A Qualitative Technology Evaluation Scoreboard for Digital Fabrication in Construction

Konrad Graser[a], Jens Hunhevicz[a], René Jähne [b], Alexander N. Walzer[a], Fabian Seiler[a], Roman Wüst[a], Daniel M. Hall[a]

[a]Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, Switzerland
[b]National Center of Competence in Research Digital Fabrication, ETH Zurich, Switzerland
E-mail: graser@ibi.baug.ethz.ch

Abstract –

Adoption of digital fabrication (dfab) in AEC promises great advantages in productivity, sustainability, and new design and delivery opportunities. Companies are interested in adopting dfab, but lack an overview of emerging dfab technologies and their use potential, as well as tools to evaluate their match with the own needs and business interests. Based on a qualitative analysis of five emerging dfab technologies, we developed an easy-to-use scoreboard to guide firms' decision-making when adopting dfab technologies towards industrial implementation.

Keywords

Digital fabrication, additive manufacturing, technology transfer, technology adoption

1 Introduction

Adoption of computationally driven manufacturing in the AEC industry, commonly called digital fabrication (dfab), promises great advantages in productivity, sustainability, and new design and delivery opportunities. 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 [1]. Particular attention is given to dfab technologies for additive manufacturing using concrete, the world's most-used building material by volume and a major contributor to global CO2 emissions. Many such dfab technologies are currently developed worldwide in research centers but these are often in pre-commercial development stages (e.g. in demonstrators or exploratory pilot projects). Overall adoption of advanced dfab technologies by industry is lagging due to challenges with technology transfer from research to industry.

For firms in search of innovative technologies to bring to market, the diversity of potential solutions presents a challenge. Companies with interest in adopting dfab lack an overview of emerging dfab technologies and their use potential, as well as tools to evaluate their match with the own needs and business interests.

In this study, we seek to understand the relevant key parameters of interest for such an evaluation tool, particularly in the case of additive concrete dfab technologies. Our assessment is based on researcher and industry interviews at the Swiss National Center of Competence in Research (NCCR) dfab, a leading dfab research center. We synthesized our findings in an evaluation framework to create a comparative overview of dfab technologies and assess the prospective users' needs. Based on this framework, we developed an easy-to-use scoreboard to guide firms' investment decisions in further R&D aiming at adopting dfab technologies towards industrial implementation.

2 Point of departure

In many industries, the shift toward digitalization and automation has fueled the development of new processes, new products, and an increase in productivity. By contrast, the AEC sector has lagged in automation and digitization in the past decades [2]. With the shift of the AEC sector towards industry 4.0 now accelerating, dfab technologies are on the rise in construction [3]. Dfab can contribute to increasing productivity and sustainability in AEC by its potential to improve construction quality and speed, workplace safety, waste reduction, and resource efficiency [4]–[6]. After roughly two decades of experimental research in construction-scale dfab, a variety of dfab technologies are now approaching maturity levels sufficient for industry implementation. Evidence of this can be seen in an increasing range of additive production methods developed by several research centers and companies worldwide, encompassing a multitude of materials and processes [7], [8]. However, industry uptake of advanced dfab technologies is still slow, despite their many potential advantages. Adoption is lagging due to challenges with technology transfer from research to industry [9], [10].

This transfer challenge has multiple reasons, but we found the following two of particular importance in the context of the NCCR dfab. First, for firms in search of innovative technologies to bring to market, the diversity of potential solutions presents a challenge. Second, firms lack an overview of the application potential of emerging dfab technologies, and tools to evaluate their match with the own needs and business interests.

Little research has looked into how to overcome these challenges by systematically matching industry needs and technology properties. In order to address this, we ask the following questions:

- What are properties of dfab technologies that matter for industry?
- How can these properties be generally described in a manner so that firms can evaluate and compare dfab technologies?

3 Research method

3.1 Methodology

Dfab in AEC is a nascent research area where quantifiable data is lacking. Therefore, we chose a qualitative research approach. Grounded Theory (GT) is a common qualitative method well suited to investigate our stated research aims [11]. GT is based on the analysis and categorization of qualitative data, such as interviews, notes, and observations. The qualitative data is analyzed in an inductive "open coding" process in which relevant categories are developed directly from the content of the data rather than from pre-existing theory or hypotheses. Theoretical sampling, i.e. the targeted collection of additional data as the theory develops, allows the researcher to focus the inquiry on data that has relevance in the area of study. The focus of the method is on developing a system of categories in order to develop theory from qualitative case [12].

