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Qualitative technology evaluation of digital fabrication with concrete: Conceptual framework and scoreboard

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ABSTRACT

The adoption of digital fabrication with concrete (DFC) has the potential to bring sustainability, productivity, and process innovation to the construction industry. However, DFC adoption towards market-ready construction systems is lagging due to a lack of understanding in matching its technology capabilities with the needs of potential adopters. This paper describes a DFC Evaluation Framework, analyzing current advancements in DFC through a Conceptual Framework Analysis. The framework is focused on the inputs, process parameters and outcomes of a given technology solution independently of the enabling technology type. It can be used to classify and compare DFC technologies along their systemic characteristics, which are both technical and non-technical in nature. The DFC Scoreboard, an interactive tool to match DFC technologies with the needs of prospective adopters, is developed and tested based on the framework. The paper discusses how the DFC Evaluation Framework and Scoreboard offer one of the first systemic overviews of DFC adoption, with the capability to match technology capabilities and user needs in the technology adoption process.

1. Introduction

Digital Fabrication 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]. Recently, there has been a steady rise in interest for the application of digital fabrication technologies with concrete (DFC), including approaches such as 3D printing of building components, 3D printing of concrete formwork, automated slip forming, and other forms of digitally controlled processing of concrete materials. After roughly two decades of experimental research in construction-scale DFC, various DFC technologies are approaching maturity levels sufficient for industry implementation. Currently, an expanding range of additive production methods is being developed in research and companies worldwide, encompassing a multitude of materials and processes [2–6]. Furthermore, a growing number of full-scale demonstrator projects showcase various DFC technologies, in both on-site and prefabrication applications [7–9].

Wider-scale adoption of DFC could have multiple important implications for the construction industry. Concrete is the world's most-used building material by volume and a major contributor to global CO2 emissions [5]. The awareness of the environmental impact of concrete production is rising, and there is growing attention to more material-efficient construction methods [10]. DFC promises improvements in this resource-intensive sector through its ability to reduce material volume used in concrete construction. DFC can economically produce tailored, structurally optimized shapes [11,12] through the use of advanced material technology [12–14], resulting in better-than-conventional overall system sustainability at the building scale [15]. In addition to reducing embodied carbon emissions, DFC has considerable potential to eliminate construction waste through the elimination of material-intensive formwork and support structures [11,12,16] and increase the productivity of the industry [14,17–19].

Because of these implications, DFC technologies are currently under development worldwide at many universities and research centers. These mostly exist as pre-commercial developments (e.g., in demonstrators or exploratory pilot projects). Likewise, concrete DFC technologies developed in the construction industry are either in a pre-market stage or have entered the market as niche applications [20,21]. Thus,

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although DFC technologies have in principle been shown to be suitable for full-scale application, as of now they have not reached a substantial market share. For DFC to realize its expected potential, continual scaling-up of market applications can put DFC technologies on a pathway towards innovation diffusion. This adoption will rely on transdisciplinary collaboration processes in industry and research joint-ventures to solve the persisting technical and organizational challenges associated with transferring research to industrial-scale processes and building practice [22–24].

However, potential early adopters of emerging DFC technologies face several challenges. First, DFC technologies are at various early stages of maturity and their industrial use potential is not fully understood by the stakeholders involved in their development [25]. Second, companies with interest in adopting DFC lack an overview of potential solutions available to them. As the diversity of emerging DFC technologies grows, it is hard to keep track of the dynamic development in this field without access to a specialist network or previous knowledge of digital fabrication. Even with knowledge of ongoing DFC developments it remains difficult for potential adopters to compare which technology is most suitable to their needs [26]. Hence, there is a need to evaluate the application potential of available solutions and its match with user needs.

To address these two challenges, our research seeks to understand the relevant key parameters necessary to evaluate DFC technologies in the context of technology transfer. To do this, we conduct a Conceptual Framework Analysis [27] based on interviews with leading researchers, developers and users of DFC and supplemented with process observations and technical documentation. The Conceptual Framework Analysis identifies and categorizes the factors relevant for successful industry transfer of DFC technologies. Based on this framework, we develop a user-friendly qualitative DFC Scoreboard tool. The DFC Scoreboard enables users to compare different DFC technologies, and to visualize and compare the use potential of emerging technologies against prospective users' needs and business interests. The Scoreboard is intended to connect businesses with interest in adopting DFC with ongoing technology developments. Its use can open further opportunities for adoption, scale-up and co-development towards industrial application of DFC.

2. Point of departure

2.1. Classification of DFC processes

2.1.1. Overview

DFC is still emerging, and its processes and methods vary widely. Recent literature has provided early classifications of DFC [2,4,5]. We identify six types of DFC that currently show relevant potential for industry transfer, based on an extensive survey of literature, triangulated with the authors' first-hand experience with implementing DFC technologies in demonstrator projects at the Swiss National Center of Competence in Research (NCCR) Digital Fabrication [8,23], a leading research center on digital fabrication in construction. The following Section 2.1.2 summarizes their principles and illustrates each type with one example of a DFC process studied for this research. We hold that these six major types capture most of the varied technologies in the current DFC field and their different implications for the construction process, although the developing technology landscape includes additional types and variations which may gain importance in the future.

- Type 1: Direct material extrusion
- Type 2: Fused deposition modeling (FDM)
- Type 3: Binder jet printing
- Type 4: Shotcrete 3D printing
- Type 5: Slip-forming
- Type 6: Mold-less shaping with internal matrix

2.1.2. Types of DFC

Type 1: Direct material extrusion. Direct material extrusion, often referred to as concrete 3D-printing, describes processes directly layering small-aggregate concrete or mortar extruded from a nozzle (See Fig. 1). The resulting layer thickness is usually in the range of a few centimeters. This requires a special concrete mix: 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. The setting behavior is typically controlled by chemical admixtures added in the printing process [4]. Integrating reinforcement in the layer-based process remains challenging, mainly because of the layered material disposition principle is incompatible with continuous reinforcement [28].

Type 2: Fused deposition modeling (FDM). FDM is a method to layer thermoplastic materials in various shapes. In DFC, FDM is used to produce reusable or disposable formwork (See Fig. 2). Reusable FDM formwork is characterized by a high number of reuse cycles and high precision [29]. Disposable formwork is destroyed during removal. Depending on the filament used, the material can be recycled or even dissolved [30]. The printed structures can be thin-walled to save material and production time but require additional support structures to avoid deformation or breakage due to formwork pressure Formwork pressure can also be reduced through the use of set-on-demand and self-compacting concrete [31].

Type 3: Binder jet printing. The process of binder jetting layers powder material (e.g., sand) and selectively bonds it by injecting an organic or cement-based binder (See Fig. 3). Repeating this process leads to creating a 3D structure. During printing, the powder bed acts as a support structure, allowing for overhangs and internal voids. Results offer high precision surface resolution. After printing, unbound powder material is removed and can be re-used [32]. In DFC, the printed form acts as either removable or lost formwork for concrete casting or shotcrete application, allowing for a variety of reinforcement types. The binder jet principle has also been prototypically applied for direct printing of building elements [33].

Type 4: Shotcrete 3D printing. The process of spraying concrete is commonly referred to as shotcreting. A nozzle is mounted at the end of an industrial robotic arm or CNC gantry and projects the material mix at high velocity onto a surface, substrate or a rebar cage using compressed air (See Fig. 4). In DFC, shotcrete can be built up in layers without formwork or in combination with a shaping mechanism attached to the nozzle. After spraying, the final surface can be post-processed. Ongoing developments in this field also include the addition of fibers in the material mix to increase composite structural strength, exploring geometrical freedom, and reducing the thickness of the sprayed elements. While rebar integration is considered easier than with extrusion-based 3D printing, controlling the material deposition is more complex [34,35].

Type 5: Concrete slip-forming. Slip-forming refers to the method of pouring concrete in a continuously moving formwork in an extrusion-like process (See Fig. 5). It can be applied vertically or horizontally [36], e.g. for silos, towers, bridges and roadbeds or curbs. The concrete element is a result of the geometry of the formwork and its motion during the forming process. This allows the production of parts much larger than the formwork itself. The principle has been adapted to small-scale DFC processes using reusable actuated formwork to allow changing cross-section during the vertical forming process [6], enabling waste-free fabrication of bespoke, linear concrete elements. Reinforcement can be integrated in the process, e.g. by slipping around pre-placed rebar.

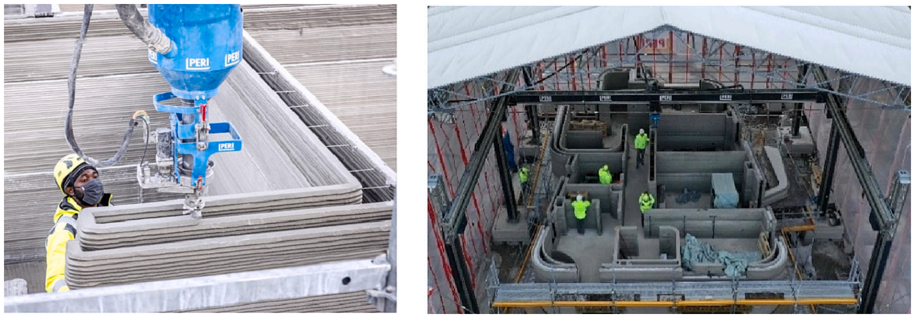

Fig. 1. Example of concrete extrusion printing (credit: PERI SE).

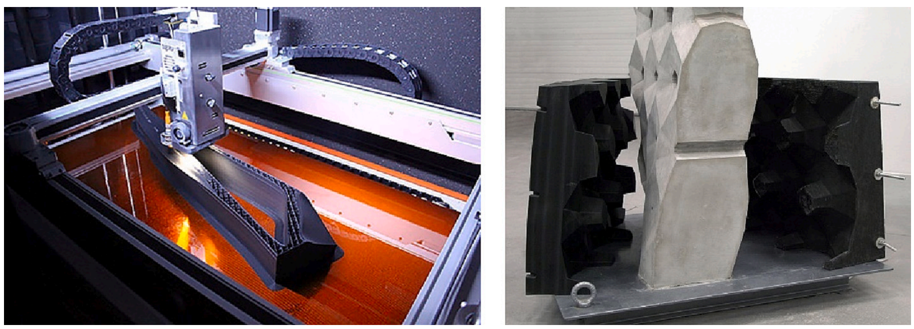

Fig. 2. Example of FDM printed formwork (credit: Bigrep Forward AM).

Fig. 3. Example of binder-jet printed formwork (credit: digital building technologies, ETH Zurich).

Fig. 4. Example of shotcrete 3D printing (credit: Mobbot SA).

Type 6: Mold-less shaping with internal matrix. This category aims at avoiding the use of formwork altogether by combining a digitally fabricated internal, spatial matrix structure with low viscosity concrete materials (See Fig. 6). The matrix resembles a cage or space frame. Acting as a lost formwork, it determines the shape of the resulting component. It is either made of non-structural extruded thermoplastic material [37] or of welded steel rebar to double as structural reinforcement [38]. In a subsequent step, concrete is cast or pumped into the

Fig. 5. Example of concrete slip-forming (credit: NCCR Digital Fabrication, ETH Zurich).

Fig. 6. Example of mold-less shaping with internal matrix (credit: NCCR Digital Fabrication, ETH Zurich).

voids to form a composite structure. The surface can be treated to create a variety of finishes.

2.2. Technological challenges to DFC adoption

Despite recent progress in DFC technologies, technical challenges still abound primarily in four areas.

First, *integrating reinforcement* in DFC processes persists as a largely unsolved challenge, despite many current investigations into an array of possible solutions. The integration of reinforcement is critical to achieving structural performance values comparable to conventional concrete. In-process reinforcement of DFC poses challenges related to compatibility with the fabrication logic, hardware constraints, and geometry [28,39–44]. Post-process reinforcement allows for more conventional approaches but requires additional production steps beyond the scope of the digital fabrication process itself [42,45].

Second, there are challenges with *material control*. This applies in the fluid state and setting phase of DFC materials where consistent properties are required for precise and continuous material deposition [46,47]. In the hardened state, DFC materials differ from conventional cast concrete and often have inferior mechanical properties, e.g. due to weak layer interfaces [48] or the effects of additives and limited aggregate size [49]. There are tradeoffs between optimal material properties for processing and hardened material [50]. In addition, the current lack of a characterization methodology for hardened DFC materials is a hindering factor to widespread use of DFC in practice [49].

Third, *quality control* is a challenge in DFC. Generally, the parameters of DFC materials need to be more tightly controlled than in conventional concrete application, e.g. when in-process addition of admixtures or fibers can lead to issues with material homogeneity or adhesion, so new in-process measurement and control approaches are required. [39,51,52]. Dependency on material consistency and operating parameters can lead to robustness problems hampering the performance of the resulting components, a factor that can prohibit the commercial use of DFC [53].

Fourth, *physical upscaling* from lab experiments and small prototypes to full-size construction presents its own technical challenges. For example, the mixing and processing of larger material quantities can result in variations not present in small batches [22], the structural behavior of DFC parts cannot be reliably extrapolated from small scale samples, making full-scale tests necessary, and variations in dimensional tolerances can accumulate [7]. Further factors hindering full-scale application are: production speed and cost [14,31]; the lack of codes and standards for load-bearing DFC parts which will rely on experimental data not yet sufficiently available to be established [25,54]; and challenges with the complexity of on-site fabrication tasks [55].

2.3. Non-technical barriers to DFC adoption

In addition to technological challenges, adoption of DFC is lagging due to organizational and process-related barriers to technology transfer from research to industry application [56,57]. Little research has investigated the non-technical barriers with specific focus on DFC adoption. There are some exceptions, such as a few review papers on the state of DFC that reflect on management or integration in their otherwise technology-focused classifications, for example the need to integrate DFC with appropriate digital planning methods [54] and the interdisciplinary effort DFC development demands [4]. In addition, some DFC implementation case studies touch on implications for organization and practice, e.g. the challenges of interdependencies between architectural design and fabrication parameters [7], the complexity of project organizing for DFC adoption [23], the difficulty of reconciling DFC processes with the uncertainties of construction sites [58], and expected changes to construction workflows and professional roles due to DFC [59]. However, the focus of DFC research has been placed overwhelmingly on the technology development itself.

Non-technical barriers to technology transfer in construction have been studied thoroughly, both in general [60] and, to a lesser extent, specifically for digital fabrication [61,62]. This previous research gives indications of three such adoption barriers faced by DFC.

First, *DFC constitutes a systemic innovation* [63]. The adoption of DFC in construction affects the processes of multiple planning and construction trades and crosses disciplinary and professional boundaries between architecture, material science, engineering and manufacturing [64]. Systemic innovations only achieve their full value when implemented across organizations [63,65], which is difficult in construction with its strong discipline boundaries and weak coordination between stakeholders [66]. In the construction industry, systemic innovations are considerably less likely to be adopted than innovations that fit within existing organizational boundaries, despite their potentially superior economic performance and resource-efficiency [67].

Second, *DFC adoption relies on process integration.* Conventional construction processes are mirroring the industry's project-based organizational structure [68], in which competitive bidding and loose ties between stakeholders cause weak communication and high participant turnover between project phases and projects [66,69]. This fragmented organizational model lacks the continuity required for implementing the direct data link between planning and construction and the upstream consideration of constructability constraints required for DFC to be effectively implemented [70]. In addition, established construction methods have been developed within a network of interdependent solutions, which makes it difficult to integrate or replace them with new solutions developed outside this network [71]. Such integration can be achieved through, for example, computational design tools specific to digital fabrication [24,72] or product configurators reflecting production systems and their constraints [73]. Integrating BIM and digital fabrication has been proposed in research but not implemented in practice [74–76]. Recent literature has highlighted this need for integration by endorsing the integral role of DFC as part of the transition to Construction 4.0 [77,78].

Third, *DFC adoption relies on technology acceptance*. Adoption of new technologies by enterprises depends on technology acceptance on the grounds of their perceived usefulness by their future users [79]. Even with this acceptance, practitioners face difficulties selecting the most useful to their needs among many technology choices [26]. Construction project organizations are socio-technical systems in which innovation adoption is a negotiation process between multiple involved stakeholders and firms [80,81]. For systemic innovations such as digital fabrication, this requires a process of "co-design" [24]. Therefore, integration of digital fabrication into the practice environment requires interdisciplinary collaboration, learning and information exchange [82,83]. As collaboration is redefined, the importance of organizational and social factors for technology adoption can equal that of technological factors [62,84].

2.4. Research gap & research questions

Despite the recent technology advances, DFC presents unsolved technical challenges related to integrating reinforcement, material control, quality control, and physical upscaling. Because DFC is a systemic innovation and relies on process integration, solving these problems will require the transdisciplinary effort of technology providers and industry adopters to co-develop and integrate DFC into construction operations. To be adopted, DFC must be accepted as a potentially useful solution to address tangible needs across this spectrum of actors. To gain this acceptance, stakeholders with differing disciplinary backgrounds, professions and functions must be enabled to understand and compare the potential offered by various DFC technologies to address their needs.

However, little research has focused on systematically evaluating DFC technology properties and industry needs. There is a need to identify and synthesize the diverse characteristics of DFC technologies that must be considered for successful adoption. Such synthesis must be done in consideration of both the technical and non-technical barriers described above. Without this, potential industry adopters of DFC lack guidance in matching their needs and business interests with the advancing technology capabilities that the emerging field offers.

To address this gap, we pose the following two research questions:

- ***RQ1***

How can properties of emerging DFC technologies be generally described in terms that allow stakeholders from different disciplines and backgrounds to understand and compare their usefulness?

- ***RQ2***

How can we use these categories to effectively match DFC technology capabilities and adopters' needs in practice?

3. Methodology

This research follows a two-fold methodological approach. First, as the analytical basis, we performed a Conceptual Framework Analysis [27] to categorize the properties of DFC technologies relevant for its adoption to practice. Second, we proposed and tested the DFC Scoreboard, a practical tool using the Conceptual Framework to match DFC technology capabilities and user needs.

3.1. Definition of method

To address RQ1, this research conducts a Conceptual Framework Analysis, an eight-phase qualitative process of analysis proposed by Jabareen [27]. The method derives a Conceptual Framework which consists of "interlinked concepts that together provide a comprehensive understanding of a phenomenon", especially one "linked to multiple bodies of knowledge situated in multiple disciplines." [27] "A conceptual framework is not merely a collection of concepts but, rather, a construct in which each concept plays an integral role" and thus aims at qualitatively *understanding*, rather than merely describing, the target phenomenon, grounded in multidisciplinary knowledge rather than in consensus within one particular field of study (ibid.). It this research, we argue that DFC, both as an emerging interdisciplinary research field and a practice, stands to benefit from a conceptual framework offering a set of categories to provide a structure for further inquiry.

Conceptual Framework Analysis uses Grounded Theory principles for building the conceptual framework. Grounded Theory is one of the most widely accepted qualitative methods due to its "well-defined analysis procedure" [85]. It is based on the analysis and categorization of qualitative data, such as interviews, texts and supporting material in an inductive process of theorization. The qualitative data is analyzed through "open coding", a technique in which categories are developed directly from the content of the data rather than from pre-existing theory or hypotheses [86]. The technique relies on "on continuous comparison of data and theory" [87].

To address RQ2, this research creates a practical Scoreboard tool by providing a four-point Likert-type rating scale for each category of the Conceptual Framework developed in the Conceptual Framework Analysis. Four choices are generally considered the minimum number required to return valid results, and four-point Likert scales are the most widely used format when avoiding a fifth, neutral option often chosen out of indecision [88]. A "coarser" rating scale is adequate for early-stage evaluation of DFC where many stakeholders do not possess the level of knowledge required for a more detailed rating to be meaningful. Furthermore, a four-point response format is adequate if subjects have varying pre-existing knowledge of the object of study (e.g. DFC specialists vs. construction contractors), and statistical analysis is not intended [88]. The qualitative character of the rating is emphasized by using the words *Low, Moderate, High,* and *Very High* rather than numbers.

3.2. Data collection

Phase 1 of Conceptual Framework Analysis is *mapping of data sources* or *scoping*. It consisted of defining the interviewee sample and conducting of semi-structured interviews; a literature review on construction application of DFC; and the collection of supporting evidence.

Since the aim was to establish a systemic perspective on DFC underreported in literature, first-hand knowledge and experience reflecting the actual state of development of DFC was deemed most important. Therefore, the primary data source was "interviews with practitioners, specialists, and scholars from various disciplines" (ibid.) as "knowledgeable agents" [89]. The initial interviewee sample of 22 interviewees was identified through the co-authors' academic and professional network according to the principle of purposeful sampling [90], which allows to select subjects according to their assumed knowledge of the object of study. Ten additional interviewees were added based on knowledge gained in the interviews, leading to the final sample of 32 interviewees. This represented the point of theoretical saturation where additional data did no longer produce new characteristics or categories [91]. All chosen interviewees represent global leaders in DFC in research and industry. Table 1 shows an overview of the interviewee sample.

For the literature review, the authors used their background knowledge of DFC to compose a body of relevant literature. In addition, a document search on the Scopus Database was conducted [92], searching article titles, abstracts and keywords with the search terms (construction) AND (concrete) AND (digital AND fabrication) OR (3d AND print) OR (additive AND manufacturing) returned 221 journal papers. After eliminating overlaps with the initial literature, the authors reviewed the abstracts of these results for relevance to the topic of this study. Papers were deemed relevant if they contained process descriptions of full-scale implementation or physical experiments and pilot projects applying DFC processes at 1:1 scale.

In addition, technical documents and process recordings were provided by interviewees and collected as supporting evidence, in keeping with the qualitative research principle that "the data should […] come from a variety of types." [27].

3.3. Data analysis and development of conceptual framework

The data analysis of this research follows Phases 2 to 8 of the Conceptual Framework Analysis. Importantly, the phases defined by the method of Conceptual Framework analysis are iterative, not sequential [27], and therefore were executed with significant overlap in terms of time and content.

Phase 2, *extensive reading and categorizing of data*, and Phase 3, *identifying and naming concepts*, subsume the critical phase of coding the data. "Coding is the pivotal link between collecting data and developing an emergent theory to explain these data." [93] In this case, a first set of Concepts was developed through line-by-line coding of the interview data. While line codes can be competing or contradictory [27], these concepts strictly followed the principle of induction, an important pillar of justification of assertions made in Grounded Theory research [89]. Line-by-line coding was done until patterns started to emerge in the named concepts, in this case after ca. one third of the total interview material. In keeping with inductive coding practice, this is the time when focused coding should start [91]. At this point, we started subsuming related concepts by *focused coding* to establish initial analytical *Categories* [89]. These categories were used to code the entirety of the interview data and were further refined during this process. Examples of how *Concepts* were subsumed *Categories* are shown in Fig. 7. For triangulation, Concepts identified in these Phases were also compared to descriptions in the assembled literature. Where a more detailed understanding of a mentioned concept was necessary, the authors consulted the supporting evidence, e.g. available technical process descriptions or videos.

Table 1
Overview of interviewee sample ($n = 32$).

Company business	Position / rank	Company size	#yrs exp.	#yrs exp. DFC	Disciplinary background
Chem. products	Head of department	110′000	20	10	Architecture
Constr. materials	Head of department	35′000	22	8	Material science
Constr. materials	Head of department	4500	30	6	Chemistry, business admin.
Civil Eng./ constr.	Tech. project manager	2600	35	5	Master builder
Mech. engineering	Mechanical Engineer	950	20	5	Mechanical engineering
Concrete prefab	CEO	110	39	15	Mechanical engineering
Concrete prefab	Technical director	110	20	5	Civil Eng., business admin.
Concrete prefab	Head or engineering	70	12	7	Civil Eng., business admin.
Civil engineering	Engineer	60	5	2	Civil engineering
DFC tech./constr.	Senior design assoc.	50	10	7	Architecture
DFC tech./constr.	Founder / CEO	30	18	10	Constr. management
DFC technology	Founder / CEO	20	4	4	Mechanical engineering
DFC tech./constr.	Founder / CEO	10	20	7	Mineralogy, physics
DFC tech./constr.	Co-founder / co-CEO	7	6	8	Architecture
Struct. engineering	Principal / struct. Eng.	6	14	5	Structural engineering
DFC technology	COO	4	4	10	Architecture
Architecture	Principal	4	15	10	Architecture
DFC tech./constr.	Founder / CEO	3	16	7	Architecture
DFC tech./constr.	CEO	3	20	12	Architecture
	Univ. professor		15	12	Architecture
	Univ. professor		20	12	Architecture
	Univ. professor		25	8	Material science
	Univ. professor		18	12	Architecture
	Senior researcher		15	6	Chem. Eng., mat. science
	Postdoc. researcher		7	5	Architecture
University research	Tech. transfer officer	n.a.	18	8	Mechanical engineering
	Ph.D. researcher		6	4	Architecture
	Ph.D. researcher		5	7	Struct. Eng., mat. science
	Ph.D. researcher		12	11	Architecture
	Ph.D. researcher		*5*	*5*	Architecture, constr. manag.
	Ph.D. researcher		5	5	Civil Eng., constr. management
	Ph.D. researcher		9	7	Architecture

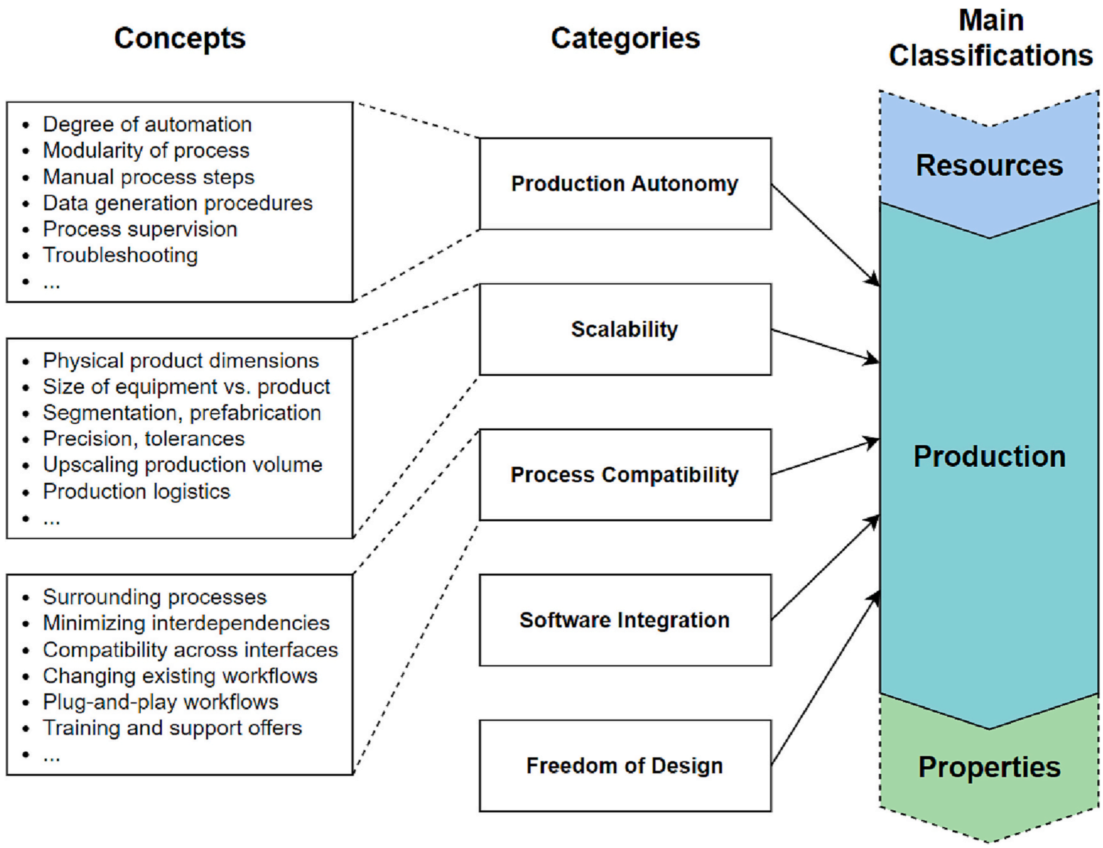

Fig. 7. Coding data structure (adapted from [89]).

Phase 4, *deconstructing and categorizing concepts*, and Phase 5, *integrating concepts*, are interlinked phases of refining the analytical coding data structure, which involves iterative "going back and forth between data and [the] developing analysis" (ibid.). In this phase, we combined and reframed the categories until they became sufficiently distinct and relevant for the specific problem of DFC adoption. For example, the final category of *Production Autonomy* was reframed from the preliminary categories "level of automation" and "manual processes", as it became clear that the overall autonomy, including automated and non-automated steps, was most relevant. Similarly, aspects of "product quality" were divided into the final categories *Structural Properties* and *Surface Quality*. Phases 4 and 5 also included *theoretical sampling*, i.e. the targeted collection of additional data as the theory develops [91], in the form of additional interviews and solicitation of feedback to "actively construct[…] the data in concert with […] participants" [93], with the goal of ensuring "effective representation of each discipline" [27]. The two specific tasks of theoretical sampling were applied in this study: (i) we conducted of ten additional interviews to generate additional data on concepts emerging from the original round of 22 interviews; (ii) after a preliminary version of the conceptual framework was established based on ten interviews, the current version of the developing framework was shown to the interviewee at the end of the remaining interviews, inviting feedback on the clarity and completeness of the categories.

Phase 6, *synthesis* was the step configuring the Conceptual Framework presented in Section 4.1 of this paper by ordering the categories thematically and grouping them under three *Main Classifications*. Although induction was the main principle used for building the concepts, the synthesis also included reflecting on existing models of technology diffusion offering heuristic concepts of technological change. These models include the TOE model, which frames decision-making in technology innovation around the factors Technology, Organization, and External Environment [62,94], and the Multi-level Socio-technical Perspective on systemic innovations, which uses the analytic dimensions of Socio-technical systems, Rules, and Actors [95]. Taking these theories as context, the Conceptual Framework proposed in this paper specifically analyzes one type of technology innovation, DFC, along the dimensions of Resources, Production, and Properties.

The procedure concludes with Phase 7, *validating the framework and* Phase 8, *rethinking the conceptual framework.* While validation methods in qualitative research differ from quantitative methods, several measures can be taken to promote qualitative research validity [96]. Five such measures were employed in this research.

- *Data triangulation*, by using multiple data sources.
- *Reflexivity,* by maintaining a culture of critical self-reflection on potential biases in the research team
- *Peer review*, performed by three of the authors with three external peers on the preliminary framework after one-third of interviews, to establish descriptive validity of its categories
- *Participant feedback*, by asking participants of the remaining interviews to provide their feedback on the developing preliminary framework.
- *Focus group:* A four-person focus group was conducted after the final round of interviews to obtain consensus on the completeness of the framework and the validity of its constructs. The focus group was composed of representatives from different, independent organizations (two research / two industry) to control for biases such as social desirability and group think. The focus group reached consensus on the 15 proposed categories of the framework and rectified remaining inaccuracies, omissions, and redundancies in the category descriptions. The focus group constituted the element or *Rethinking the Framework* by confirming its coherence at the given point in time while also reflecting on its potential to evolve in future iterations.

4. Results

4.1. DFC evaluation framework

This section provides an overview of the DFC Evaluation Framework. The framework was developed in response to Research Question 1: *How can properties of emerging DFC technologies be generally described in terms that allow stakeholders from different disciplines and backgrounds to understand and compare their usefulness?*

Section 4.1.1 presents an overview of the framework structure, its Main Classifications and Categories. Section 4.1.2 presents a synopsis of the findings structured by the categories of the Framework. In qualitative research, it is good practice to "include the data in the paper […] to give the reader sufficient evidence to evaluate the accuracy of the constructs." [97] In accordance with this principle, direct quotes from the interview data are used to exemplify the data from which each category was derived.

4.1.1. Overview of framework

In the analysis process, we identified fifteen Categories relevant to evaluate the match of a given DFC technology with a prospective user's needs. We also establish three Main Classifications under which to group these categories: *Resources*, *Production*, and *Properties* (Fig. 7). Three categories are shared between two of the Classifications.

A - Resources include the Categories *Energy and Emissions*, and direct inputs generally defining productivity (measuring output for a given input), denoted in *Equipment, Material*, *Workforce*, and *Production Time* (shared with Production).

B - Production subsumes Categories of the production process itself which are key factors in adoption decisions: *Production Time* (shared with Resources), *Production Autonomy*, *Scalability*, *Workflow Integration*, *Software Integration*, and *Freedom of Design* (shared with Properties).

C - Properties of the resulting products strongly influence the adoption potential of DFC technologies. Categories in Properties are *Freedom of Design* (shared with Production), *Versatility*, *Surface Quality*, *Structural Properties*, *Code Compliance*, and *Circularity* (shared with Resources).

4.1.2. Description of categories

A - Resources

Energy and emissions. This category includes embodied energy and energy demand for production. Through the carbon footprint associated with energy expenditure, "energy and emissions […] are tied together." Embodied energy is the larger share, both as a measure of environmental sustainability and as a potential future cost driver based on energy cost and CO2 prices. It can be controlled through material savings by volume, e.g. by depositing "concrete exactly where it is needed structurally and aesthetically". This "shape efficiency" is a strength of DFC, as non-standard geometries can be produced more economically and with less formwork waste. Secondary savings effects include reduction of foundations due to lower structural weight and lower transportation energy. Still, there are trade-offs between volume saving and cement content in many DFC technologies, as "3D printing […] or any kind of [formwork-free] processing with concrete is inherently going to increase the cement content", e.g. through a higher paste-to-aggregate ratio. Therefore, concrete which is "great for [DFC] process [is] not necessarily great for the environment." The energy demand of the equipment is a minor share. In one 3D printing example, "the printing process [requires] less than 10% of the total energy."

It is important to consider Energy and Emissions over the entire supply chain of a DFC process. Generally, reducing CO2 emissions is a "motivating factor" for DFC adoption, especially as "the market is huge […] and this industry sector has a large impact." However, better measuring techniques are needed, and multiple DFC suppliers reported gaps in their emissions tracking over the process chain, e.g. in the material data or the processing energy. Finally, in addition to carbon emissions, some materials, e.g. hazardous organic binders used in formwork printing, cause harmful emissions. The need to eliminate these materials is crucial for industry adoption, not least because of high disposal cost.

Equipment. Equipment for DFC varies widely in complexity and cost. DFC-specific production equipment requires substantial initial capital expenditure – e.g. EUR 150 - 300 K for a 3D print set-up – and can present an entry barrier to using DFC. However, as a production cost factor, the equipment as a one-time investment is "vanishingly little" compared to running cost such as material expenses, labor and floor space. When comparing DFC to using precast equipment, which is also costly, equipment cost amortization depends on other factors, e.g. production output per unit. Equipment availability, lead times, and maintenance requirements also need consideration. Adopters struggle with a lack of options offered by equipment providers, who are "very fixated on their systems."

DFC includes diverse types of equipment. For example, direct extrusion requires a feed system and a mortar extrusion nozzle attached to a robot; printing formwork requires a filament or binder jet printer; concrete slip forming uses a movable formwork and automated feeding. DFC systems integrate standard equipment (e.g. a robot arm or gantry) with specialized parts (e.g. an extruder) by means of proprietary software developed in an integral process with the hardware. Different equipment ownership, leasing and equipment-as-s-service models are offered. While these create dependency on the equipment provider, reliable maintenance service is crucial for wear and tear parts such as extruders. To compete with conventional processes, DFC equipment providers must offer fast repair or replacements so that producers are "able to fulfil [their] production plan and don't have to wait three months for a special part." Leasing models for specialized parts allow continuous improvement based on user feedback. This is necessary, as DFC "has a lot to do with machines and machine settings" to match "the process, the material and the resulting product."

Material. DFC processes tend to be highly dependent on material properties and short processing windows. Additive DFC technologies rely on "on-demand" mortar or concrete where "the material behavior can be digitally controlled." This requires "highly sophisticated material" and "highly precise work as there is little room for errors", including temperature and humidity control in the production facility. The raw materials of concrete have variations, so for "consistent quality of the building part, e.g. […] compressive or flexural strength, the process must be precisely monitored." The concrete recipes also rely on chemical admixtures, with partially unknown long-term effects on material durability. In addition, processing issues such as shrinkage cracks and interlayer bonding are not fully resolved in many DFC applications.

Most DFC processes rely on standardized, proprietary materials which tend to be costly. "Material development takes a lot of time. It's a fairly irreducible effort." Therefore, DFC technology providers often partner with concrete suppliers in the development of proprietary materials which must be exclusively used with the equipment, creating a dependency on a single material supplier. These materials are a significant cost factor in production and a revenue stream for the material providers who "sell the ink". Other DFC suppliers allow the use of open-source or local materials, passing integration and quality control on to the user but also resulting in more cost-effective and sustainable solutions, avoiding "sending sand across the world." Generally, material science is seen as one of the most crucial factors for wider DFC adoption to succeed, despite being "the tricky part" and a potentially underestimated challenge. Material cost is an incentive to optimize designs to save material, and DFC is successful in precise tracking of material use. In casting-based DFC, non-cementitious formwork and support print materials are used, e.g. in plastic filament printing and sand-based binder jetting. These materials usually build on material developments from other industries.

Workforce. Labor productivity is one of the most frequently used productivity measures in construction, and Workforce, as a running cost, is a driving cost factor impacted by labor time as a direct input as well as the required skillset of the workforce. DFC can increase process automation to target labor intensive tasks. E.g., 3D printing of formwork or direct printing of building parts can help in “replacing labor for formworks and for masonry.” This is a great potential, as “the labor, the cost of concrete is in the formwork.” Thus, labor savings can quickly offset costs for DFC equipment and set-up, even if “the investment in a machine is expensive compared to a job” in the short term.

Adopting a new DFC system requires higher skilled labor than the operation of an established set-up. Adopting a DFC technology to industrial production can be “challenging in terms of motion […] material development and […] product development.” This can be a barrier, as in AEC firms “you seldom have the competencies. […] You do not have R&D departments. It often depends on one or two persons in a firm.” The bulk of operating DFC systems is expected to be “a low-skilled process” mechanically and logistically, requiring training of between two days and several weeks. A skill gap is mainly expected in preparing digital data for production, where companies “need people that are interested in digital fabrication from the software side.” When expanding operations, there is potential to reduce manpower, e.g. by using “one robot operator for six bots at a time.” DFC usually reduces labor hours, addressing a shortage of skilled labor where “there are ever fewer good craftspeople […] on construction sites.” This shift can contribute to work safety, reducing the “hidden costs” in “dangerous work.”

A - Resources / B - Production (shared)

Production time. Output per unit of time is an important factor for the industry adoption potential of DFC processes: “When you are speaking of economic feasibility, it is always also about speed.” Most DFC processes are a combination of automated and manual tasks. Total production time consists of the processing speed dictated by the equipment and the material setting behavior, equipment preparation (set-up, calibration, and cleaning), material preparation (concrete, formwork, or reinforcement), manual tasks (e.g. post-processing), and curing time. To evaluate DFC against a conventional alternative, “one has to look into the whole process, including finishing, and […] compare it.” For example, after calibration, equipment set-up and cleaning after production, “of eight hours you are left with five and a half” of effective production time in a workday. In addition, technological limitations, such as material setting time, slow down production. While net printing time is recorded in print protocols, manual steps are often not systematically tracked.

Low processing speeds can be offset by running automated steps overnight, e.g. for formwork printing, or by operating more equipment simultaneously, leading to a time-cost tradeoff. Eventually, “it doesn’t matter how slow your process is if you can do many of them at the same time.” Other strategies to reduce time are optimizing designs and tool paths to minimize machine time (“how the robot moves can shave seconds that add up over time”), or by 3D printing reusable formwork which allows “up to 40 or 50 pulls.” If visual surface quality is not a requirement, deposition speed or layer thickness can be increased, leading to “rougher” parts. DFC producers emphasized that, rather than absolute print speed, “you basically think about the turnaround time of the actual product” as the relevant parameter. For example, by adding “a demolding cycle during a workday”, a company could “essentially be doubling their production during one workday.”

B - Production

Production autonomy. Production autonomy is determined by the degree of automation of each production step and by the integration between the individual automated steps of the production procedure. Some DFC processes are modular, as for example formwork printing, where «you can turn on [the robot] during the day and run it through the night and the next day the formwork is ready.” This process can require intensive preparation of data, so “the most productive part of the day is the night,” whereas “throughout the day, […] we are tuning prints, generating toolpaths, working on designs.” In addition, preparation and close-out tasks are often not automated. While a concrete printer can mix and feed material and run the fabrication code without intervention, “when it stops running, we have to dismantle and clean” manually.

While automation of DFC steps is a prerequisite for production autonomy, the degree to which this is possible is largely determined by the number of required production steps and how many manual interventions are necessary before, in between and after these steps. This is an integration and a technology challenge. For most DFC processes, “the technical challenge is […] the reinforcement. The thing that’s driving everything is labor reduction or replacement. And the installation of reinforcement isn’t an automatic process.” In addition, post-processing (e.g. the smoothing of edges or the removal of inaccuracies) and formwork assembly and casting is usually done manually. Two other factors crucial for production autonomy are avoiding fallout from unavoidable interruptions (e.g. by self-cleaning deposition devices) and troubleshooting. Basic supervision can potentially be automated, e.g. by using computer vision, but for the foreseeable future, “you will always need also a human operator that basically steers the process as a whole, that troubleshoots, that controls the robots.” While “the robots are working well, […] it’s really […] the specific processes that tie all these things together” that need to be solved to increase the production autonomy of DFC.

Scalability. How a technology can be scaled in physical size and production volume for industrial production is a key question in DFC adoption, as the physical size of the products distinguishes construction from other industries. “In architecture, you simply have to deal with large scale parts.” Increasing size presents challenges: For example, if “the printer must be bigger than the building [it prints], you are limited because you will never do an apartment complex.” This problem can be overcome by segmenting and prefabrication, similarly to conventional pre-cast, so there “is no fundamental reason why you could not scale it up to building size.” However, “a larger build space is more efficient [as you have] fewer single elements.” Upscaling the build space poses major technical challenges. “Everyone can print one by one meter, but [at] 3x6m, there are big challenges to handle” in terms of precision and robustness. In addition, scalability in prefabrication is limited by transportation and handling, structural performance, and building codes.

Upscaling production volume typically requires changes to the manufacturing set-up, e.g. to handle large material quantities, increase speed, robustness, and level of automation. As a result, the mature industrial production process may differ substantially from earlier developments. For example, “a second robot set-up alone does not help» unless logistics and workforce are available. Factors inherent in each DFC technology, such as material behavior, can hinder upscaling. For example, ‘there’s [...] this benchmark to 3D printed building in 24 hours, and nobody’s really done it because of technological limitations. They have to wait for the material to set.’ Production volume often determines the economic feasibility of commercial DFC use, e.g. when a printed formwork can be re-used, as then ‘the formwork part [of the cost] gets smaller and smaller.’ For DFC adoption to succeed, «existing technologies must be adapted to the requirements of construction […] in a way that makes them economically feasible.”

Process compatibility. The compatibility of the DFC process across interfaces with its surrounding processes and workflows determines extent to which a DFC process can be integrated with the production environment of the adopting company. In particular, “the degree of automation depends strongly on the surrounding overall system.”

Some DFC solutions try to minimize interdependencies and offer a contained, stand-alone workflow with few interdependencies, e.g. the printing of a formwork that allows “to build a shape that does not yet exist” but otherwise has similar properties to a conventional formwork. By containing the complexities of DFC in prefabrication, “you don’t have to make any changes on the construction site."

However, other DFC technologies require process changes in surrounding workflows, possibly even disrupting business-as-usual. For example, formwork contractors consider on-site 3D printing that could potentially replace formwork. But independently of the technology used, the goal of adopting new construction methods must be "to optimize the processes so that things can be produced more easily." Compatibility across interfaces is key: «you can have the best 3D printed formwork in the world, but if you can't use it with the standard system on site, it will always generate a lot of extra effort." DFC processes forcing changes in surrounding existing workflows requires investments in complementary production systems, new worker skills and cultural change. "You can easily buy hardware for large-scale 3D printing, but that doesn't mean you can use it." While large companies may have resources to "address this topic more broadly", this is not easily done by smaller companies who would consider DFC as a «concrete solution for a concrete problem." Therefore, providers of more complex DFC solutions increasingly offer a "plug-and-play" approach with service contracts to ease adoption. In these models, the purchase of DFC hardware is combined with training, a service contract and software support.

Software integration. As a digital fabrication process, DFC relies on s direct data link between design and engineering information into digital manufacturing code. When using novel digital processes "it is a high barrier in the construction industry, [knowing] what the final part should look like, […] to have the know-how to prepare the data."

Most DFC providers aim to "provide a process to automate the generation of fabrication data" for their systems. The software packages must be able to minimize the effort of translating part geometry to fabrication information. If this process is manual or too labor intensive, it can undercut any productivity gains of DFC. DFC software should enable its user to influence the built geometry within the constraints the DFC technology imposes. To do so, it must effectively encapsulate knowledge of fabrication constraints to support informed design decisions. Without this software functionality, it is impossible for users "to define the building elements that can be produced with the technology." Simulation and rendering capabilities can assist communication between DFC technology providers and users.

DFC is effective in the precise protocol of production time, material consumption and energy use through its control software, allowing users to "constantly collect data from project to project and improve on that." Most DFC processes are operated using a highly integrated, technology-specific software package, which is usually developed in parallel with the hardware and requires constant development as hardware advances. The capabilities, interoperability, and usability of this software environment are key determinants in DFC adoption decisions. "It's about ease of use. How can we make the equipment usable?" Users need "a human-machine interface, where you can load information from a tablet and start," and users do not "have to be able to program to print anything."

B - Production / C - Properties (shared)

Freedom of design. Freedom of Design is a unique selling point of many DFC technologies. DFC can achieve a higher flexibility in design compared to traditional means of construction, offering a chance "to realize precisely what the client has a need for."

DFC is well-suited for non-standard, geometrically complex design elements that are typically material-, time- and cost-intensive. Typical design examples are bespoke or small-series production of unique and complex geometries that can feature internal voids, openings, or surface patterns.

These capabilities are used to optimize material use, manufacture to fit, increase structural performance and explore new architectural possibilities. The customizability is a fit for architecture where there is demand for "many individual solutions". DFC offers options "to produce unconventional building components at a reasonable price point." DFC can revive architectural details or efficient structural designs no longer deemed feasible due to skill shortages or high labor cost. There is also demand for one-of-a-kind products in civil engineering "like geotechnical [applications] or ducting and piping […]. These have a large potential market given there is a lot of need for custom pieces."

Still, DFC technologies widely vary in the degrees of freedom they allow. Layer-based element or formwork production favors vertical structures and allows for limited overhangs or undercuts. When using 3D printed formwork, demolding intricate geometries can be problematic, and casting thin elements requires special, self-compacting concrete mixes. In addition, design freedom can be constrained by factors like structural reinforcement or building codes, e.g. when prescribed concrete cover affects part dimensions. Generally, DFC is assumed to be more competitive for non-standard geometries due to the higher cost of fabricating them conventionally. Therefore, freedom of design provides opportunities for the market uptake of DFC technology.

C - Properties

Versatility. Versatility measures the potential of a DFC technology to produce different results and process different materials, determining the range of possible products. Versatile DFC technologies allow the production of various product groups, e. g. walls, slabs, and columns, while others are restricted. E.g., extrusion printing is limited to vertical elements, while filament-printed formworks or internal matrices can produce "any complex pre-cast structure," and offer a choice between prefabrication and on-site casting. This versatility is also visible in the range of functions a DFC product can fulfil simultaneously if designed to be "truly multifunctional." Using DFC, "you can integrate acoustic effects, […] direct natural light in a room, [and] use thermal activation," while "saving weight in multi-story buildings" and eliminating secondary elements, e.g. drop ceilings to cut cost, construction time and emissions. Applying different finishes in a separate production step can increase versatility, e.g. by offering a rough finish for structural applications or a smooth, architectural finish.

The versatility of a DFC process is also determined by its expected future application range. Early-stage applications of DFC technologies do not typically cover all their potential capabilities, but the process can be made more versatile "by modifying it and tailoring it to new requirements," e.g. by adding new material variations, reinforcement options or recycled materials. Such future incremental innovations can be highly relevant for adoption. A still little explored aspect of DFC is its potential to be combined with conventional technologies. "With 3D printing, we have a new toolbox to do things that so far haven't worked. An if you combine conventional processes with 3D print, you really win." This can also extend application into the realm of retrofitting and renovation, e.g. by "digitally scanning existing buildings that are in need of repair […] and creating a glove fit" with DFC parts.

Surface quality. Surface quality is specific to each DFC process and affects both performance and market acceptance. Many DFC processes have specific surface expressions resulting from the DFC equipment. Surface quality can determine the application range of the DFC product: For example, it affects durability for exterior elements, and dimensional imprecisions can preclude use of the technology where tight tolerances are required.

The visual surface quality can be decisive for architectural applications. "Architects have very high expectations […]. If you see a print layer, that can have a disturbing effect," even if it is "in the millimeter range". Surface patterns resulting from DFC processes are also seen partially as a limitation, partially as a value-add "telling a good story" about the new digital method. In architecture, such tool paths are used as unique design features, extending the variety of finishes available in conventional products. However, the range of surface qualities DFC offers is directly coupled with the process parameters and tool paths and cannot yet match the choices offered by conventional options. Although DFC products may always look different, and "there will be a habituation effect," architectural DFC application must "place emphasis on high-quality surfaces" to gain market acceptance.

The surface quality of concrete DFC products differs largely, e.g. displaying a rough, layered appearance, a microstructure from 3D printed formwork, a smooth extruded surface, or a customized, post-processed finish. Higher precision often requires slower processing speed, e.g. due to smaller-scale deposition layer size or better resolution in formwork printing, so some DFC methods aim at "producing rough shapes fast and large," either when visual quality is not a requirement or as a basis for subsequent surface finishing or treatment with other methods. The labor required for such post-processing can diminish the competitive advantage of DFC; "if you print a complex [formwork] part but then have to […] brush on Epoxy to get a formwork surface, you stand no chance in an industrial process."

Structural properties. Concrete DFC products vary widely in structural performance, which is a key factor in their adoption. In general, a value proposition of DFC is the ability to optimize the geometry of a manufactured part precisely for specific load cases. This can increase structural efficiency and lower material consumption, which is expected to be an argument for its economic feasibility. DFC technologies based on printed formwork and casting tend to be more structurally performant than parts fabricated with direct printing which lack the isotropic properties and compression strength of conventional concrete.

However, the structural properties of concrete products are also highly affected by reinforcement, which can be challenging to integrate in an additive concrete DFC. Developers and adopters of DFC alike see this as "the biggest challenge in the whole process." Reinforcement options have different drawbacks: pre-placed rebar must be custom fabricated to match part geometry and can clash with DFC tools; rebar added in-process is labor intensive and lacks structural continuity; post-tensioning cables in pre-printed channels are costly to install and often require additional rebar; adding reinforced concrete in pre-printed voids limits shape freedom, and casting can cause cracking; internal matrices as lost formwork require manual casting and finishing; ductile (e.g. fiber-reinforced) printing materials are effective in preventing cracking and during transportation but are not sufficient for larger structural tension forces.

In addition to the reinforcement topic, the material durability and longevity of DFC products varies depending on the material deposition process. This can further restrict the application range, e.g. for load-bearing parts or when exposed to the elements, especially as the durability is often still unknown. For parts with low structural requirements, DFC can be a suitable solution, e.g. to replace masonry structures in indoor environments. In the non-loadbearing segment, DFC also extends the application range of concrete into filigree dimensions typically not feasible.

Code compliance. The properties of DFC are often outside of prescriptive norms and building codes. "Fire resistance, durability, environmental facts, frost resistance, chemical, […] insulation properties, acoustics. These are all properties related to code compliance." DFC lacks long-term experience values, particularly when material properties are altered by concrete admixtures or layered deposition. As a result, using DFC for essential building components requires certification based on physical testing and calculations. "A product certification is a big effort and costs a lot of money," especially as it must done separately for local regulations in each jurisdiction where the product is used and for each product change. Single-case certifications are another option, but these add schedule uncertainties and cost on the project level. Permit procedures are still largely unregulated, and "if you have to submit "200 pages of calculations, the workload makes a project uneconomical." In addition, quality control protocols and long-term monitoring agreements may be required.

Liability is another adoption barrier. "From a technical perspective, it is possible […] to let the printer drive automatically to the right location and start printing […]. [But] if something goes wrong you are not insured, and we find it too risky […] That's the same [as] with autonomous cars. It's still a difficult area." Product certifications can help: "People will implement something more readily […] and insurance will say this can be approved."

DFC can be merged with norm-conforming conventional components to meet code requirements. E.g., extrusion printing is used as "lost formwork" selectively filled with reinforced concrete, or concrete cover is increased in formwork-based DFC. These are trade-offs with the theoretical optimization potential of DFC. In the long run, "the topic of standardization will have to be addressed, otherwise it just won't be usable in the construction industry." But in the short term, hybrid approaches help "not to be [too] restricted by standardization" without precluding the structural use of DFC.

C - Properties / A - Resources (shared)

Circularity. Circularity includes the use of recycled or renewable material content as well as future recyclability and reusability of the DFC product. The use of recycled content in DFC concrete usually consists of downcycled aggregate and offers similar potential to conventional concrete. DFC has the advantage of combining material saving potential with recycled material use. "It is our goal to save 40% of the material and to produce with fully recycled materials." However, this has not yet been achieved and requires substantial material research. In addition to reducing carbon footprint and raw material consumption, circularity offers potential cost savings.

DFC technologies using polymer filament printing allow for a higher number of reuse cycles for non-standard formworks compared to conventional wood, hard foam, or resin. They offer the option of downcycling after use or the use of biodegradable polymers to avoid landfill. Other forms of formwork printing, e.g. binder-jetting with mineral binders, allow grinding down and reusing the formwork material either for new prints or as a concrete additive, creating a closed material cycle. Binder-jet printing particularly poses circularity challenges. The use of organic binders and epoxy surface coatings results in non-separable landfill and in some cases hazardous waste. This is a permanent loss of valuable raw materials, e.g. quartz sand, and waste deposition is an environmental and economic liability that "has to be avoided because of the large volumes" produced at the building scale. Full circularity has not been introduced in concrete DFC, but its potential is under investigation by many adopters of DFC. However, much of it relies on progress made in the concrete industry and is not proactively driven by DFC. One area where DFC contributes to enabling circular construction is the cross-fertilization of digital deposition technologies developed for DFC, e.g. shotcrete and material extrusion, with rammed earth or clay materials.

4.2. DFC scoreboard

This section presents the DFC Scoreboard. developed in response to Research Question 2: How can we use these categories to effectively match DFC technology capabilities and adopters' needs in practice?

Section 4.2.1 describes the functionality and user interface, and Section 4.2.2 presents the results of pilot testing the Scoreboard, and Section 4.2.3 presents a simple first use case.

4.2.1. Functionality and user interface

To address our second research question - *how can we use these categories to effectively match DFC technology capabilities and adopters' needs in practice* – we propose the DFC Scoreboard as an interactive, practical tool to match technology potential and industry needs.

The Scoreboard adds two further elements to Conceptual Framework: (i) a functionality to rate the level to which a DFC technology addresses each category, or to which each category must be addressed to suit a prospective adopter's needs; (ii) a practical interface for users to interact with the framework and rate the categories.

As the user interface, we developed a simple representation in

Microsoft Excel consisting of a list of the 15 categories in the Conceptual Framework with a drop-down menu to select one of the four rating choices (See Fig. 9). The tool displays a short qualitative description of each rating step for all Categories in a drop-down menu. In addition, a 120-word description of each category included with the Excel Scoreboard tool to clarify the content of the category. Examples of the rating steps are shown in Table 2. The full rating scale and description of all categories is provided in the Appendix.

Based on the selected ratings, the tool generates a radar chart as a "profile" (Fig. 8). The selected scores are translated to the chart as follows: In case of the Categories in *Resources* (light blue), this means a rating labeled *High* or *Very high* is associated with a lower score on the chart (reflecting that the high rating expresses a disadvantage, e.g. in terms of high material cost, time, or emissions). In case of the Categories in *Production* and *Properties* (turquoise and green), this means a higher rating score is associated with a higher score on the chart (e.g. a high degree of software integration or surface quality).

The resulting "profiles" can serve a range of purposes. First, technology suppliers of DFC can create a *capability profile* assessing the potentials and qualities, but also possible challenges and weaknesses of their technologies and make these profiles available to adopters. Second, prospective DFC adopters can generate a *needs profile* to assess their needs and preferences when looking for a DFC technology to improve their processes or launch new products. These profiles can subsequently be compared, e.g. to evaluate one needs profile against a range of potential DFC technology solutions.

4.2.2. Scoreboard pilot testing

A round of pilot testing of the DFC Scoreboard was conducted with potential users to establish three indicators of the practical utility of the tool:

I) *Variation in the capability profiles:* The tool should be able to capture distinctions in the capabilities of the different technologies rated.
II) *Consistency of independent ratings:* The tool should return similar ratings for the same technology.
III) *Variation in the needs profiles:* The tool should be able to capture variation in the demand for DFC technologies.

The DFC Scoreboard was circulated to two groups of candidates:

- *DFC providers* were asked to generate capability profiles for their specific technology. They were given the DFC Scoreboard tool without any prior knowledge of how it works and asked to rate their technology. Participants were selected across all six types of DFC.
- *DFC adopters* were given the DFC Scoreboard without any prior knowledge and asked to generate a needs profile for their business context. DFC adopters are representatives of contractors and manufacturers who wish to use DFC but not certain of which technology best matches their business needs.

All testers received the identical DFC Scoreboard tool and category descriptions. Below we present the results of the scoreboard testing.

I) *Variation in the capability profiles*

This research established that DFC subsumes various types of technologies with distinctly different properties and potentials. Therefore, we expect rating these types of DFC to result in different profiles if the

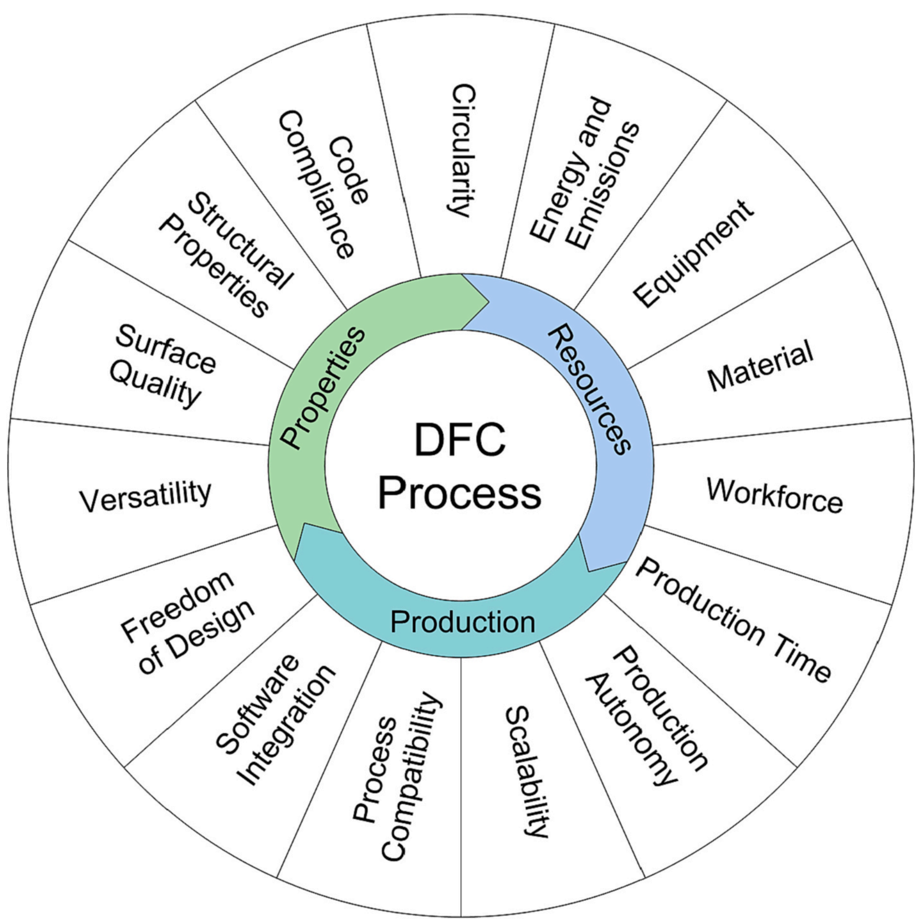

Fig. 8. DFC evaluation framework.

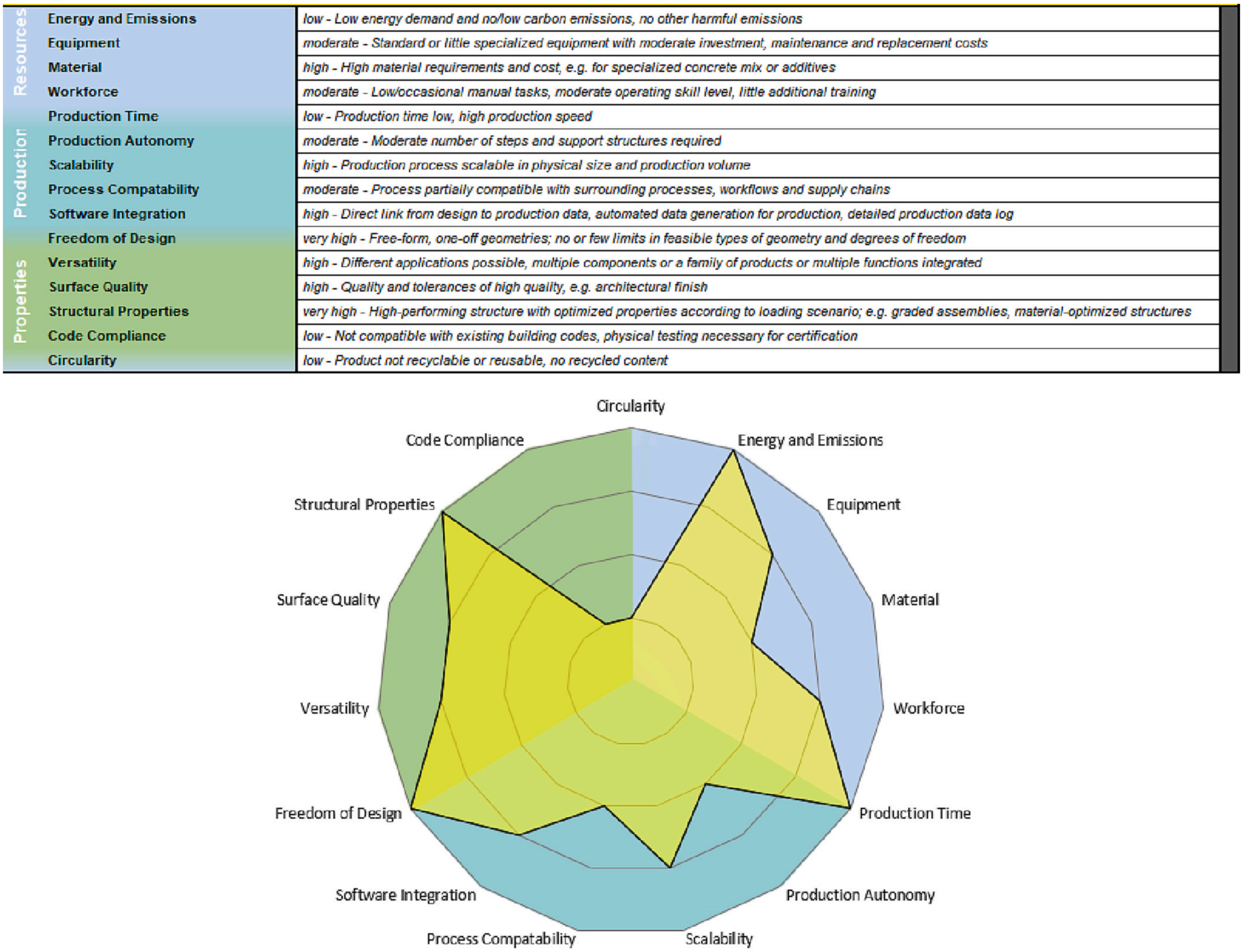

Fig. 9. User interface of DFC Scoreboard with example profile.

categories are sufficiently clear and distinct. In the sample of 22 ratings received, we find a spread of 3 or 4 in each category. The results also give an indication of the tool's ability to uncover distinctions in the use potential of different DFC technologies by showing their strengths and weaknesses in complementary areas. Fig. 10 illustrates one exemplary rating for each DFC type identified in Section 2.1.

II) *Consistency of independent ratings*

Fig. 10.)

Next, we verify that the variation in the scoring results stems from actual differences in the rated technologies and not from the respondents' different interpretations of the meaning of the categories. To test for this, we asked for parallel ratings to check for their consistency. For three DFC technologies, we received independent ratings from two individuals. Identical results were not expected for the qualitative constructs; the three exemplary results had identical scores for 50% or more of the categories and were within 1 rating step for all others (Fig. 11), giving a preliminary indication of the tool's ability to repeatedly produce similar results [97].

III) *Variation in the needs profiles*

Variation in the needs profiles indicate that potential adopters of DFC have divergent needs and are capable of evaluating them in a differentiated manner using the Scoreboard. This suggests a potential need for a variety of DFC technologies (Fig. 12). It shows that a nuanced assessment of user needs is attainable independently of a specific DFC technology.

4.2.3. *Use case example*

To exemplify the matchmaking capability of the DFC Scoreboard, we tested a simple three-step use case with one single potential adopter. The respondent was a division head at a leading Swiss construction contractor. The company had previously participated in a DFC demonstrator project and had expressed interest in adopting DFC technology. The use case was structured as follows.

- First, the respondent created a needs profile using the DFC Scoreboard. This was done in an online meeting with two of the authors present to answer questions about the categories and Scoreboard functions.
- Second, the authors selected three capability profiles previously collected from DFC providers that best matched the needs and returned to the respondent together with the complete list of available capability profiles. The capability profiles were color coded by technology types and the description of the technology types was included.

Table 2
Examples of category rating scale.

main category	category (example)	Rating choices
Resources	Equipment	• ***very high*** **-** Highly complex or specialized equipment with very high investment costs, frequent maintenance or replacements • ***high*** **-** Complex or specialized equipment with substantial investment maintenance and replacement cost • ***moderate*** **-** Standard or little specialized equipment with moderate investment, maintenance and replacement costs • ***low*** **-** Simple equipment with low investment, maintenance and replacement costs
Production	Scalability	• ***low*** **-** One-off production not scalable in physical size and production volume • ***moderate*** **-** Production process somewhat scalable in physical size and/or production volume • ***high*** **-** Production process scalable in physical size and production volume • ***very high*** **-** Very high scalability in physical size and production volume
Properties	Structural Properties	• ***low*** **-** Low structural performance; additional reinforcement required to provide load bearing capabilities • ***moderate*** **-** Moderate structural performance, e.g. load-bearing wall for single-story structure or non-loadbearing wall • ***high*** **-** Good structural performance, e.g. load-bearing columns, walls or shear walls • ***very high*** **-** High-performing structure with optimized properties according to loading scenario, e.g. graded assemblies, material-optimized structures

- Third, we the respondent was asked to review the matches, select alternative matches if desired, and rank their three top choices according to their perceived usefulness for their business.

The following feedback was received:

- The respondent agreed with the choice of best matches as theoretical options to further investigate.
- The respondent was able to rank the profiles by their perceived usefulness to the company. The ranking shown in Fig. 13.
- The respondent would not have been able to create the user needs rating without the chance to ask questions in the moderated process, indicating that the user interface was not yet intuitive enough.

5. Discussion of results

5.1. Systemic understanding of DFC

At the departure of this study, we recognized that DFC constitutes a systemic innovation [63]. Its adoption therefore relies on process integration and technology acceptance, both of which requires a shared understanding across a diverse spectrum of actors in design, engineering, management, manufacturing and construction of how a given DFC technology's resource requirements, process characteristics and output properties result in its capability to address their user needs. The existing DFC literature has focused on two aspects: First, the description and classification of DFC in terms of technology types and the identification of the technical challenges prevailing in each type [2,4]. Second, the identification of specific, isolated non-technical barriers to DFC implementation, e.g. the need for better integration with digital planning tools [54], more interdisciplinary development [4], integrating fabrication parameters in the design [7], cope with uncertainties on construction sites [58], or establish new workflows and roles [59]. This research establishes the first analytical framework that can be used to classify and compare DFC technologies along their systemic characteristics, which are both technical and non-technical in nature. Where previous DFC research has not yet fully acknowledged the systemic nature of DFC, this paper argues for the equal importance of technical and non-technical considerations as DFC develops towards more widespread

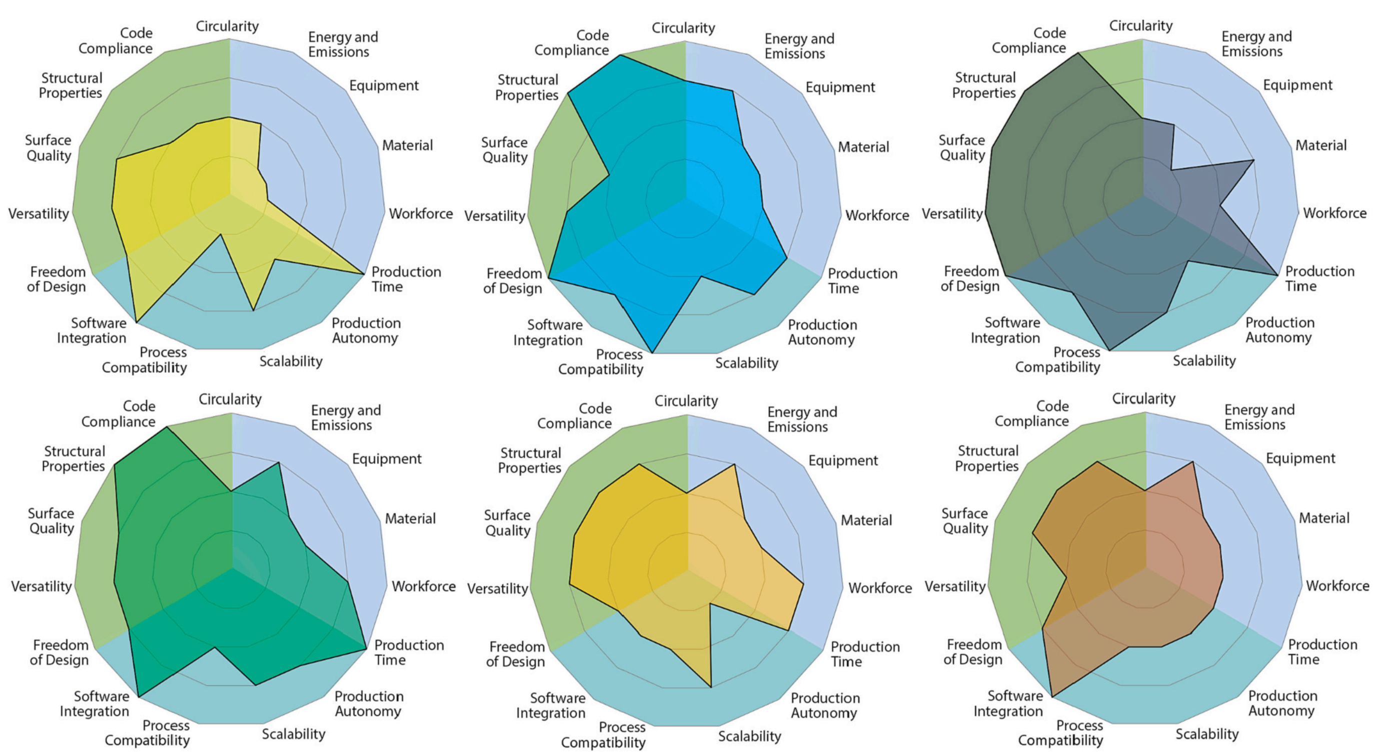

Fig. 10. Exemplary results of Scoreboard testing (top row from left: direct material extrusion, FDM, binder jet printing. Bottom row from left: shotcrete 3D printing, slip forming, mold-less shaping with internal matrix)

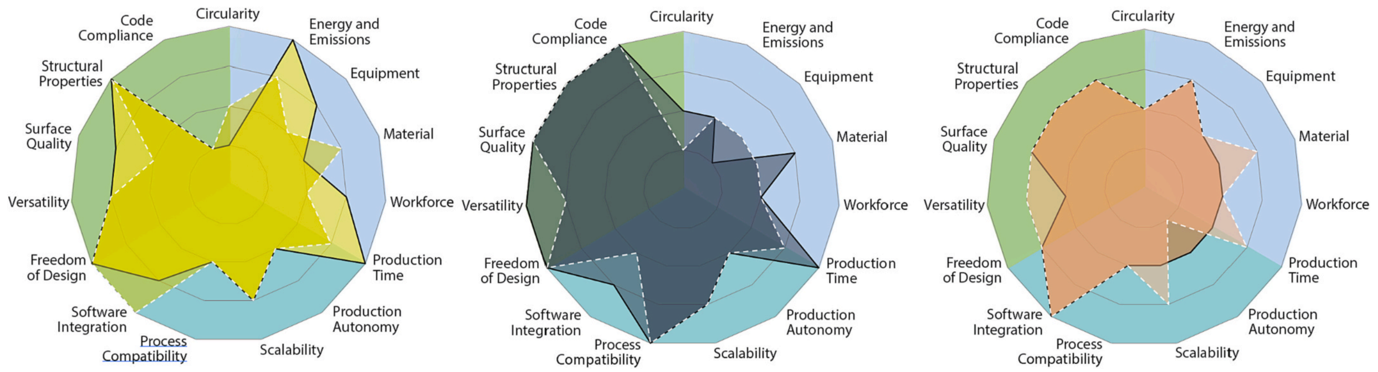

Fig. 11. Comparison of independent ratings of the same DFC technology (from left: direct material extrusion, binder jet printing, mold-less shaping with internal matrix)

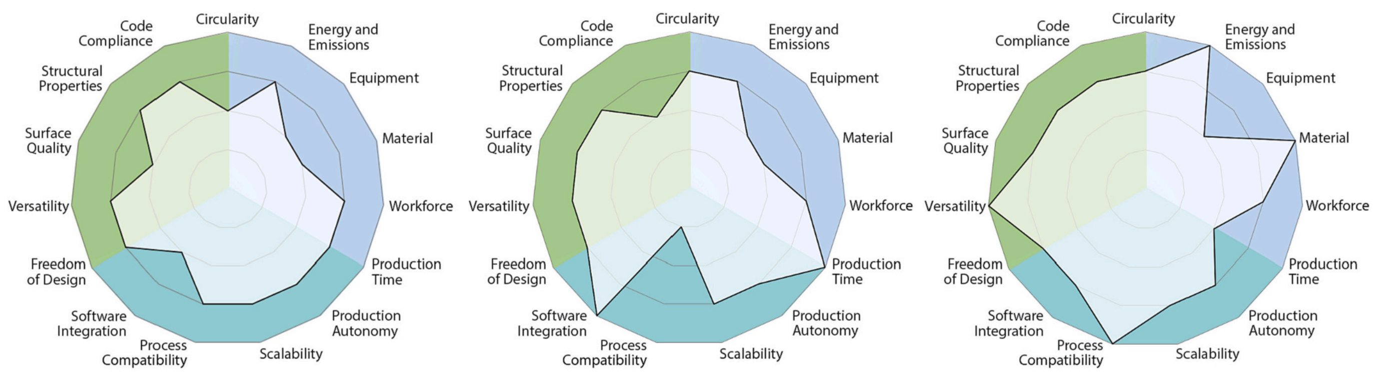

Fig. 12. Exemplary results of needs evaluation (from left: concrete construction contractor, industrial concrete prefabricator, architectural element prefabricator).

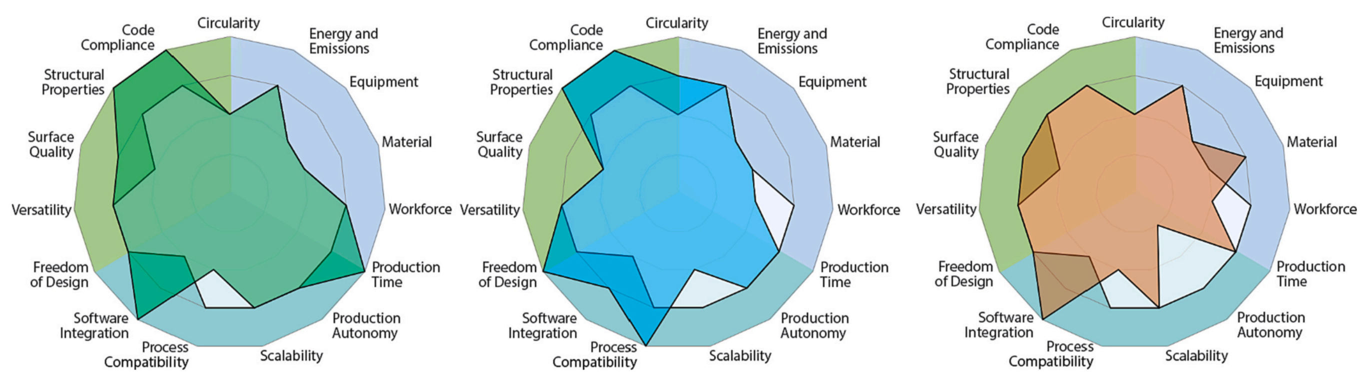

Fig. 13. Needs profile (white shaded) overlayed with three capability profiles ordered by the respondent's ranking (from left: shotcrete 3D printing, FDM, mold-less shaping with internal matrix).

implementation.

This systemic analytical framework for the evaluation of DFC offers an opportunity to unify the classification of technologies across the DFC spectrum. The proposed system of categories focuses on the inputs, process parameters and outcomes of a given technology solution in a manner that is *independent of the enabling technology*. While previous studies might take some consideration to these factors in the context of one particular technology [7,19,33,53,62], this research establishes for the first time a unifying analytical format to evaluate and compare processes across different technical classes of DFC. The resulting framework is a theoretical contribution that promotes understanding of DFC as a systemic process classification rather than an aggregation of separate technology types that share little but the fact that they are designed to process cementitious materials. The evaluation of the adoption potential along the proposed analytical categories therefore does no longer start with a technology choice (e.g. 3D extrusion printing) but with an evaluation of technology capabilities across the entire spectrum of DFC and their match with potential user needs.

The qualitative data analysis reveals many ways in which the potential of DFC adoption to practice hinges on a combination of technical challenges with process-related, organizational and sociotechnical characteristics. The analysis results underscore the systemic character of DFC, as each evaluation category is composed of technical and non-technical concepts found in the qualitative data. Because the framework was inductively developed from a qualitative data set representing a variety of DFC types, organizations, roles, and disciplines, it reflects a balanced combination of relevant evaluation categories. Thus, it establishes a holistic view with focus on what DFC can do, independently of the type of technology. This creates a new approach to evaluating the utility of DFC independently of technical details, which is complementary to the existing technical classifications structuring the understanding of DFC by its technology type or method, e.g. [2,4]. Because DFC Evaluation Framework was informed by a broad sample of different DFC technologies, it can claim applicability across the spectrum of today's emerging DFC technologies and processes.

One example illustrating the systemic nature of the Framework is the inclusion of non-automated steps of DFC in the analysis of many categories. This reflects the reality of practice, where such additional steps are what turns a stand-alone digital fabrication technology into a usable construction process. It is also where considerations of interfaces with complementary process steps and workflows, other actors, and established technologies come into play, further underscoring the systemic nature of DFC. The analytical categories aim at creating a general description of a DFC technology in terms that can be understood by stakeholders from different disciplines and backgrounds, thus answering the challenge addressed in our first research question.

5.2. Matching technology capabilities and user needs

Analyzing a DFC technology in its early development stages along the categories of the DFC Evaluation Framework can reveal relevant information when it is usually unavailable or hard to evaluate for those outside the technology development team or expert networks. The possibility to evaluate a potential user's needs along the same categories for comparison offers the opportunity to analyze the properties of a DFC technology in terms of their potential value to an adopter. Thus, the analytical framework assigns the same importance to the adopter needs as to the capabilities of a technology considered for adoption, thereby putting the focus simultaneously on supply- and demand-side constraints. This is important in the context of technology adoption because the user perspective is an important driver of innovation in construction [98], and the environment in which a future user of a DFC technology operates is potentially more important to successful adoption than the properties of the technology itself [62].

The DFC scoreboard represents a simple example how this matching of technology capabilities and user needs could be facilitated in practice. The addition of the scoring system and the simple visualization of the results contributes a practical element to turn the evaluation framework into a tool to effectively match DFC technology capabilities and adopters' needs in practice, giving an exemplary answer to our second research question.

This direct comparison, structured by the analytical categories of the DFC Evaluation Framework, establishes an alternative perspective to either the "push"-perspective often favored by DFC researchers and suppliers, who focus on their technology capabilities as determinants of adoption, or the "pull" model favored by users, who may discard partial matches as they seek technology solutions to address their specific business needs.

The pilot testing of the DFC Scoreboard gives a preliminary indication how DFC capability profiles can be matched with the needs of adopters both with and without previous knowledge of DFC. Besides identifying the best overall matches between capability and needs profiles, the tool was able to identify within those matches in which of analytical categories there are remaining differences between the user's needs and technology capabilities must be addressed.

The matching function demonstrated here in principle could be further developed into the following use scenarios.

Use Scenario 1. In its simplest form, the DFC Scoreboard could be made available as an open-source tool for download and used by individual research groups and firms to create technology capability and user needs profiles, juxtapose, and compare them as illustrated in Fig. 13.

Use Scenario 2. The DFC Scoreboard could be used by a consulting firm or a research organization acting as an integrator. It would be made available, e.g. as a cloud-based tool, to engage select partners on both the supply and demand side of DFC in a moderated process of information exchange between potential partners guided by the integrator.

Use Scenario 3. The DFC Scoreboard would be made available as a web-based application. Its basic functions, e.g. the self-rating of needs or technology capabilities, could be open access. At the back end, the tool could be combined with a database of needs and capability profiles provided by users; from this database, top matches could be returned to the scoreboard user.

5.3. Limitations and future research potential

This study has several limitations. First, it is a purely qualitative study limited to DFC technologies, a class of digital fabrication which to date has seen little industry adoption at scale. As it stands, the conceptual framework cannot claim applicability beyond the field of DFC. To reflect the growing diversity of digitally enabled construction systems, this study could be extended to a more diverse sample of digital fabrication technologies and material systems.

Second, the scope of this study does not address the potential of coupling the holistic qualitative evaluation proposed in this paper with quantitative metrics, e.g. on productivity or environmental Life Cycle Assessment (LCA) [99]. Several but not all categories in the proposed framework could lend themselves to quantification. Future research is called for to address the question how to unify the qualitative and quantitative perspectives.

Third, this study focused on establishing a tool set for qualitative technology evaluation of DFC. The pilot testing performed is merely illustrative. To create an impact on technology transfer to practice, this tool will need further validation of its effectiveness through broader application and testing. More data is necessary to scale the use of the Scoreboard and increase chances of successful market transfer of DFC.

Fourth, there is future research potential in developing methods to control the accuracy of ratings for the Scoreboard to be applied more broadly in the industry. There are several open questions about how to ensure accuracy of the data entered by users. For example, self-ratings by technology providers could potentially be "inflated" by optimism bias or by the desire to return more matches. Possible strategies are allowing other users to rate the accuracy of capability profiles, administering the input process individually, or penalizing over- as well as under-performance compared to a given needs profile when evaluating matches.

6. Conclusion

Based on interviews with 32 research and industry leaders in DFC, we developed a Conceptual Framework to assess the transfer potential of DFC technologies using qualitative methodology. The framework offers insights into the inputs, process parameters and outcomes of a given DFC technology, and establishes a unifying analytical format that can be used to compare processes across different technical classes of DFC. We then condensed our findings in the DFC Scoreboard, an evaluation tool designed to match the capabilities of emerging DFC technologies with potential adopters' needs, aiming to offer guidance in technology decisions made by the construction industry on adoption and further development of DFC. We described the functionality of the tool and reported on its first pilot testing. We discuss the implications of the results for a unified systemic understanding of DFC and for matching technology capabilities and user needs in the technology adoption process. The proposed systemic understanding of DFC builds a basis for future research and industry development to pursue more needs-based and scalable digitalization strategies for concrete construction fit for the wide-spread adoption needed to unlock the still unused potential of digital fabrication to address the persistent productivity, sustainability and versatility challenges of concrete construction.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Daniel M. Hall reports financial support was provided by BASF Schweiz AG.

Data availability

The data that has been used is confidential.

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Appendix A. Category rating scale

Category		Rating	Description
Resources	Energy and Emissions	very high	Very high energy demand, carbon and/or other harmful emissions
		high	Energy demand and/or carbon emissions high, possibly other harmful emissions
		moderate	Energy demand and/or carbon emissions moderate, no other harmful emissions
		low	Low energy demand and no/low carbon emissions, no other harmful emissions
	Equipment	very high	Highly complex or specialized equipment with very high investment costs, frequent maintenance or replacements
		high	Complex or specialized equipment with substantial investment maintenance and replacement cost
		moderate	Standard or little specialized equipment with moderate investment, maintenance and replacement costs
		low	Simple equipment with low investment, maintenance and replacement costs
	Material	very high	Very high material requirements and cost, e.g. for unique, cost-intensive material with additives or multiple materials
		high	High material requirements and cost, e.g. for specialized concrete mix or additives
		moderate	Moderate material requirements, e.g. conventional concrete mix
		low	Low material requirements, e.g. no special mixes, savings through reduced material volume, recycled materials or reuse
	Workforce	very high	Very high labor and/or skill requirements, substantial training of workers required
		high	High labor and/or skill requirements, special training required
		moderate	Low/occasional manual tasks, moderate operating skill level, little additional training
		low	Can be operated with little labor and/or with minimal operating skills
Production	Production Time	very high	Very high production time expenditure, very low production speed
		high	Production time high, low production speed
		moderate	Production time expenditure, speed moderate
		low	Production time low, high production speed
	Production Autonomy	low	Multiple manual steps and/or permanent supervision required; additional support activities or structures required
		moderate	Moderate number of steps and support structures required
		high	Automated process with little supervision, small number of manual production steps, little additional support activities or structures
		very high	Highly automated process with minimal manual production steps, no additional support activities or structures required
	Scalability	low	One-off production not scalable in physical size and production volume
		moderate	Production process somewhat scalable in physical size and/or production volume
		high	Production process scalable in physical size and production volume
		very high	Very high scalability in physical size and production volume
	Process Compatibility	low	Process not compatible with surrounding processes, workflows and supply chains
		moderate	Process partially compatible with surrounding processes, workflows and supply chains
		high	High compatibility with surrounding processes, workflows and supply chains
		very high	Process fully compatible or integrated with surrounding processes, workflows and supply chains
	Software Integration	low	No link between design and fabrication data, no production data log
		moderate	Simple translation from design to fabrication data, basic production data log
		high	Direct link from design to production data, automated data generation for production, detailed production data log
		very high	Bi-directionally linked design and production data, feedback of production constraints to designers, recording of as-built state, detailed production data log
Product Properties	Freedom of Design	low	Only one type of geometry with limited variation (max. One degree of freedom, e.g. height)
		moderate	Only one type of geometry with more than 1 degree of freedom variable (e.g. height and diameter)
		high	Multiple types of geometry and degrees of freedom, customizable geometry (e.g. cross-section, height, angles, etc.)
		very high	Free-form, one-off geometries; no or few limits in feasible types of geometry and degrees of freedom
	Versatility	low	Only one specific application possible, mono-functional product
		moderate	One specific application with variations possible, minor additional functions integrated
		high	Different applications possible, multiple components or a family of products or multiple functions integrated
		very high	Almost any application possible (fully versatile tool that can process multiple materials); wide range of products possible
	Surface Quality	low	Very low quality, e.g. very high variations in geometry relative to model, very low/porous surface quality (e.g. for underground application)
		moderate	Moderate quality, e.g. geometric tolerances relative to model, porous surface, pronounced tool paths
		high	Quality and tolerances of high quality, e.g. architectural finish
		very high	Very small dimensional variations relative to model, highly refined surface and detailing, high control of smoothness or custom texture
	Structural properties	low	Low structural performance, additional reinforcement required to provide load bearing capabilities
		moderate	Moderate structural performance, e.g. load-bearing wall for single-story structure or non-loadbearing wall
		high	Good structural performance, e.g. load-bearing column, walls or shear walls
		very high	High-performing structure with optimized properties according to loading scenario, e.g. graded assemblies, material-optimized structures
	Code Compliance	low	Not compatible with existing building codes, physical testing necessary for certification
		moderate	Not compliant with norms and standards, substantial calculations or equivalency assessments necessary for certification
		high	Code compliant in principle, some individual evaluations or calculations necessary
		very high	Fully conforming or certified to existing norms, codes and standards
	Circularity	low	Product not recyclable or reusable, no recycled content

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Category	Rating	Description
	moderate	Downcycling possible or uses downcycled materials
	high	*Re*-use, recycling/upcycling possible or uses recycled/upcycled material
	very high	Fully circular material and process, reusability, closed material cycle

Appendix B. Description of categories

This table explains the categories. Please read before entering your ratings in the DFC Scoreboard.

Category		Description
Resources	**Energy and Emissions**	This category includes energy demand for production and embodied energy in the materials. Energy demand of the equipment as a direct input is a minor cost factor. Embodied energy is more relevant as a measure of environmental sustainability and as a potential future cost driver based on CO2 prices and energy cost as a contributor to material cost. Embodied energy can be controlled through the primary material properties, material savings and the avoidance of waste and secondary material use. In addition to carbon emissions, some materials cause harmful emissions either in the raw material extraction or the DFC process itself. When rating Energy and Emissions, it is important to consider the entire supply chain of a DFC process.
	Equipment	Equipment for DFC varies widely in complexity and cost. DFC-specific production equipment requires substantial initial capital expenditure and can present an entry barrier to using DFC. Equipment availability, lead times, and maintenance requirements also need consideration. Equipment types for concrete DFC are diverse. E.g., direct extrusion requires a feed system and a mortar extrusion nozzle attached to a robot or gantry; printing formwork requires a filament or binder jet printer; concrete slip forming uses a movable formwork and automated feed system. DFC systems require differing degrees of integration between their individual parts controlled by proprietary software. Different equipment ownership, leasing and service models can help mitigate these issues but also create dependency on the equipment provider.
	Material	DFC processes tend to be highly dependent on material properties. In the additive DFC technologies, the primary mortar or concrete material used is highly specific, with processing steps strictly coordinated based on tightly controlled material properties. Materials used in DFC tend to be costly. Formwork and support print materials require equal consideration. Most DFC processes therefore rely on standardized, proprietary materials. This can create dependencies on single material suppliers. Advantages of high material control are the potential to save material by precise deposition and the elimination of formwork.
	Workforce	Workforce is a key parameter for DFC adoption. Labor productivity is one of the most frequently used productivity measures in construction since labor is usually the driving cost factor. DFC offers potential to increase process automation and reduce process supervision requirements, impacting both labor time as a direct input and the required skillset of the workforce. Both factors have cost implications. DFC usually reduces labor hours but to varying degrees. The required skill level of the workforce varies greatly, ranging from very high to low depending on the DFC process. Time and cost for training the workforce must be considered. The shift away from manual labor can contribute to work safety.
Production	**Production Time**	Output per unit of time is an important factor for the industry adoption potential of DFC processes. Most DFC processes are a combination of automated and manual tasks. Total production time consists of the processing speed dictated by the equipment and the material setting behavior, equipment preparation (set-up, calibration and cleaning), material preparation (concrete, formwork or reinforcement), manual tasks (e.g. post-processing), and curing time. Increasing processing speed often adversely impacts surface quality. Low processing speeds can also be offset by operating more equipment simultaneously, leading to a time-cost tradeoff.
	Production Autonomy	Production autonomy is determined by the degree of automation of each production step and by the integration between the individual automated steps of the production procedure. In addition, preparation and close-out tasks are often not automated. While automation of DFC steps is a prerequisite for production autonomy, the degree to which production is autonomous is largely determined by the number of required production steps and the degree to which manual interventions are necessary before, in between and after these steps. Some DFC technologies allow alternative sequences affecting Production Autonomy, such as pre-printing vs. simultaneous printing of a formwork or different reinforcement options.
	Scalability	Understanding scalability is a key parameter in DFC technology adoption decisions. It describes whether a technology can be scaled in physical size or production volume for industrial production. Upscaling typically requires changes to the manufacturing set-up, e.g. to handle large material quantities, increase speed, robustness, and level of automation. As a result, the mature industrial production process may differ substantially from earlier developments. Scalability can also be limited due to transportation and handling, structural performance, or building codes. Scalability often determines the economic feasibility of commercial DFC use. Factors inherent in each DFC technology (e.g. material behavior) can hinder or enable upscaling. Technology maturity at the time of adoption is also a factor. Business models (e.g. equipment as a service, leasing) can help scalability.
	Process Compatibility	This category describes the compatibility of the DFC process across interfaces with its surrounding processes and workflows. It determines extent to which a DFC process can be integrated with other production processes and business activities in the adopting company. A DFC process can be a stand-alone, plug-and-play workflow without interdependencies, or it can require process changes in surrounding workflows to realize its full potential. A DFC process forcing changes in surrounding existing workflows is more disruptive and requires investments in complementary production systems, new worker skills and cultural change. The ease of adopting a technology and integrating it into established workflows and existing supply chains is highly relevant in DFC adoption decisions.
	Software Integration	Software Integration concerns the data flow from definition of a design to digital production instructions. DFC is defined as a fabrication or building process relying on a seamless conversion of design and engineering data into digital manufacturing code. Its use therefore hinges on the direct link between the design and fabrication process. Using DFC effectively requires knowledge of fabrication constraints in the design process to maximize design freedom, and automated generation of fabrication data from a design model. A strength of DFC is the ability to precisely track production time, material consumption and energy use using its control software. Most DFC processes are operated using a highly integrated, technology-specific software package. The capabilities, interoperability and ease of use of this software environment is a key determinant for DFC adoption decisions.
Product Properties	**Freedom of Design**	Freedom of Design is a unique selling point in the adoption of many DFC technologies. DFC 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 unique and complex geometries, internal voids, openings or surface patterns. These capabilities can be used to optimize material use, manufacture to fit, increase structural performance and explore new architectural possibilities. Still, DFC technologies widely vary in the degrees of freedom they allow. In addition, design freedom can be constrained by factors like structural reinforcement or building codes. Freedom of Design can strongly determine the possible uses of a DFC technology.

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Category		Description
	Versatility	Versatility measures the potential of a DFC technology to produce different results and process different materials, determining the range of possible products (e.g. walls, slabs, columns, etc.) In addition, it determines the range of functions a DFC product can fulfil, e.g. by including insulating or acoustic properties or integrating building systems to increase construction efficiency. Versatility of a DFC process could also allow easier switching to recycled or reused materials. When early-stage DFC technologies are first adopted, their implementations do not typically cover all future capabilities of an emerging technology. The range of different future manufacturing options a DFC technology affords can strongly affect its adoption potential. Versatility depends on the properties of the DFC technology and can be a significant value-add.
	Surface Quality	Surface quality is specific to each DFC process and affects both performance and market acceptance. Many DFC processes have specific surface expressions resulting from the DFC equipment. Surface quality can determine the application range of the DFC product: it 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. Surface quality of concrete DFC products differs largely, e.g. displaying a rough, layered appearance, a microstructure from 3D printed formwork, a smooth extruded surface or a customized, post-processed finish. Higher precision often requires slower processing speed. Surface patterns resulting from DFC processes are also used as unique design features, extending the range of finishes available in conventional products.
	Structural properties	Concrete DFC products vary widely in structural performance and therefore in their potential application, which is a key factor in their adoption. In general, DFC allows optimizing the geometry of a manufactured part precisely for specific load cases. This can increase structural efficiency and optimize 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 DFC. Options include ductile (e.g. fiber-reinforced) printing material, pre-placed rebar, post-tensioning, or adding reinforced concrete in pre-printed voids. In addition to the reinforcement topic, material durability and longevity of DFC products varies depending on the material deposition process. This can further restrict the application range, e.g. loadbearing vs. non-structural, outdoor vs. indoor use.
	Code Compliance	DFC processes differ in many ways from conventional construction processes. Therefore, the properties of DFC are often outside of prescriptive norms and building codes. In addition, long-term experience with DFC products is lacking due to the novelty of the approach, in particular with material properties altered by concrete admixtures, layered deposition processes, and recycled materials. As a result, using DFC products as essential building components usually requires time- and cost-intensive individual certification processes. Solutions to this challenge in built examples vary. For example, DFC production steps can be merged with norm-conforming conventional components (e.g. as lost formwork with reinforced, cast concrete), tests performed to verify structural performance, or use restricted to non-structural applications. These solutions require trade-offs with the theoretical optimization potential of DFC and can pose design limitations.
	Circularity	Circularity includes the use recycled or renewable material content, as well as recyclability and reusability of the DFC product. The use of recycled content in DFC concrete materials usually consists of downcycled aggregate and offers similar potential to conventional concrete. DFC technologies using polymer filament printing, e.g. for formwork production, offer a high number of reuse cycles for formworks, the option of recycling after use or the use of biodegradable polymers. Other forms of mineral printing, e.g. binder-jetting, also offer potential to grind down and reuse the printing material. In addition to reducing carbon footprint and raw material consumption, circularity offers material cost savings when using recycled material from earlier production runs. Full circularity has not been introduced in concrete DFC but its potential is under investigation by many adopters of DFC.

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