.4)
Opportunities	**Threats**
• Building early understanding of fields of expertise required for implementation (A.1) • Making stand-alone DFAB technologies part of integrated production system (A.2) • Learning about relevant safety, cost, and implementation parameters (A.3) • Understanding practical challenges (A.4) • Gaining awareness of relevant issues not present at smaller scale (A.4)	• Incomplete awareness of required expertise at project outset (A.1) • Lack of process maturity as threat to future implementation (A.2) • Lack of understanding how to collaborate with digital machinery (A.2) • High skill expectations towards future "digital construction worker" (A.3) • Difficulty aligning technology with building codes and safety approvals (A.4)

Table 2B. SWOT analysis of integrating project management and organisation for DFAB adoption.

Strengths	Weaknesses
• Bottom-up organising allowing role flexibility (B.1) • Self-managed, integrated organisational modules for DFAB development (B.2) • Operative project management independent of DFAB modules (B.2) • Co-location for short communication paths and direct interaction (B.3) • Using virtual reality and rapid prototyping for communication (B.4)	• Inefficiencies and unclear responsibilities in bottom-up organising (B.1) • Challenge of coordinating interdependencies between DFAB developments (B.2) • High dependence on in-person interaction (B.4) • Challenge of communicating design in flux (B.4) • Unrealised DFAB potential due to inadequate communication (B.4)
Opportunities	**Threats**
• Exploration to fully understand the possibilities of DFAB (B.1) • Identifying interfaces and workflows for further DFAB integration (B.2) • Co-development of DFAB through early involvement of key stakeholders (B.3) • Combining DFAB with intuitive visualisation, simulation, and interaction tools (B.4)	• Lack of "recipe" to tackle novel developments (B.1) • Risk of "indefinite exploration" without implemented results (B.2) • Dependency on boundary spanners with cross-topic understanding (B.3) • Difficulty of communicating DFAB rules, limitations, and potential as threat to future implementation (B.4)

Table 2C. SWOT analysis of merging social and cultural perspectives for DFAB adoption.

Strengths	Weaknesses
• Developing a common language through repeated interaction over time (C.1) • Establishing shared practices between research and industry (C.2) • Breaking up disciplinary thought silos (C.2) • Generating new research and industry partnerships (C.3)	• Misunderstandings causing errors and rework (C.1) • Information loss due to lack of common terminology (C.1) • Few established collaborations between disciplines to build on (C.2) • Resources required to establish and maintain industry partnerships (C.3)
Opportunities	**Threats**
• Bridging research and practice mindsets (C.1) • Recognising non-technical roadblocks to technology deployment (C.2) • Forming new experts in the emerging field of DFAB (C.2) • Cracking resistance to change in the workforce (C.2) • Creating a community of DFAB practice (C.3)	• Communication obstacles threatening DFAB implementation (C.1) • Resistance to change in the workforce (C.2) • Lack of education in non-technical aspects of technology diffusion (C.2) • Loss of industry partner putting project at risk (C.3)

Table 2D. SWOT analysis of generating and capturing knowledge from a collaborative experimental DFAB project.

Strengths	Weaknesses
• Learning through direct interpersonal information exchange and observation (D.1) • 1:1 implementation resulting in broader data sets than lab research (D.2) • Including industry in scientific inquiry (D.2) • High-profile scientific publications (D.3) • Encoding project knowledge in software (D.4)	• Time and resources required to establish collaborations (D.1) • Project challenges competing with immediate research objectives (D.2) • Challenge of documenting and publishing non-technical findings (D.3) • Challenge of quantifying field data (D.3) • Lack of protocols to retain implicit and non-technical knowledge (D.4)
Opportunities	**Threats**
• Knowledge co-production between multiple knowledge areas (D.1) • Collective experiment as source of new evidence, ideas and research questions (D.2) • Identifying DFAB limitations and development opportunities (D.2) • Rethinking accepted metrics for interdisciplinary research results (D.3) • Practical experience for future DFAB implementation (D.4)	• Dependence on heterogeneous knowledge inputs to generate results (D.1) • Lack of established scientific methodology for project-scale research (D.2) • Lack of measurable return of DFAB R&D prohibiting further investment (D.3) • Challenge preserving implicit knowledge in transient teams (D.4) • Difficulty reusing project-specific DFAB code (D.4)

Table 2E. SWOT analysis of understanding and leveraging the project's impact on DFAB adoption outside project boundaries.

Strengths	Weaknesses
• Proving feasibility of DFAB at scale (E.1) • Reducing remaining distance to market (E.1) • Investments enabling and complementing DFAB in firms and research (E.2) • Increasing technology readiness of project participants (E.2) • External and internal signalling of DFAB capabilities by firms (E.3)	• Open questions about implementation beyond research demonstrator (E.1) • Limited, incremental investment in new capabilities (E.2) • Resources required for project dissemination (E.3) • No traceable effects on new work acquisition for firms (E.3)
Opportunities	**Threats**
• Increasing industry acceptance of DFAB (E.1) • Securing industry buy-in for DFAB (E.1) • Spin-offs for DFAB commercialisation (E.2) • Follow-on collaborations to build IP and file patents (E.2) • DFAB gaining visibility, societal acceptance and trust (E.3)	• Lack of follow-on use for DFAB investments (E.2) • Critical reception by audiences with different values and expectations (E.3) • Reservations towards DFAB in the workforce (E.3) • Risk of negative fallout from failures (E.3) • Negative perception and connotations of automation (E.3)

complementary expertise (e.g., robotics, structural engineering and material science). Industry experts and trained technicians were directly included in R&D activities, and executing contractors participated as future users of the technologies, contributing their expertise in determining how best to apply a technology. One firm's CTO remarked, "That's the crucial difference with this project, that we actively pursued solutions together with the research groups and the project management."

Researchers and industry alike emphasised the value of building an early understanding of the different fields of expertise required for "looking into all the complexity that one technological development needs", albeit an incomplete awareness of needs could make the ex-ante forming of consortia challenging.

A.2 Integrating digital processes and workflows. Project implementation required making stand-alone DFAB technologies part of a production system integrated across scales and functions. For example, Mesh Mould required the development of a new robotic end-effector, its integration with the mobile robotic base, and an optimized repositioning sequence.

Integrating digital information from design to production was central to the project. Especially important was the upstream integration of production parameters (e.g., the limitations of robot reach or the angle constraint of a saw blade). Data integration offered synergies, such as embedding analysis and fabrication data in one model, automating fabrication data generation, and streaming back sensor data to an as-built digital model. Limitations were also reported. Digital workflow integration lagged behind the technically feasible. For example, a structural analysis workflow proposed by researchers to provide immediate feedback on design iterations proved unfeasible as it lacked interoperability with a contracting engineer's established tools. Additionally, a lack of maturity in process automation led to time-consuming iterations and "fiddling". Researchers viewed these drawbacks as challenges to integrating DFAB in future construction processes.

The integration of digital and manual tasks was essential for the project. No DFAB process was fully automated. The need for a better understanding of collaborative processes with digital machinery was frequently highlighted. A contractor said DFAB required a new type of "digital construction worker" with "knowledge in computing and robotics and practical knowledge of doing the work onsite", a skillset that will likely continue to be hard to find in the workforce.

A.3 Scale-up and prototyping. To achieve scale-up from laboratory experiments to viable full-scale construction, all core teams included researchers from additional disciplines and professional experts. One planner called this the moment "when an engineering approach entered the research." Physical prototyping was used for the concurrent development of the emergent technologies, design and implementation processes. It allowed for learning about relevant parameters in advance of full-scale implementation, for example, structural safety, the true cost of the system, and full-scale assembly challenges. Multiple prototypes enabled improvements through trial and error, a time-consuming process sometimes requiring fundamental changes. Unexpected problems - making things "more complicated than you think" – frequently occurred, but raised the R&D teams' awareness of important factors originally not considered. Industry professionals embedded in the teams raised constructability concerns and brought in practical experience researchers were lacking.

A.4 1:1 implementation of DFAB. The stated project goal was implementing DFAB with construction grade quality and full functionality in "a building beyond one research project or specific design task."

Researchers were challenged by tight delivery schedules and the sheer "scale and volume of production." The project was more complex than anticipated and required more resources and suppliers. One research leader said: "What I really learned was how complicated it was to make a very simple, flexible formwork. That the system has many more constraints than I had ever imagined."

Many saw rewards, too: Dealing hands-on with site conditions and external constraints, researchers "gained insights you wouldn't have had without the 1:1 project." Likewise, industry partners emphasised the relevance of "being close to the process" and learn about practical and legal challenges. A technician underscored, when building in 1:1 "you see what's possible, what's not."

Making the researchers' ideas comply with building code and safety approvals proved challenging. As a PM observed, approvals were "not part of DFAB thinking" yet. For example, DFAB technology enabled design changes up to the last minute, while administrative approval timelines forced earlier design freezes. Successful permitting lent the technologies legitimacy, but researchers found some constraints currently imposed by codes misaligned with the potential of DFAB.

B. Integrating project management and organisation

Four practices addressed Main Challenge B, *How to manage and organise the adoption of new DFAB methods.*

B.1 Bottom-up organizing. Self-organising was crucial in implementing multiple new DFAB processes in parallel. Researchers described the project organization as a dynamic process in which they were "not being assigned a task but more organically developing the project together." Because DFAB implementation required role flexibility, bottom-up organizing enabled new roles to emerge in response to specific needs. For example, one research assistant described his role as "jack of all trades, master of none", filling responsibility gaps emerging as DFAB processes developed, such as wiring and trial runs of one-off robotic tools.

Network-like, horizontal decision-making strongly relied on regular personal exchange. Communication between disciplines was "less formal exchange and more intermingling". Informal "coffee meetings" were instrumental between roboticists, structural engineers, and material scientists. Bottom-up organizing led to unclear boundaries of responsibility and redundant developments. However, industry partners and the client recognized the need "to let [researchers] use their imagination and explore" to fully understand the possibilities of DFAB.

B.2 Managing modularity and interfaces. In addition to bottom-up organising, an element of top-down control balanced self-directed exploration with the realities of project delivery. The research-led development was important, a contractor remarked, but "if you would have let them do this indefinitely, there still wouldn't be a finished building." To mitigate this required both modularity and integration in the project organisation.

Modularity was necessary to allow independent technical development of the DFAB applications, each of which was developed within a separate, self-managed and highly integrated organizational module. This kept complexities and uncertainties of DFAB development away from the interfaces. One PI likened this to software development; operative project management was separated from technology development and focussed on integration, relieving researchers of the "managerial side" of the project.

Nonetheless, coordinating the interdependencies between multiple parallel DFAB developments was challenging. A CEO said, "it was essential to look at the interfaces in a seamless way without sharp lines saying 'This is where my responsibility ends'." Well-coordinated interfaces at module boundaries enabled the integration between the different DFAB applications. "You are just a part of the project, you are not alone … Everyone depends on the others." Thus, project organisation depended on actors with a "bridge function" who had the breadth of skills and experience to manage information exchange across module interfaces.

B.3 Integration of project delivery. Organising the successful delivery of DFAB at the project scale hinged on the integration of actors, most importantly through *early stakeholder involvement* and *co-location*.

Early involvement of stakeholders was considered crucial to DFAB implementation by researchers, contractors and the client. The development team for each DFAB application included the main trade (e.g., concrete or timber) contractors in the earliest conceptual project stages, along with essential engineering specialists, and involved every party to the final project in hands-on prototyping. Notably, this included construction crews to contribute their ideas about feasibility and gain experience for final execution. A site foreman said, "you could really develop [the DFAB process] together", a stark contrast to their usual experience.

Co-location supported short communication paths and direct interaction with DFAB tools. Most of the project team was "sitting together as a bigger body of knowledge". Industry partners were present on a regular schedule, allowing for "constant interaction" during development, prototyping and fabrication. This allowed decision makers in planning, research and industry to not just "judge things from their office" but to be physically close to the production process and better understand how to make improvements.

B.4 Communicating DFAB workflows. Finding communication strategies for DFAB processes was challenging in three ways: communicating a design in flux typical for DFAB; the complexities and interdependencies inherent in DFAB workflows; and the potentials and limitations of novel DFAB technologies. Some potential of DFAB was "left by the wayside" for lack of a communication strategy; to contractors, the difficulty to communicate the requirements and rules of DFAB between stakeholders is a likely hurdle to its future commercial adoption.

Accordingly, actors tried to find more intuitive ways of communicating. Tangible techniques such as virtual reality and model-scale rapid prototyping were used alongside ad-hoc methods such as sharing digital 3D models on-screen, exchanging sketches and screen captures, and live DFAB observations. Participants noted that DFAB practice would benefit from more intuitive ways to simulate, visualise and interact with DFAB processes, e.g., augmented reality applications or model-based collaboration tools. Such options would decrease dependency on in-person interaction, ensuring inadequate communication will not cancel out the efficiency gains DFAB promises.

C. Social and cultural factors

Main Challenge C is *mitigating and leveraging the social and cultural diversity of a project for DFAB adoption*. Three practices addressed this.

C.1 Developing a common language. Advancing the nascent field of DFAB, a researcher observed, "only makes sense in an interdisciplinary manner." This required cooperation of a broad diversity of actors, but "the biggest challenge was just how to be able to understand each other in a way that would promote the success of the project."

The initial lack of a common terminology was an obstacle: "You come in, you misunderstand each other." This was seen as a threat to future DFAB implementation. However, the two-year project timeframe and the repeated interactions it required were a good precondition for developing a common language.

A researcher described this process as follows.

"Because I do not have the background, the information that [another team member] gives out doesn't stick. Then it takes … going back to the same points again and again. Then these things start to stick. You start to learn the language. All of a sudden you can start to connect it to your background … That's where the innovation starts."

Misunderstandings were a common issue between researchers and practitioners. When groups used the same term to talk about different things (e.g., "ribs" as structural elements vs. surface articulation), it led to confusion, errors and rework. When construction professionals were working with researchers, "what's crystal clear, or not worth mentioning to one person is 'never heard of' to another." However, actors with prior interdisciplinary work experience felt better equipped to avoid such misunderstandings.

C.2 Pushing disciplinary boundaries. DFAB depends on interactions across discipline boundaries, ensuing the transfer of expertise to and from others outside one's own discipline. This pushing of disciplinary boundaries was considered one of the central opportunities of the project, as it resulted in new solutions no one would have thought of individually. For example, roboticists getting their technology "into the hands of people that are not … familiar with the way we think" received back new ideas about "how you can use and what you can do with it."

Researchers said DFAB helped break open ensconced thought silos in academia. They learned to "understand the other disciplines' point of view", even between traditionally distant research fields. "Structural engineers and material scientists are in the same departments, but they don't work together, and I think DFAB has changed that." A structural engineer experienced an "enormous widening of the horizon" towards knowledge of materials, robotics and computer science. In addition, DFAB HOUSE taught them socio-technical aspects: "What are the roadblocks on the way to deployment of technology? The social and human aspects … This is something that, as engineers, we're absolutely not trained to think about."

The cross-over extended to the traditional divide between research and professional cultures as well. Researchers and contractors challenged each other "to find out how far they can deviate from their usual ways" in establishing new shared practices. Practitioners learned "what possibilities already exist" and to accept the risk of failure. Researchers learned about pragmatic industry needs, market focus and external constraints.

As a result, participants started identifying as experts in the emerging field of DFAB. "You understand the importance of those collaborative settings when you cannot any longer get back into a research field where that doesn't happen." At the time of project completion, one of them said, "I have about three and half years in this. Considering how young the field is, it kind of made me an expert by default."

The pushing of disciplinary boundaries has significance beyond the individual: participants saw in DFAB HOUSE a case-study of a new work environment and "digital culture" firms will need once DFAB technologies enter the market. A CEO said "It is important for a firm to ... take part in this expansion of the horizon, "and to "crack open the resistance to change" prevailing in the workforce.

C.3 Building networks and relationships. Networks and relationships across research, industry and the client organisation enabled DFAB implementation in three ways.

First, connections between researchers were important. DFAB research caused groups to establish new connections with other disciplines, and build new personal relationships. A coordinating researcher stated, "I got new skills, but still I [now] know people that are much more talented in these skills."

Second, connections between research and industry partners were a major value proposition of the DFAB HOUSE project. On the research side, a technology transfer manager said, "DFAB HOUSE is the NCCR project that has produced the most industry partnerships." An engineering PI called DFAB HOUSE a "door opener" for industry involvement: DFAB had "changed the scale" by attracting the interest of global industry leaders who were looking for insights into new technologies.

Third, DFAB HOUSE created a new network for industry partners around DFAB both inside the firm and with external complementors and clients. A CTO said DFAB HOUSE R&D moved them from "outsider" to "insider" in an expert network around digital capabilities: it helped them know who to ask about digital topics, get help on other projects, and validate potential new hires. In addition to direct partnerships, the project created a new ecosystem of likeminded partners.

However, building and maintaining partnerships requires effort and resources. In early project phases, NCCR management and research groups organised firm visits, research presentations and networking events to find partners. Still, a successful partnership took two years to ramp-up, requiring constant attention to balancing mutual interests. In one case, losing an industry partner led to resource problems and increased workload for researchers. Partnerships helped the project succeed and become "a binding object that creates a community around it." Going forward, a researcher stated, the project network was a good basis for "knowing who to make the next steps with."

D. Generating and capturing knowledge

Four practices responded to Main Challenge 4, *how to capture knowledge in a collaborative experimental DFAB project.*

D.1 Knowledge sharing and generating collective knowledge. Direct, interpersonal information exchange was clearly identified as the main source of learning on the project, followed by observing the other disciplines' approaches. Participants continuously learned throughout the project, making it what an industry partner called a "new learning territory."

Two ways of knowledge trading dominated the project. First, *sharing knowledge* formerly residing just with one individual or group, leading to a broader common knowledge base. In a team of experts with disparate backgrounds each could broaden their knowledge. An engineer remarked, "those who needed to learn from me were exactly the people I needed information from." For example, roboticists learned about construction while an architecture researcher acquired robotics skills, and both learned understand the material science behind their processes. Industry experts helped researchers better understand important external constraints. The experts, in turn, gained insights into new technologies.

Second, *generating collective new knowledge* by learning together on the job, yielding a new transdisciplinary body of knowledge specific to DFAB. Establishing meaningful collaborations with experts from other fields took time, a team leader said. However, "eventually we built up this collective knowledge [to] tackle a very specific challenge, which is beyond your discipline, and beyond their discipline, but you can solve it together." A researcher said Mesh Mould exemplified this process: "It's not my work, it's really a work that has been created through the knowledge of many." In turn, results could only be achieved in an environment where such complex and heterogeneous knowledge inputs were available.

D.2 Conducting the project as experiment. Rather than a mere demonstration of previous research results, DFAB HOUSE constituted a collective experiment and thus a source of new evidence, ideas and research questions. A researcher called this "empirical research on a 1:1 scale." Our findings support this statement in four ways.

First, research had to address "a lot of other challenges that are not necessarily responding to your objective" (e.g., structural engineering, facade planning, and approvals) and integrate industry in the inquiry, along with its different priorities and skills. The research became contextualised, addressing cross-topics "isolated research" could not explore.

Second, the project expanded the scope of DFAB research to include questions of integration into practice. A researcher said, "It's integration of all these layers, all the complexity that make one building happen, the economy, the approval, all that." This required learning how to do collaborative research on a project scale, a task a project manager suggested "should have been a research project on its own". A PI said this could broaden the definition of DFAB research, emphasizing "higher scale thinking … in a context where it's not just a pure technical challenge." However, a scientific methodology for project-scale research in AEC was lacking.

Third, going from research lab to construction yielded different and broader datasets because of scale and the need to consider more variables. A robotics researcher said, "in a prototype, we wouldn't have had many of the findings." In addition, long-term data collection after completion (e.g., by built-in sensors) allows continued analysis of structural behaviour over the building lifecycle.

Fourth, full-scale implementation helped find limitations of DFAB and identify opportunities for its further development. A researcher called DFAB HOUSE "a huge enabler for really finding out where the problems are in the systems under development." For example, understanding the material science of early concrete hydration was "a completely new problem in the industry."

D.3 Substantiating scientific output. The primary outlet for research results from the project were scientific publications. Collaborative, interdisciplinary papers focussed on the broader DFAB applications. In-depth technical papers on specific components (e.g., a robotic end-effector or feedback system) were published in discipline-specific journals and conferences. In sum, "every researcher wrote one or two papers on this collaborative effort with the focus on very specific topics." Researchers emphasised the project's importance in producing high-profile academic publications.

However, relying on technical publications had limitations. It mostly captured outcomes deemed scientifically relevant in the separate technical disciplines, leaving other important project learnings undocumented. Some results could be crucial for construction but dispensable for scientific output. While implementation knowledge is essential for advancing DFAB, a PI said, it may not get researchers "the scientific recognition that will boost [their] academic career."

In addition, proper quantification of outcomes proved challenging. A researcher said field data from a single project-specific application was not meaningful for measuring DFAB performance, for example, on material efficiency. Thus, data output differed from quantitative results expected in the various disciplines. Researchers highlighted a need to rethink established metrics to avoid losing critical knowledge outputs in an interdisciplinary research domain such as DFAB.

Likewise, industry partners could not quantify most effects of their DFAB R&D investments on firm performance. While a CEO said, "that is not a reason not to do it," a continued lack of such evidence would likely deter higher management of firms from investing in DFAB.

D.4 Managing and preserving implicit knowledge. Managing and preserving knowledge not captured in science publications was recognized as a significant issue, in order "to not forget what we all have learned, and to somehow make it accessible to others." Passing on such implicit know-how in transient, interdisciplinary teams was a new challenge researchers faced: "We don't have special protocols. We probably should." Despite this, three strategies prevailed.

First, archiving software and machine code as "algorithmic know-how" was a knowledge preservation strategy considered highly important for DFAB. Making existing code available for new projects required documentation protocols and use instructions not yet fully established in many research groups. This was also considered a potential barrier to establishing complex DFAB in industry.

Second, research groups tried to produce internal project reports to bundle the "sticky", localised practical knowledge single group members had won when implementing DFAB. Although such documentation was an opportunity for retrospective learning, it was challenging to divert time and resources away from new research projects.

Third, understanding and sharing non-technical experience values required a more in-depth "discussion of projects." A PI realized: "I think what we're lacking is a proper debriefing." Some industry partners, on the other hand, conducted debriefings to share experience and report challenges and chances resulting from the project, both internally and with the client.

E. Leveraging impact

The case data show three practices responding to Main Challenge E, *how to understand and exploit the impact of the project on DFAB adoption beyond its organizational boundaries.*

E.1 Delivering proof of concept. Proving the technical feasibility at scale was credited with increasing acceptance of DFAB as a viable option to further explore in AEC in four ways.

First, researchers found their own initial doubts dispelled about whether DFAB could be translated to real applications, because "the project simply showed that you can very well master such big challenges." Within the research community, a PI said "it gave us credibility to show that our research can be applied on a scale that was never done before."

Second, DFAB HOUSE secured essential industry buy-in. "Showing that you can reach real, commercially usable results" convinced multiple companies to move forward with partnerships aimed at developing market-ready technologies. The maturity DFAB had reached on the project reduced the remaining distance to market and helped industry acceptance. A PI said, "it contributes to … an increased belief that digital transformation will take place in construction."

Third, contractors used the project to signal their digital capabilities to clients. When showing clients "we've actually built this building using this technology, they're going to believe you that you can actually deliver things later on as well." A client's representative confirmed: "In AEC you need physical reality to demonstrate it's feasible. Without this end achievement it's not trusted and won't be accepted in the market."

Fourth, stakeholders outside AEC needed convincing. A leading researcher said a demonstration like DFAB HOUSE was necessary, as "many decision-makers in politics, press, general public, universities etc. only then start to see and believe," as do building authorities and regulators. For these audiences a "hands-on", "real" and "tangible" experience was important. With this, the client emphasised, "we can prove it is possible. We can do things differently." Despite such initial proof, many open questions regarding DFAB implementation beyond the demonstrator, and how to commercialise, remained unanswered. Still, a leading investigator said, "when you look back in 20 years, you will see that this has led to [innovation]."

E.2 Expanding capabilities enabling DFAB. DFAB HOUSE presented an opportunity to researchers and firms alike to build new capabilities persisting beyond project completion.

Research teams developed new, re-deployable methods and systems for the project, along with the expertise to use them. For example, the effort to implement a fully functional version of the on-site robotic fabrication system was contingent on DFAB HOUSE. The project also allowed the research institution to expand its technology capabilities by adding functionality to the Robotic Fabrication Lab (e.g., an automated tool changer and developing reusable core algorithms).

Several formalised industry collaborations sprung from DFAB HOUSE. A researcher observed that "ramping up" the technology for DFAB HOUSE helped "bring it to a stage where now industry wants it." Follow-on industry collaborations are targeting product development as well as joint building of IP and filing patents. For example, two spin-outs were formed with leading industry partners, aiming specifically at market implementation of the demonstrated DFAB technologies.

Partnering firms used the project as a vehicle to extend capabilities as well: they rapidly developed processes enabling or complementing DFAB applications, invested in DFAB equipment and hired new know-how. New processes such as 3D printed formwork or post-tensioning (a high-performance reinforcement method) in curved concrete elements were fundamentally new solutions that are now available to clients. One contractor used process knowledge from DFAB HOUSE to implement an automated 3D planning tool for standard products. Equipment investments triggered by DFAB HOUSE included an automated concrete batching system (enabling DFAB applications), advanced software, and an industrial robot retrofitted for DFAB tasks. One firm reported hiring full-time digital planning and DFAB specialists as a direct project outcome.

However, firms were aware of the risk that these investments could not be fully utilised in day-to-day operations after project completion and therefore favoured incremental capability-building. Nevertheless, they saw even small investments as a substantial increase in readiness to adopt DFAB innovation. A CEO called them the "missing puzzle piece" necessary for taking on "new chances and changes" complementary to their core business.

E.3 Increasing visibility of DFAB. As a first-of-its-kind demonstrator of DFAB in construction, the project aimed at increasing visibility of DFAB to a variety of audiences. The project was disseminated through many channels, both during construction and after completion. Formats included live tours on site, the project website, a dedicated video channel, social media, as well as press, radio and TV coverage. As a result, a leading researcher said, DFAB HOUSE "is clearly … already seen as a major realisation in the field [and] an icon of DFAB integration."

However, this communication required significant resources from research institutions, industry partners and the client. Addressing a varied audience, the project's message could not be tailored just to one group's expectations and values (e.g., automation, sustainability, architectural design). Rather, it needed to strike a balance and thereby expose itself to critical reception. In addition, publicising the construction process bore the risk of exposing failures or shortfalls for research and industry alike.

Many researchers found value in the extended visibility of their research. It "increased the chance of technology transfer" and helped attract research funding. For the NCCR as a young research centre, building DFAB HOUSE "was a very good move, because building something ... generates a huge amount of interest in the AEC world." This lighthouse effect created an international following. In addition, a technology transfer officer said, it generated "a completely different perception" of DFAB research in the AEC industry which now could "see what's already possible today."

Industry partners welcomed the project's high visibility. A manager said, "externally, on the market, it's a brilliant statement: the firm helps develop and test something new … That's a strong, very effective signal." However, effects on new work acquisition were not yet measurable. Internally, firms could signal their innovative mindset to their own workforce: "The whole firm noticed that we were part of an innovative project ... and thinking seriously about the future," a much needed chance to tell employees "be more open!" A field worker confirmed: He felt proud of his contribution, and had lost common reservations towards working with DFAB.

The architectural scale of DFAB HOUSE was credited with appealing to the general public more than a merely technology-focussed demonstrator. This public perception bore risks, too: For example, concerns about the negative effects of automation on employment and workplace quality needed to be addressed carefully "in the research arena, but also within the society in Switzerland." In fact, a lead investigator said, DFAB HOUSE triggered a "cultural discourse on the digital in architecture" that could prove essential for increasing societal acceptance and trust needed to support the ongoing digitalisation effort.

Socio-technical framework of DFAB adoption

The strategies and practices identified above are diverse and could be taken as individual lessons; however, they are unified in a twofold manner: First, all of them are ways to overcome challenges to DFAB adoption in AEC. Second, they could not have been learned without implementing a full-scale demonstrator of DFAB. Through further analysis of how these strategies and practices relate to each other, we can develop an early a socio-technical perspective of DFAB adoption in the project context.

The Focal Strategies of DFAB adoption can be divided into two interrelated spheres we label the *Project-internal environment of DFAB adoption* and the *Project-external environment of DFAB adoption*. The former, *internal* environment relates primarily to the ability to successfully adopt DFAB within project boundaries. Main Challenges A and B fall into this sphere, because actions responding to them primarily have consequences for DFAB adoption within the project itself. The Focal Strategies A and B and their Practices, consequently, are geared towards enabling DFAB implementation within the project scope.

The latter, *external* environment relates mainly to the effects the project has on DFAB adoption beyond its boundaries. Main Challenges D and E belong in this environment, as action taken in response to these challenges has consequences for DFAB adoption in the project's surrounding environment (e.g., academic research, AEC industry and potential clients) and beyond the project organisation's limited lifespan (e.g., follow-on projects and long-term investments). Accordingly, Focal Strategies D and E, with their associated Practices, have effects exterior to the project.

These two spheres are connected by a third we name the *Socio-cultural setting of the DFAB project*. Main Challenge C, taking a central role by its relevance to both the *internal* and *external* environments, belongs into this setting. Focal Strategy C and its Practices, by making a meaningful multi-sided exchange possible in the transdisciplinary project collective, are informed by the Practices in the internal and external environment. In turn, they represent the socio-cultural tissue that enables all these Practices. By recognising the central role of the *socio-cultural setting of the DFAB project*, we arrive at a full conceptualisation of the project as a socio-technical system.

Based on this reasoning, we lay out the findings in a comprehensive socio-technical framework of DFAB adoption in AEC projects. This framework conceptualises the relationships and mutual influences between the Focal Strategies, and practices, of DFAB adoption.

Discussion

At the outset of this case study, we asked two questions. First, how do we recognise and address challenges to, and seize opportunities of DFAB adoption in the project context? And second, what are the implications for DFAB adoption in AEC practice beyond the project boundaries?

In the case data, we found various specific challenges and opportunities of DFAB uptake, and a set of corresponding strategies and practices used on the project. We subsumed these findings in a conceptual framework, offering a template for areas of relevance to the adoption of DFAB in future AEC projects.

In the following section, we take a holistic view of these findings and their relevance. As we do so, three overarching implications stand out:

I. Full-scale projects are an effective exploration method of DFAB in AEC
II. Implementation at scale increases acceptance of DFAB in AEC.
III. Projects are instrumental in establishing an emergent practice of DFAB.

Full-scale projects are an effective exploration method of DFAB in AEC

The case of DFAB HOUSE shows that a building-scale demonstrator project of DFAB in AEC, rather than a mere validation of prior knowledge, constitutes an effective format of exploration. Therefore we suggest that DFAB HOUSE, rather than just a demonstrator, is more aptly defined as an exploratory project (Lenfle *et al.* 2019) for two reasons.

First, the project *informs DFAB on the level of applicability at scale*. It is a first-time introduction of DFAB construction technologies to their relevant context. It thus offers a first chance to test each technology against constraints and influences that are external to its technical core but nevertheless critically important to its successful implementation. These external constraints relate to the robustness of processes at scale, production time and cost, integration with established technology, logistics, and codes and regulations, among other factors. Thus, full-scale project implementation opens up an application-centred perspective rather than a fundamental research perspective of DFAB, acting as an instrument for technical integration. AEC projects as a rule span organisational boundaries (Katila *et al.* 2018). The exploratory project provides one organisational unit in which multiple parties in industry and academia can co-develop new DFAB solutions. Therefore, it is uniquely suited to enable systemic innovation activity in an industry defined by inter-organisational projects, where R&D internal to one firm or organisation cannot cover the scope of change required to implement DFAB technologies.

Second, the project *informs DFAB on the level of socio-technical interaction*. The full-scale DFAB project represents a first-time engagement of each new technology with the full set of project collaborators present on AEC projects. It introduces precisely those stakeholders in its planning and implementation who are not typically involved in technology development but will be instrumental in future applications of DFAB. By facilitating the mutual exposure of technology researchers, industry practitioners and decision-makers, the exploratory project provides a common framework for a diversity of stakeholders and perspectives usually not present in either practice or academia. This is a unique value proposition of using a project for exploration. It opens up a new perspective on DFAB which addresses the needs of the prospective users (Slaughter 1993) and the practice environment (Hartmann and Trappey 2020), rather than the stand-alone technology only. Because it brings together a transdisciplinary constellation of actors, the organisational context of a full-scale DFAB project raises socio-technical challenges that do not emerge when research stays confined to a laboratory setting.

Exploration, by definition, aims at new knowledge. The exploratory project generated new technical and socio-technical knowledge in the act of DFAB implementation. This new knowledge, embodied in the practices we identified in the framework, is produced and shared between the participating disciplines and organisations. In their unique ability to integrate complex knowledge (Lindgren *et al.* 2018), projects allow exploration that can make a significant contribution to an emerging body of knowledge specific to DFAB in AEC.

Implementation at scale increases acceptance of DFAB in AEC

The case data show that project implementation increases acceptance of DFAB as a viable part of AEC practice. DFAB adoption relies on acceptance both *inside and outside the project organisation*.

Inside the project organisation, acceptance of DFAB grew on the part of participating firms, research groups, and the client organisation. This acceptance is grounded in the immediate project experience, and can be tied to multiple identified adoption practices across all the Focal Strategies. For example, co-development of DFAB processes lead to a positive identification with the results across a wider range of participants; early integration of management and execution secured buy-in for DFAB by both these realms; reaching across disciplinary boundaries allowed new vantage points to see past discipline-specific perceptions of barriers to using DFAB; establishing relationships across complementing areas of expertise expanded the notion of feasibility; joint knowledge enabled this feasibility; and achieving proof of concept extended the participants' trust in their own abilities to use DFAB.

One of the most significant effects of this inside acceptance is the ability of firms to build social support for DFAB adoption from within. Adoption of new technologies depends on its acceptance and perceived usefulness (Davis 1985). The case data show how through the project DFAB acceptance in firms expanded from the initiating individuals or small groups to a broader basis spanning from key strategic management to field workers. We argue that through a mechanism like this, DFAB exploration can become part of the firm culture. Through direct engagement in an exploratory project, this mindset can be communicated to the entire workforce, convince sceptics, and encourage exploration. By creating a culture around digital capabilities and learning, firms can acquire contextual ambidexterity, i.e., the ability to explore in parallel with their exploitative core business activities on many levels within the workforce (Birkinshaw and Gibson 2004). However, most adoption processes by users in the industry usually begin when technologies become available on the market. By contrast, to get exposure to DFAB in AEC requires engaging with experimental, pre-market technologies. Our case data indicate that demonstrators of such technologies offer a unique chance to create acceptance of DFAB inside firms through hands-on experience, increasing their readiness to absorb DFAB in their workflows once technologies become available in the future.

Outside the project organisation, full-scale implementation also enhances acceptance of DFAB. Building a real project can put new technologies "on the map", generate visibility and disseminate new ideas not yet known outside the specialised DFAB community. As a signal to the environment – which includes leadership in the AEC industry, regulators and policy makers, and the general public, among others – it can break down perceptual barriers and change expectations. For example, by making tangible the potential DFAB has for sustainability, safety, and construction quality, full-scale projects may help break stereotypes, such as the one-sided association of DFAB with full automation and reduction of labour cost or its reputation as a tool for high-end, boutique designs. Thus it may help strategic and public support for DFAB in AEC that could be crucial for adoption, especially because AEC innovation depends strongly on the external environment (Pries and Janszen 1995). This case study allowed early observations on the subject of the outside perception of DFAB projects in AEC, an area that warrants further attention going forward.

Projects are instrumental in establishing a new praxis of DFAB

The case study shows how a project implementing DFAB produces DFAB practitioners – actors who combined their disciplinary and practical backgrounds with new skills to become experts in the young field of DFAB in AEC. In sum, the actions of these practitioners are *what people actually do* when implementing DFAB, and we can argue that they amount to a new praxis of DFAB in AEC. In projects, "a dynamic setting for action is created on the local arena where knowledge and action come together in practice" (Blomquist *et al*. 2010). Our case study shows how, through a number of specific practices employed towards its adoption, a new praxis of DFAB can emerge from such a project setting. As a consequence, the praxis of DFAB is informed by the core strategies and enabling practices we identified in the framework of DFAB adoption. Thus, its roots are in process and organisation, socio-cultural factors, and knowledge specific to DFAB.

On the spectrum of these factors informing the new DFAB praxis, two are particularly noteworthy. First, in its current early forming stage, the new praxis of DFAB is grounded in the unique knowledge derived from the process of implementing DFAB technologies in the project context. This dynamic process facilitated the combination of a diversity of explicit scientific and technical knowledge but also the integration of tacit, hands-on skills (Nonaka and Lewin 1994). The practitioners of DFAB form a new community of practice, bound together by their joint knowledge as well as a shared identity (Brown and Duguid 2001).

Second, the new practice of DFAB draws from another, perhaps more lasting effect: the changing of disciplinary and professional cultures, which often starts with individual experiences but has effects beyond them. By practicing DFAB, individuals and organisations acquire not only technical capabilities but also a different cultural disposition. Bringing together disciplines is a necessity for enabling DFAB. The new, wider cultural setting it creates can open up new avenues of exploration by preventing over-socialization and helping "un-learn" some discipline-specific limitations in thinking. Challenging established disciplinary and professional cultures through the practice of DFAB may amount to a first step in shaping a new disciplinary culture of DFAB.

Recent literature has conceptualised new roles emerging in the context of DFAB in AEC at a high level and projected their growing share of participation in the construction organisation (García de Soto *et al*. 2019). Complementing this perspective, our case study allowed us a first chance to empirically study the practical reality of these emerging roles. Thus, DFAB HOUSE helped us gain an early understanding of the actual shape these roles may take in the future practice of DFAB, and who the practitioners are who will occupy these new roles. Importantly, this empirical angle may help us better understand how people, not technologies alone, change an industry.

Limitations and future research opportunities

This research has several limitations. First, it is a single case study, and generalisation can only be reached within the case context. Outcomes of other projects may be different. Furthermore, this study is limited to the project perspective; DFAB innovation adoption could be further studied from a firm and market-focussed perspective to address the multi-scale challenges of innovating and "transforming" the AEC industry (Glass *et al.* 2020).

Second, the proposed framework is conceptual and represents early-stage findings. It should be tested and refined through further case study research and/or comparative case studies as DFAB adoption progresses in AEC.

Third, DFAB HOUSE allows preliminary observations on future production capacity, productivity and organisation of DFAB (García de Soto *et al.* 2018, 2019, Lloret-Fritschi *et al.* 2019), but further research is needed to substantiate and quantify how future DFAB implementations will compare to other construction alternatives.

Fourth, this research focuses on the planning and implementation stages of DFAB but does not consider the later life cycle stages of the built result. With longer-term data on DFAB structures becoming available in the future, research is called for to assess the implications of DFAB for operation and maintenance, reconfiguration, and circularity of the built environment.

Conclusion

With this research, we make two contributions to the field of construction management.

Our first contribution is an early socio-technical framework of DFAB adoption in AEC projects. DFAB is expected to play an increasingly important role in AEC, and this framework is a first comprehensive overview of the challenges to consider and the strategies available to successfully adopt DFAB technologies to the benefit of future construction and project delivery. The findings show how uptake of DFAB technologies may shape project organisations and vice versa, how socio-technical integration plays a central role in DFAB adoption, and what effects DFAB implementation has on knowledge and practice in AEC. It is important to keep in mind that DFAB will depend on complementing advances in other areas of digitalization to play an essential role in the digital transition of the AEC industry to a more connected, sustainable, and productive future.

Second, we establish three theoretical propositions that demonstrate the relevance of adopting DFAB in the context of demonstrator projects. These propositions are: (I) *Full-scale projects are an effective exploration method of DFAB in AEC* (II) *Implementation at scale increases acceptance of DFAB in AEC.*; and (III)

Projects are instrumental in establishing a new praxis of DFAB.

We conclude that exploratory projects bringing DFAB technologies to full-scale construction are an important source of learning about how to integrate DFAB technologies into the socio-technical context of design and construction practice. They facilitate the adoption of DFAB in AEC by prompting the use of individual practices to address technological, organisational, socio-cultural, knowledge-related and perceptual barriers hindering DFAB adoption in today's AEC industry.

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