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# Fostering innovative and sustainable mass-market construction using digital fabrication with concrete

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ABSTRACT

The construction industry produces buildings and infrastructure. These *construction works* are typically immobile and customised, and must meet many criteria to provide value to modern society: structural safety, durability, serviceability, aesthetics and integration, environmental sustainability and construction efficiency. Accordingly, traditional construction methods, along with the resulting construction works, have been adapted to comply with these multifaceted requirements for more than a century. However, the construction industry has a considerable environmental impact, with reinforced concrete as its primary driver due to its extensive use, and will be facing an ever-increasing responsibility to tackle climate neutrality in the upcoming years. Digital fabrication with concrete is a young yet already broad discipline that brings about the potential for the necessary reduction of the environmental impact and further industrialisation of the construction industry while being compatible with the multifaceted requirements for construction works. Still, it has not penetrated the construction mass market, which is paramount for making a significant difference towards improving the environmental impact of the construction industry. The present study tackles this issue by (i) assessing traditional construction and digital fabrication on a value-driven basis, identifying and summarising their inherent strengths and challenges, and (ii) proposing a value-driven ideation process to identify relevant mass-market levers of digital fabrication in the construction industry. The presented methodology indicates two exemplary applications of how traditional construction and digital fabrication processes can be combined to tackle the persistent environmental sustainability challenges.

## 1. Introduction

Buildings and infrastructure (embraced as *construction works* in the following) are commonly the final products of the construction industry, providing value to society. