DFAB House: A comprehensive demonstrator of digital fabrication in architecture

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Publication date:
2020-04-06

Permanent link:
https://doi.org/10.3929/ethz-b-000447227

Originally published in:
https://doi.org/10.2307/j.ctv13xpsvw.21

DFAB HOUSE
A COMPREHENSIVE DEMONSTRATOR OF DIGITAL FABRICATION IN ARCHITECTURE

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ETH ZURICH / NCCR DIGITAL FABRICATION

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Introduction

This paper describes the making of DFAB HOUSE, a multi-technology demonstrator of digital fabrication in architecture, engineering and construction (AEC). While most individual digital fabrication technologies used to build DFAB HOUSE have been presented independently at conferences and in journal articles, this paper describes how, in concert, they amount to an architectural achievement that is more than the sum of its parts. To do this, the paper does three things: it describes the process of conceiving and delivering the overall project; secondly, it highlights challenges in implementation; and finally it discusses the significance of DFAB HOUSE in the context of a rapidly transforming architectural research and practice.

Research Context

Project Setting and Objectives
DFAB HOUSE is an architecture project with a unique purpose: to learn about the possibilities of digital fabrication in a real-world setting. The initial idea originated at ETH Zurich within the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication, an interdisciplinary research initiative involving architecture, structural design, materials science, computer science, control systems engineering and robotics. The NCCR's founding in 2014 coincided with the launch of NEST by Empa (Swiss Federal Laboratories for Materials Science and Technology), a modular innovation incubator. NEST is a four-storey 'backbone' providing construction sites for experimental NEST Units, co-funded by Empa, research partners and industry. NEST Units are fully code-compliant buildings and follow strict performance standards (Richner et al., 2018).

The vision for DFAB HOUSE was to combine research from seven NCCR-affiliated ETH professorships in a single NEST Unit and realise it in collaboration with more than 40 industry partners. The three-and-a-half-year project timeline included: 1) investigating the application potential of NCCR research; 2) synthesising research into novel building processes, termed Innovation Objects; 3) conceptualising their role in the overall architectural project; 4) upscaling to application-ready state; and 5) constructing the building.

State of Digital Fabrication Demonstration
Architectural demonstrators allow research to be turned into a technically mature application outside of market constraints. Prior to DFAB HOUSE, digital fabrication research demonstration has largely been limited to single-storey pavilion structures focusing in-depth on one digital fabrication system. Seminal examples are the University of Stuttgart's ICD research pavilions, including the LAGA exhibition hall (Schwinn et al., 2016), Elytra Filament Pavilion (Prado et al., 2017), and the recent BuGa Wood and Fibre Pavilions (icd.uni-stuttgart.de). In addition, there is a trend towards construction demonstrators of additive manufacturing by industry. Examples are the Chicon House by ICON 3D, housing prototypes by Apis Cor, and 3D Housing 05 by CLS Architects and Arup (Valente et al., 2019). Few full-scale construction projects have integrated digital fabrication, among them the Sequential Roof at ETH Zurich (Apolinarska et al., 2016) and the Théâtre Vidy in Lausanne (Robeller et al., 2017). Otherwise, industry adoption of digital fabrication is currently very limited despite the need for AEC to embrace digitalisation (McKinsey & Co., 2016), and to improve efficiency, waste reduction, on-site safety, and productivity (Bock, 2015; World Economic Forum, 2016; Agustí-Juan et al., 2019). In this context, DFAB HOUSE, a three-storey, permitted and inhabited building, positions itself as today's most comprehensive multi-technology demonstrator of digital fabrication in architecture.

Research Questions
Digital fabrication research today is developing a growing number of tools and methods. However, little research has looked at integrating these technologies in the complex process of planning and constructing fully functional buildings. With respect to DFAB HOUSE, a two-fold research gap remains. First, there is currently no comprehensive description of the process of conceptualising, planning and implementing such a complex architectural demonstrator. Second, there is a lack of critical reflection on the overall project, evaluating both its significance to the field and its challenges. To address this gap, this paper seeks to answer two questions. First, how can a complete habitable building be designed and built primarily using multiple digital fabrication processes? This includes: how can research be scaled up from the lab to real-world 1:1 application? How can several new construction methods be integrated and interfaced? How can research and industry combine their resources and expertise? Second, what lessons are learned from such a project? This includes: how do new possibilities stand up to realistic constraints? How can risk and uncertainties, in terms of budget and schedule, be mitigated? What new forms of collaboration arise in this diverse multi-disciplinary space? This paper presents how DFAB HOUSE delivered an exemplary answer to the first question. It then addresses the second question, reflecting on its larger implications.

Realisation of DFAB HOUSE

Project Scope
DFAB HOUSE subsumed three parallel challenges under a holistic process: design integration, upscaling, and execution. For these tasks, the NCCR established a dedicated project management team.

Design integration included evaluation of the NCCR's evolving body of research in joint workshops with the research groups, Empa, and industry which assessed technology readiness, performance and future market potential. A deliberately open and inclusive design process shaped the overall project, where accommodating unknowns and changes was paramount. The project design intentionally kept interfaces between Innovation Objects simple to contain risk, yet made these interdependencies a subject of study. The use of parametric interfaces to link computational design and structural evaluation helped synthesise the stand-alone technologies into a comprehensive system.

Upscaling was the task of turning research at vastly different levels of development into construction-ready applications. Consortia were assembled early on by

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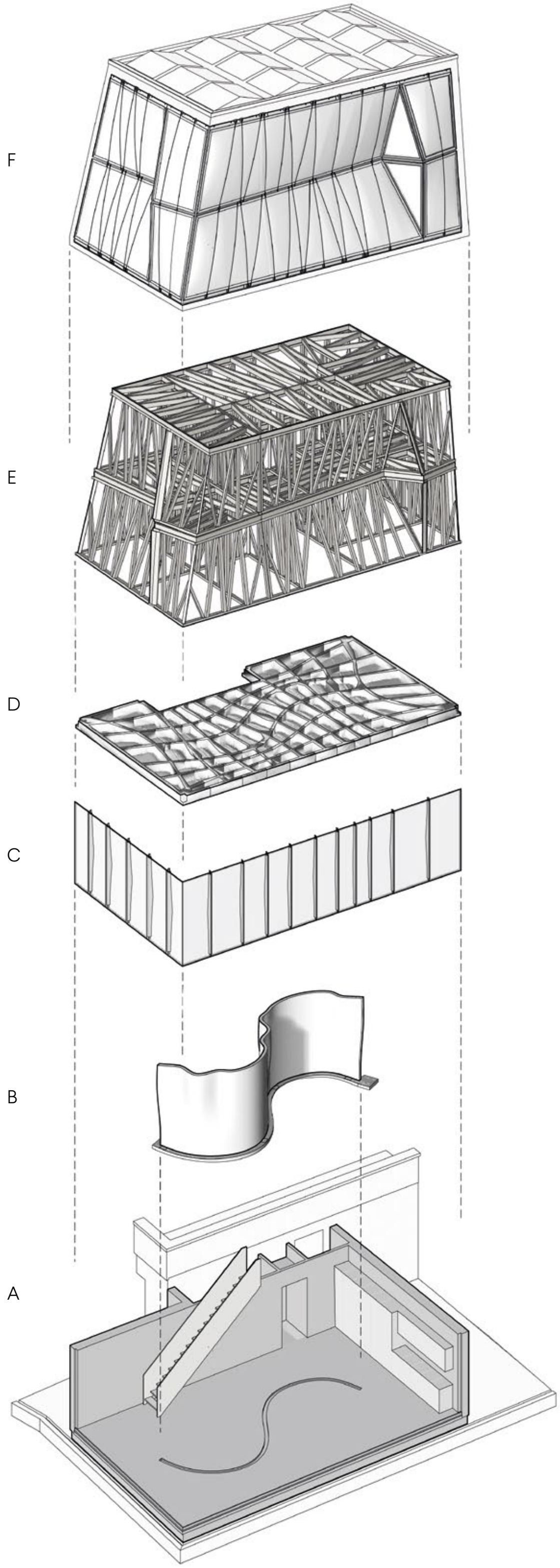
engaging each research group's pre-existing network of industry partners and approaching new partners for DFAB HOUSE. Partnership contracts and agreements were set up to formalise responsibilities and liability. This push to add industry knowledge and expertise enabled full-scale co-development of technically mature applications. Physically proving that regulations, structural requirements and quality standards could be met was essential for approval by the client and authorities, so a dedicated budget was established to cover labour and material for structural tests, material samples and full-scale prototypes.

For execution, digital fabrication workflows were integrated into the reality of the construction practice. This included system design and engineering, technical detailing, design coordination through a central model, and the generation of construction data. Digital fabrication was performed both on site and off site. Importantly, construction contractors, not only researchers, were substantially involved in the execution of DFAB HOUSE. This led to previously untested levels of collaboration, knowledge transfer and risk mitigation between research and executing firms.

Innovation Objects

DFAB HOUSE combines six new digital building technologies, termed Innovation Objects (Fig. 4).

1. The In-situ Fabricator (Fig. 4A) is a generic, context-aware, mobile fabrication robot. Its on-board sensing and computation system allows for autonomous repositioning, end effector localisation, and in-process fabrication



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1. Site installation of Smart Slab segment. Photo: digital building technologies, ETH Zurich / Xijie Ma.

2 & 3. Exterior view of completed DFAB HOUSE. Photo: Roman Keller.

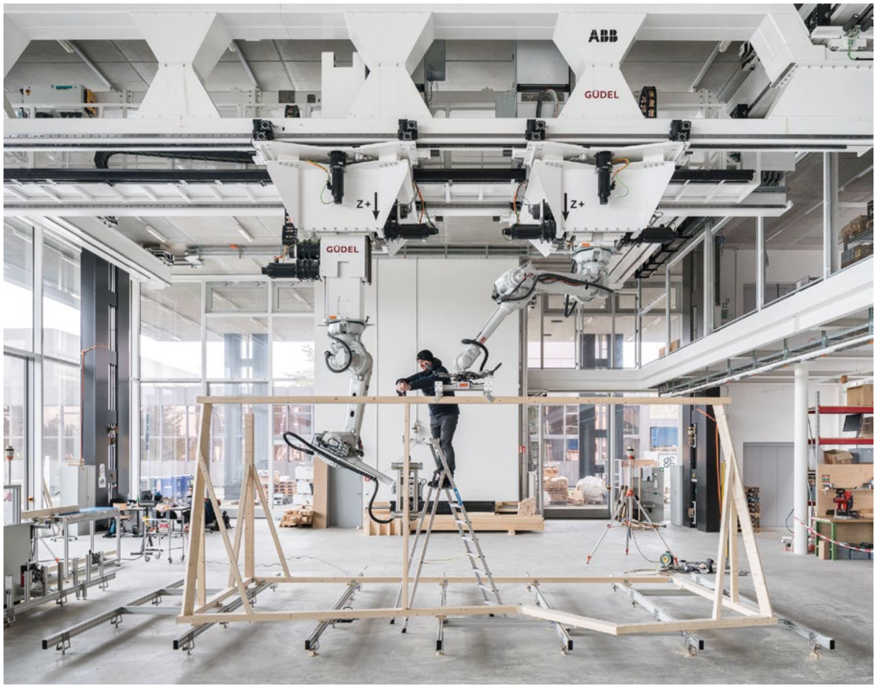
4. Innovation Objects in DFAB HOUSE, diagram. Image: NCCR Digital Fabrication / Konrad Graser.

surveying using camera feedback. A long-term ETH research project, it serves as an instrument to explore robotic on site construction processes. By deploying the In situ Fabricator, DFAB HOUSE is the first construction project presenting robotic in situ fabrication not merely as a future vision but as a reality (Dörfler et al., 2019; Buchli et al., 2018; Lussi et al., 2018; Giftthaler et al., 2017) (Fig. 6).

2. Mesh Mould (Fig. 4B) is a robotically fabricated stay-in-place formwork and reinforcement for waste-free non-standard concrete construction. In DFAB HOUSE, Mesh Mould was implemented as a twelve-metre long undulating load-bearing wall. The In situ Fabricator was equipped with an application-specific end effector. It fabricated a three-dimensional welded rebar mesh sufficiently dense to contain fresh concrete, using manually fed 8 and 6mm standard steel rebar. Added fibres controlled the concrete flow while it was pumped in laterally and then manually trowelled. A 20mm finish layer of shotcrete was applied for fire protection (Hack, 2018; Hack et al., 2017; Kumar et al., 2017; Wangler et al., 2016) (Figs 6, 7, 9, 11).

3. Smart Dynamic Casting (Fig. 4C) is an automated robotic slip-forming process for prefabrication of material-optimised reinforced concrete structures. A small dynamic formwork continuously moves along a vertical axis, shaping the concrete during the critical phase when it changes from a soft to a hard material. The enabling material technology consists of a batch of retarded, self-compacting concrete which is then accelerated in a mixing reactor just before deposition into the moving formwork. 15 individually shape-optimised façade mullions were prefabricated for DFAB HOUSE with Smart Dynamic Casting (Lloret-Fritschi et al., 2018; 2016; Reiter et al., 2018; Scotto et al., 2018; Lloret et al., 2015) (Fig. 11).

4. Smart Slab (Fig. 4D) is a custom pre-cast concrete ceiling slab fabricated with 3D-printed formwork. It adopted large-scale binder jet sand printing to fabricate formwork elements. Eleven post-tensioned segments form a cantilevering slab supported by a grid of curved ribs. The high resolution and geometrical freedom of additive manufacturing broadened the design possibilities of architectural prefabricated concrete. The design was optimised to reduce material volume, resulting in a structure significantly lighter than a comparable conventional concrete slab. The slab integrates electrical and sprinkler systems, as well as sensors for long-term structural monitoring (Aghaei Meibodi et al., 2018; 2017) (Figs 1,8, 9, 11).



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5. Spatial Timber Assemblies (Fig. 4E) is a robotic prefabrication process for non-standard spatial timber structures. The upper two storeys of DFAB HOUSE were fabricated in the Robotic Fabrication Lab at ETH Zurich using two gantry-mounted robot arms, a CNC controlled table saw, and an automated tool changer. Two robots cooperated by alternately placing timber members and acting as temporary support to the three-dimensionally assembled structure. This assembly sequence ensured stability during construction. The pick-cut-scan-place workflow included custom cutting of standard cross-section timber, pre-drilling of screw channels, and spatial assembly. Screw connections were applied manually (Thoma et al., 2018; Adel et al., 2018; Gandía et al., 2018) (Figs 5, 10).

6. Lightweight Translucent Façade (Fig. 4F) is a double-layer pre-stressed membrane envelope system with a compressed aerogel insulating filling, developed specifically for DFAB HOUSE. The system allowed for continuous, non-planar membrane panels, up to eight metres in length, without thermal bridging. The inner membrane was pre-installed on the timber modules off-site while the outer layer was installed in situ before pneumatically filling the cavity with granulated aerogel. The system exemplifies how novel construction systems, such as Spatial Timber Assemblies, can trigger additional development of innovative concepts and constructive solutions (dfabhouse.ch) (Figs 2, 3).

5. Spatial Timber Assemblies at ETH Zurich Robotic Fabrication Lab. Photo: Roman Keller.

6. On-site fabrication of Mesh Mould by in situ Fabricator. Photo: Gramazio Kohler Research, ETH Zürich.

7. Mesh Mould wall after concreting. Photo: Gramazio Kohler Research, ETH Zürich.

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Implementation Challenges

Due to the lack of technological precedence, Innovation Object development and integration did not follow a linear process. The following examples detail several challenges that shaped the project.

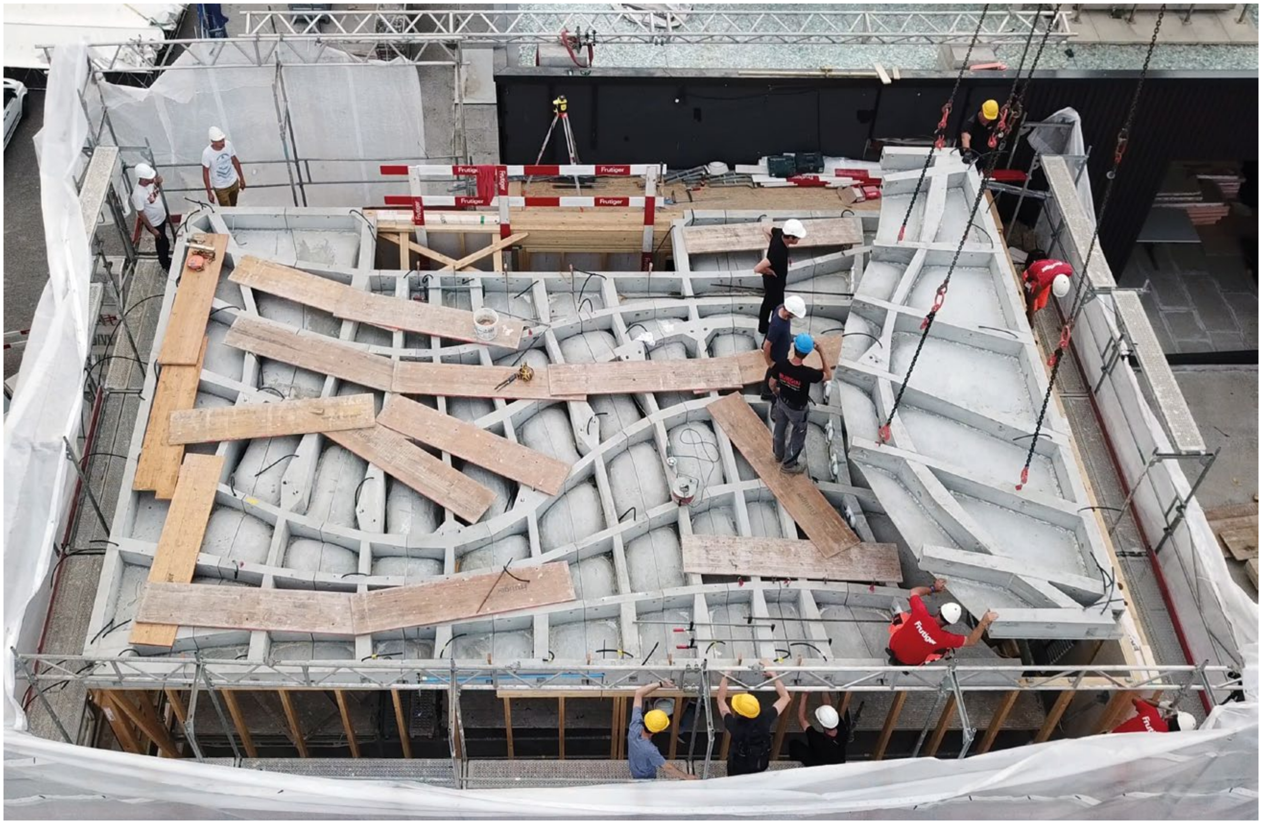
Mesh Mould best illustrates the challenges of meeting performance goals. The In situ Fabricator's reach limitations and weight predetermined the wall's ground level location. This resulted in high structural loads, calling for extensive load tests with standardised material samples. Rebar cross-sections increased, requiring a challenging full redesign of the robotic end-effector (Kumar et al., 2017). Production time was also an issue. The fabrication sequence was changed from a horizontal to a vertical build-up to reduce time-consuming repositioning steps. In addition, increasing the mesh size reduced the welding point count, cutting production time significantly over earlier versions. In the end, Mesh Mould achieved a high level of application maturity and inspired additional follow-on studies as the case studies for productivity (García de Soto et al., 2018) and sustainability impacts (Agusti-Juan et al., 2019; Mata-Falcón et al., 2019) of digital fabrication in construction.

In applying Smart Dynamic Casting, new problems arose regarding adjustments to the technology for material optimisation. Minimising mullion cross-sections increased material friction due to a greater ratio of formwork surface to concrete volume (Szabo et al., 2018). In addition, structural reinforcement was required. This combination required a highly fluid material to avoid void zones in the final structures. Variations in the raw materials further heightened the challenge. The resulting need for material adaptations required new research. This research continues with observation of the long-term behaviour of the newly developed material by sensors installed in DFAB HOUSE (Lloret-Fritschi et al., 2018; Marchon et al., 2018; Reiter et al., 2018).

The design integration of Smart Slab and Spatial Timber Assemblies exemplifies the challenge of coordination across system interfaces. To achieve an optimal structural system, the systems were linked parametrically in an early design stage. While driven by different research groups, technologies and material constraints, both systems were structurally and architecturally co-developed. This complex design interdependence required a time-intensive iterative process involving researchers, project engineers and executing parties, highlighting a need for more efficient workflows for optimisation across multiple non-standard structural systems.

In addition to these technical intricacies, DFAB HOUSE also faced organisational challenges. During fabrication, schedule and budget were more easily met by highly integrated processes such as Mesh Mould or Spatial Timber Assemblies. However, Smart Slab presented a greater challenge as it paired high complexity with more discrete production steps by independent suppliers. This shows that questions of process organisation and integration, not just technology, need to be addressed for digital fabrication to be effective.

Permit issues also posed limits. The fire code, for example, was a governing factor in the dimensioning of all primary building elements. However, performance testing of digitally fabricated components could help push structural efficiency beyond the level achieved in DFAB HOUSE.



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Communication challenges and conflicting priorities were present throughout the project, both between disciplines and between academic research and professional practice. Many formats of close collaboration helped overcome them, resulting in new forms of shared practice between the more than one hundred project participants, including over forty ETH researchers and technicians. Follow-up research by García de Soto et al. (2019) and Graser et al. (2019) has drawn early conclusions from this experience and pointed out vast future research potential.

Research Evaluation and Discussion

DFAB HOUSE has implications on multiple levels. First, DFAB HOUSE exposed digital fabrication to reality. It built upon the premise that full-scale construction in a real environment is a necessary step to better understand what digital fabrication enables us to do – and what its limitations are. It tested technical feasibility, structural safety and durability of digitally fabricated systems, building trust in their applicability. Perhaps more important, DFAB HOUSE exposed research to building regulations and both production and management limitations. Embedding 'boundless' research in the context of practice in this way is the first step to moving demonstrated technologies from research to innovation and thus broader adoption. In addition, it has raised new research questions.

Second, DFAB HOUSE required new forms of collaboration. Its management encompassed multilateral negotiation but also focused on architectural design integration and collective solution-finding on many levels, generating interdisciplinary and inter-organisational shared knowledge in the process. The forms of collaboration and co-authorship that emerged over the course of the project indicate the integration processes needed to implement digital fabrication successfully in the future: breaking down information silos, both in research and practice; developing a common language to communicate across discipline boundaries; including new stakeholders from outside AEC and their knowledge; and establishing new networks and communities of practice.

Third, DFAB HOUSE and its underpinning research aimed to rethink the process of design and building on a fundamental level, rather than adhering to business as usual. It shows how the collective development of

8. Smart Slab during installation. Photo: digital building technologies, ETH Zurich / Andrei Jipa.

9. Completed project lower level – interface of Mesh Mould wall and Smart Slab.

10. Completed project upper level – Spatial Timber Assemblies.

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processes by multiple disciplines in academia and industry can change the quality of research and practice, and create new, original solutions. Creating a physical building showed digital fabrication to be a viable concept for construction (Figs 9, 10, 11). It reframed the discourse on digital fabrication, refocusing it from a debate about technical feasibility to broader concerns about integrating its processes, its consequences in the workplace, and its value to both the AEC community and society more broadly.

The findings of this single case require additional investigation. Open questions remain in four areas in particular. First, DFAB HOUSE indicates resource saving potential on a conceptual level, but designing for digital fabrication to achieve optimal sustainability performance remains a future challenge. Second, all Innovation Objects combine digital with manual tasks but these examples hardly exhaust the theoretical possibilities. The topic of cost-benefit of automation and potential new models of man-machine collaboration offer vast opportunities for future research. Third, digital fabrication effectivity depends not on technology alone, but also on organisation and workflows. More research is required to better understand this relationship. Fourth, DFAB HOUSE offered practical lessons in interdisciplinary collaboration for digital fabrication, but important questions remain about how to best codify and preserve the resulting collective knowledge.

Conclusion

This paper summarises the interdisciplinary research and development of DFAB HOUSE and the role digital technologies played in its realisation. In addition, it describes the process of the project's realisation and details constraints, challenges and forms of collaboration. It discusses implications and limitations of this single case. It concludes that DFAB HOUSE offers new perspectives on how to implement digital fabrication in the AEC domain and opens up avenues for further research.

Acknowledgements

DFAB HOUSE and the research it demonstrates were funded by the Swiss National Science Foundation, ETH Zurich and Empa, and supported by more than 40 industry partners. DFAB HOUSE is the collective achievement of many project collaborators.

Principal investigators:
Prof. Dr Jonas Buchli, Prof. Dr Benjamin Dillenburger, Prof. Dr Robert Flatt, Prof. Fabio Gramazio, Prof. Dr Guillaume Habert, Prof. Dr Walter Kaufmann, Prof. Matthias Kohler, Prof. Dr Joseph Schwartz

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Giulia Adagazza, Dr Mania Aghaei Meibodi, Arash Adel, Isolda Agustí Juan, Julio López Alonso, Dr Aleksandra Apolinarska, Dr Marco Bahr (DRSC AG), Marco Baur, Dr Mathias Bernhard, Pascal Breitenstein (ERNE AG Holzbau), Gonzalo Casas, Tanja Coray, Prof. Dr Kathrin Dörfler, Philippe Fleischmann, Hans Flückiger (Zühlke Group), Reto Fischer (Empa), Lukas Fuhrimann, Augusto Gandía, Rena Giesecke, Dr Markus Giftthaler, Florian Goecke (Seele Cover AG), Konrad Graser, Prof. Dr Norman Hack, Matthias Helmreich, Blanca Hren, Dr René Jähne, Andrei Jipa, Orkun Kasap, Dr Thomas Kohlhammer, Dr Nitish Kumar, Alexander Kummer, Matthias Leschok, Dr Andrew Liew, Dr Ena Lloret-Fritschi, Michael Lyrenmann, Dr Russell Loveridge, Manuel Lussi, Dr Jaime Mata-Falcón, Enrico Marchesi, Jesus Medina, Melina Mezari, Dr Ammar Mirjan, Matteo Pacher, Samuel Rebelo García, Dr Lex Reiter, Andreas Reusser, Heinz Richner, Dr Peter Richner (Empa), Daniel Rönz (ERNE AG Holzbau), Nicolas Ruffray, Dr Timothy Sandy, Dr Daniel Sanz Pont, Maximilian Seiferlein, Sarah Schneider, Fabio Scotto, Dr Linda Seward, Demetris Shammas, Lukas Stadelmann, Andreas Thoma, Nicola Vasic, Alexander Walzer, Dr Timothy Wangler, Thomas Wehrle, as well as many others who have contributed their skills and support.

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