3.2 Data collection

We conducted a total of ten semi-structured interviews. First, through our network, we identified five technologies of interest and initial contact persons for each technology. Then, in a first round, five interviews were led with six researchers leading dfab technology developments (one interview per technology). Interview questions aimed at understanding the technologies, the processes and the properties of their results, along with implementation limitations and opportunities. In a second round, five additional interviews were led (two additional researcher interviews, one industry partner, one external technology consultant, one industry expert not directly related to the technology research). The second set of interviews served to better understand more specific technical aspects, industry needs, and future development potential towards industrial processes. The interviews were recorded and transcribed with the interviewees' permission.

Relying on more than one data source is important to ensure the validity in qualitative research [13]. For this reason, the interviews were complemented by direct observation of processes and analysis of images and video recordings of experiments (due to Covid-19 restrictions, some direct observations had to be cancelled and were replaced by the analysis of video material). In addition, the review of scientific publications on the technologies contributed to a more complete understanding.

3.3 Data Analysis

The collected data was analyzed to distill relevant evaluation criteria to assess and compare the different dfab technologies. In a first step, we investigated the data for different recurring topics of importance. Out of this, we identified a first set of categories with which we sorted the dataset. In a next step, the information was compared, discussed and interpreted. This inductive process led to a first comparative overview of parameters relevant to the dfab processes and/or the resulting products. Through further iterative consolidation and refinement of the parameters, a set of eleven key parameters emerged that reflected the important aspects of the dfab technologies found in the data. These key parameters were summarized and classified in the presented evaluation framework. To make the framework applicable for industry, we developed a scoreboard to help industry rate their own needs and compare these needs to the characteristics of available dfab technologies.

Preliminary validity checks were performed with industry partners and the involved research teams of the assessed dfab technologies to see whether the proposed framework and scoreboard can accurately reflect their point of view.

4 Evaluated dfab technologies

4.1 Overview

This study evaluates five experimental manufacturing technologies currently under development at ETH Zurich. Albeit these technologies have certain similarities (e.g. they are all forms of additive manufacturing with concrete), there is a great variance in their processes and properties. As such, they can be classified as following under three categories: direct extrusion, 3D-printed formwork and slip-forming. To understand, compare and develop generalizable evaluation criteria, the respective technologies will be explained in the following chapters.

4.2 Description of technologies

4.2.1 Example 1: Direct Extrusion of Concrete

Concrete 3D-printing is directly layering small-aggregate concrete or mortar. The resulting layer thickness is usually in the range of a few centimeters. Here, a special concrete mix is needed: malleable enough to be extruded and adhere to the previous layer, yet firm enough to be able to support its own weight as well as the weight of the subsequent layers. To achieve this, accelerators are typically added at the extrusion point (nozzle) when printing the concrete to precisely control the setting behavior. Adding reinforcement in the layered is a challenge not yet fully resolved. One approach to achieving structural performance is to print cavities to place reinforcement and cast conventional concrete, using the printed concrete shell as lost formwork.

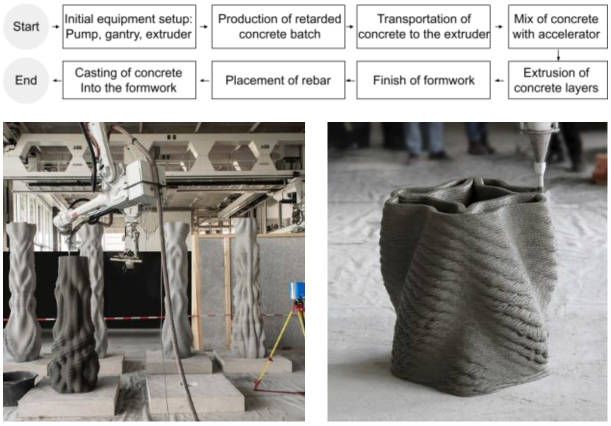

Figure 1. Concrete extrusion printing, process map and production images (credit: digital building technologies, ETH Zurich)

4.2.2 Example 2: FDM 3D-printed formwork

In this example, FDM technology is used to produce concrete formwork for complex shapes from thermoplastic material. After printing, the formwork is placed in a container filled with either sand or water simultaneously while pouring the concrete to overcome hydrostatic pressure. Self-compacting concrete is used to avoid possible damage of the thin formwork due to vibration. For stabilizing the formwork, printed support structures can be used. Generally, the formwork is destroyed during removal. Depending on the filament used, the material can be recycled and re-used for formwork printing. For more complex or fragile shapes, a dissolvable formwork material can be used, such as Polyvinyl Alcohol (PVA), a water dissolvable and biodegradable material [14].

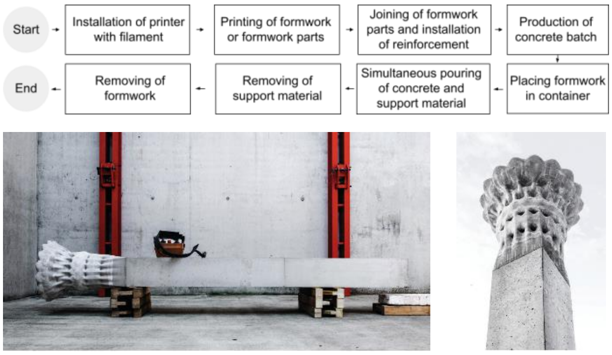

Figure 2. FDM formwork process map and results (credit: digital building technologies, ETH Zurich)

4.2.3 Example 3: Simultaneous FDM 3D-printed formwork

A system named “Eggshell” combines 3D-printing of thermoplastics (FDM) for formwork but pouring concrete simultaneously. By using set-on-demand concrete, hydration is controlled precisely during construction, reducing the volume of poured concrete in its fluid state at any given time. This minimizes the hydrostatic pressure, allowing for the use of thin-walled, material-saving formwork. Once the concrete is hardened, the formwork is removed and recycled [15]. The system allows standard reinforcement to be placed before or after casting and the use of post-tensioning in a post-production step.

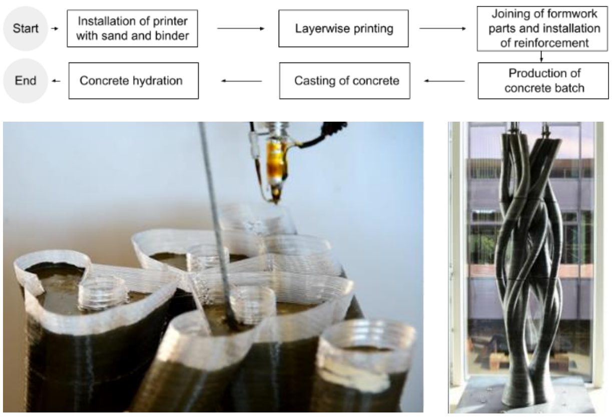

Figure 3. “Eggshell” process map and production (credit: Gramazio Kohler Research, ETH Zurich)

4.2.4 Example 4: Binder jet 3D-printed formwork

In this example, the process of binder jetting layers powder material (often sand) over a workable area and selectively bonds it using particular agents. Repeating this process several times leads to creating a 3D structure with sub-millimeter resolution. During printing, the powder bed acts as a support structure, allowing for overhangs and internal voids. Through the process of selectively binding, binder jetting has the great advantage of not demanding an auxiliary support structure. At the end, the unbound material is removed and can be re-used [16]. The printed form acts as a stay-in-place or removable formwork which can be filled with a self-compacting concrete or shotcrete and reinforced conventionally and/or with the use of fibers.

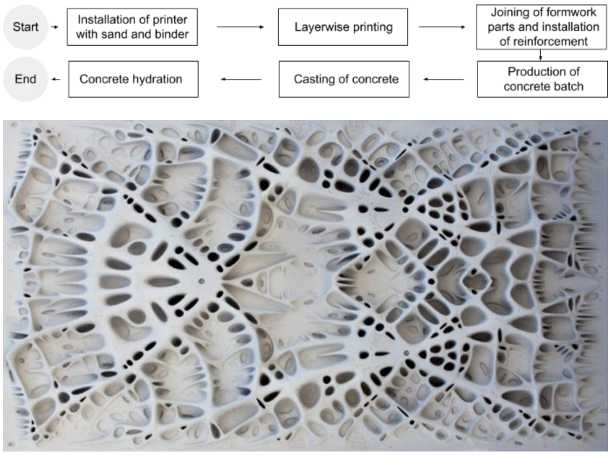

Figure 4. Process map and result of binder-jet printed formwork (credit: digital building technologies, ETH Zurich)

4.2.5 Example 5: Concrete slip-forming

Smart Dynamic Casting (SDC) is a small-scale concrete slip-forming process allowing for changing cross-section during the forming process by means of a flexible or movable formwork [17]. SDC uses a computational interface to integrate slip speed, material feed and cross-section change. A set-on-demand concrete mix is used to control material setting at an exact and predictable point in time. SDC allows for the waste-free fabrication of bespoke concrete columns and reinforcement is placed prior to slipping. The technology was demonstrated to fabricate 15 bespoke mullions for DFAB HOUSE [18].

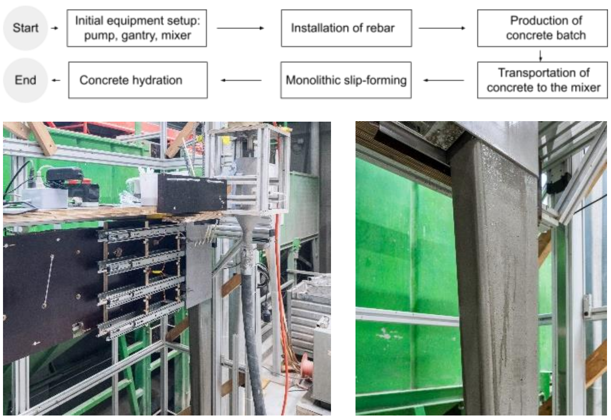

Figure 5. SDC process map and production (credit: Gramazio Kohler Research, ETH Zurich)

5 Results

5.1 Evaluation framework

We identified eleven parameters relevant to evaluate the match of a given dfab technology with a prospective user's needs. We also found three clearly distinguishable top categories under which to group these parameters: resources required by the process, the final product properties, and manufacturing at the interface between the product and processes (Fig. 6). The following subsections detail the categories and key parameters.

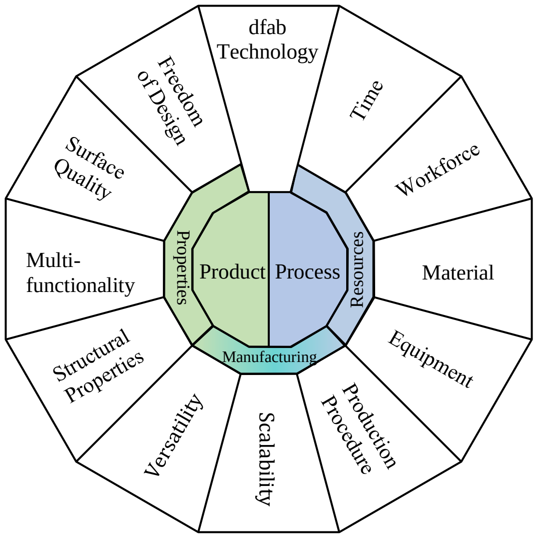

Figure 6. Evaluation Framework

5.1.1 Properties

Product properties strongly influence the application potential of dfab technologies. We identified four parameters pertaining to the finished product properties.

Freedom of Design – Dfab technologies can achieve a higher flexibility in design compared to traditional means of construction, where non-standard, geometrically complex design elements are typically material-, time- and cost-intensive. Typical design examples are undercuts, internal voids or cantilevers. Still, dfab technologies vary in the degrees of freedom they allow. Therefore, freedom of design can strongly determine the possible uses of a dfab technology.

Surface Quality – Surface quality affects durability for exterior elements, dimensional imprecisions can preclude use of the technology where tight tolerances are required, and the visual surface quality can be decisive for architectural applications. In the investigated dfab technologies, surface quality differs largely, displaying a rough, layered appearance, a microstructure from 3D printed formwork, a smooth extruded or a customized finish. Surface quality is specific to each dfab process and affects both performance and market acceptance.

Multifunctionality – Dfab allows the construction of multi-functional building elements that combine varying functions such as structural stability, insulation, electrical or HVAC integration, and acoustics and daylighting. Examples are an anti-slip surface on a concrete stair, or the use of internal voids for the integration of building systems in a slab to reduce build-up height. Multifunctionality depends on the properties of the dfab application and can be a significant value-add.

Structural Properties – Dfab allows optimizing geometry precisely for specific load cases. This can increase structural efficiency and reduce material consumption. However, structural properties of concrete products are also highly affected by the type of reinforcement, which can be challenging to integrate in an additive concrete dfab. Options include ductile (e.g. fiber-reinforced) printing material, pre-placed rebar, post-tensioning, or adding reinforced concrete in pre-printed voids. Concrete dfab products vary in structural performance and therefore in their potential application.

5.1.2 Resources

A quantitative understanding of construction speed and cost is an important decision-making factor for early adopters when comparing dfab technologies and conventional construction processes. This is generally described by productivity, which measures output for a given input [19]. The input is mostly denoted in either time or total costs, which in itself usually contains workforce, material, and equipment costs. In addition, to estimate and optimize resource requirements more precisely, a qualitative understanding of the dfab process and its individual steps is important.

Time – Labor productivity is one of the most frequently used productivity measures in construction, since labor is usually the driving cost factor [20]. Accordingly, output per unit of time is an important factor for the industry adoption potential of a future industrial dfab process. However, additional factors need to be considered, since processes are a combination of automated and manual tasks [6]. E.g., for the analyzed additive processes, total production time consists of the processing speed dictated by the technology, equipment preparation (set-up and calibration), material preparation (formwork, concrete or reinforcement), manual tasks (formwork assembly, placing of reinforcement or casting of concrete), and concrete curing time.

Workforce – Dfab offers potential to increase process automation and reduce process supervision requirements, impacting both labor costs and the required skillset of the workforce [21]. Therefore, despite uncertainties due to the early technology development stage, workforce is a key parameter for dfab adoption.

Material – Dfab technologies tend to be highly dependent on material properties. In the additive dfab technologies, the primary mortar or concrete material used is highly specific to each technology, with processing steps strictly coordinated based on the material properties. In addition, formwork print materials require equal consideration. Overall, material properties affect production speed, cost, and sustainability.

Equipment – Dfab technologies require specific production equipment, varying widely in complexity and ease of use. The investigated types of dfab exemplify this: direct extrusion requires a feed system and a mortar extrusion nozzle attached to a robot; printing formwork requires a filament or binder jet printer; slip forming uses a movable formwork and automated feed system. Furthermore, systems require differing degrees of integration between the individual parts controlled by integrated software, e.g. between the formwork printer and casting system, or the reinforcement and production system. Equipment is a central agent of dfab and a major cost-driver relevant for adoption decisions.

5.1.3 Manufacturing

The Manufacturing category subsumes key parameters of the manufacturing technology itself, pertaining to both the process and the resulting product.

Production Procedure – The production procedure is determined by the complexity of the manufacturing technology. Factors this complexity include the set-up of the production site, the number of required production steps, and the number of independent suppliers. Some technologies offer alternative sequences, such as pre-printing vs. simultaneous printing of a formwork or different reinforcement options. Understanding the production procedure is relevant for assessing the ease of adopting a technology and integrating it into established workflows and existing supply chains.

Scalability – Understanding scalability is a key parameter in technology adoption decisions. It describes whether a technology can be scaled in physical size, production volume, and product range for industrial production. Upscaling typically requires changes to the manufacturing set-up, e.g. to handle large material quantities, ensure robustness, and enable variation. As a result, the full-scale production process may differ substantially from earlier developments. Factors inherent in each dfab technology can hinder or enable upscaling.

Versatility – Versatility measures the potential of a dfab technology to produce different results and process different materials. Typically, early-stage dfab technologies are first implemented in exemplary prototypes or proof-of-concept applications. By default, these implementations do not cover all future capabilities of an emerging technology. Since some technologies offer a wider set of future applications, the number of manufacturing options a dfab technology affords could strongly affect the adoption potential.

5.2 Technology positioning scoreboard

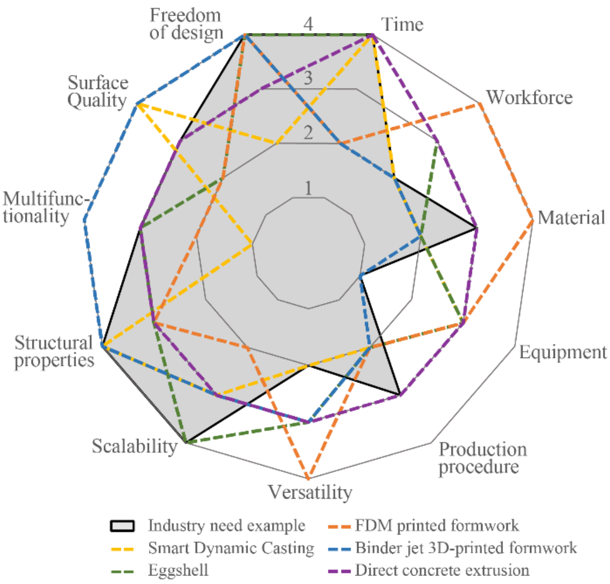

Figure 7. Radar chart showing comparison of several technologies and industry need

Based on the evaluation framework, we designed a scoreboard to easily assess prospective dfab adopters' needs and market demands for a specific use case, and to evaluate them against a range of potential technology solutions for further development towards successful industrial application. We developed a detailed four-point rating scale for each of the eleven key parameters to provide a balanced evaluation of both potential product properties (what is the quality and function of the product) and process factors (how does the process work and what resources are required). The tool creates an easily readable radar chart to compare the user's own demands with potential new technology solutions, or to compare several technologies to each other (Fig. 7). The complete table of scoring categories for each key parameter is shown in the Appendix.

In a subsequent step, the scoreboard was tested by the researchers developing the five technologies by rating their own technology using the scoreboard. For comparison, one industry partner not directly related to the research was asked to rate their process independently. Fig. 6 illustrated the result of the scoreboard testing. The industry rating (continuous line) represents the industry needs perspective, while the technology self-assessment by technology developers (dashed lines) opposes the range of available technologies. Therefore, the chart can support the industry participants in choosing one or several technologies for further consideration.

6 Discussion

6.1 Contribution and relevance

The contribution of this paper is a high-level, qualitative tool that serves to identify 1) industry needs, and 2) technology capabilities in the context of early-stage development of dfab for construction. The proposed framework and scoreboard are an attempt to provide technology providers and prospective adopters with the simplest possible way to understand and compare complex and developing technologies. The eleven categories should enable them to assess the complete picture and respective trade-offs between different dfab alternatives versus traditional construction processes. Albeit informed by the analysis of a limited range of examples, the framework is intended to be applicable also more generally across emerging technologies, materials and processes.

While the current tool allows a qualitative rating of all categories, the parameters relating to resources could be quantified. This has been done for early-stage dfab, e.g. in the productivity assessment by Garcia de Soto et al. [6]. However, quantifying the productivity of early-stage technologies necessarily leaves out qualitative factors that may bear potential to improve the future productivity of a technology regardless of current inefficiencies. There is great potential for future research to unify the qualitative and quantitative perspectives.

Future development scenarios of the scoreboard include an open-access online tool available to both industry and technology developers for self-assessment. In the longer term, the rating tool could be combined with a database of recorded technology and needs ratings.

6.2 Limitations

This is a purely qualitative study. In this early research phase, we only evaluated five exemplary technologies in one research center, and we studied only one class of dfab technologies, additive concrete manufacturing methods. While the variance in the technologies and processes allowed for some preliminary conclusions, a more diverse sample of technologies should be analyzed going forward. A quantification of some of the categories (e.g.

productivity measures) would further strengthen the research going forward and allow users of the framework a more informed decision making process. In addition, we see the need to expand the rating system to include more explicit sustainability parameters to reflect the increasing significance of this topic in technology investment decisions.

7 Conclusion

This research presents a preliminary industry evaluation tool for advanced dfab technologies to guide their investment decisions. We developed the framework with eleven evaluation categories by analyzing five different additive concrete dfab technologies using grounded research methodology. We then condensed this in a simple evaluation scoreboard to help industry compare their own needs with potential dfab technologies to meet them. While the tool with its categories is intended to work in a generalized way for various dfab technologies, this needs further verification through more research.

Acknowledgement –

Funding for this research was provided by BASF Schweiz AG.

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Appendix: Key parameter scoring categories

Freedom of Design	1	low - 1 type of geometry, no degrees of freedom	only one type of geometry can be produced with limited variations
	2	moderate - 2 degrees of freedom	only one type of geometry can be produced but more than 1 degree of freedom can be adapted (e.g. height and diameter)
	3	high - multiple degrees of freedom	customizable geometry (e.g. cross-section, height, custom angles, etc.)
	4	very high - all geometries possible	multiple types of geometry can be produced with multiple degrees of freedom, e.g. free-form, one-off geometries
Quality	1	low - high geometrical variations	very low quality (e.g. very high variations in geometry relative to model >10%, low surface quality (underground))
	2	moderate - moderate geometrical variations	moderate quality (e.g. variations in geometry relative to model <5%, low surface quality)
	3	high	quality and tolerances of high quality, e.g. architectural finish
	4	very high - no variations	very small dimensional variations relative to model, better surface quality than feasible with state-of-the art technologies
Multifunctionality	1	no function integration	no additional function
	2	partial function integration	little/peripheral additional functions, surface patterns
	3	high functional integration	integration of a central/substantial function
	4	fully integrated system	fully integrated system (e.g. plumbing, electricity, …), multiple functions
Structural properties	1	low - e.g. underground	low structural performance, additional reinforcement required to provide load bearing capabilities
	2	moderate - e.g. partition wall	moderate structural performance, e.g. load-bearing wall for single-story structure or non-loadbearing wall
	3	high - e.g. column, load-bearing wall	good structural performance , e.g. load-bearing column, walls or shear walls
	4	very high - highly optimized structures	High-performing structure with optimized properties according to loading scenario; e.g. graded assemblies, material-optimized structures
Scalability	1	low	not scalable in geometry and mass
	2	moderate	scalable in either geometry or mass
	3	high	scalable to multiple components / a family of products
	4	very high	scalable to almost any product
Versatility	1	low	only one specific application possible
	2	moderate	one specific application with variations possible
	3	high	different applications possible (e.g. columns, walls, façade panels)
	4	very high	almost any application possible (fully versatile tool that can process multiple materials)
Production procedure	1	complex	lots of steps and support structures required, multiple independent suppliers/contractors
	2	moderate	moderate number of steps and support structures required, some specialized materials/sources
	3	simple	simple process with small number of production steps, little additional support structures required
	4	very simple	very few production steps, no additional support structures, fully integrated supply chain
Equipment	1	highly complex	highly complex equipment required (e.g. high investment costs, highly skilled labor required, frequent maintenance)
	2	complex	complex equipment required (e.g. moderate investment cost, substantial training of workers required, maintenance)
	3	moderately complex	specialized equipment required; can be operated by workers with little additional instruction or training, moderate maintenance costs
	4	not complex	no complex equipment required; no additional training required, no specialized skills required to operate
Material	1	very expensive	very high material costs (e.g. unique superplasticizer required)
	2	expensive	high material costs (e.g. multiple additives required)
	3	moderate	moderate material costs (e.g. special concrete mix)
	4	cheap	low material costs (e.g. no special mixes, recycled materials can be used)
Workforce	1	very high	highly labor intensive
	2	high	requires manual tasks and/or permanent supervision
	3	moderate	low/occasional manual tasks, moderate supervision
	4	low	fully automated with minimal supervision
Time	1	very high	fabrication time substantially higher than usual
	2	high	fabrication time higher than usual
	3	moderate/neutral	fabrication time slightly higher or equal than usual
	4	low	fabrication time lower than usual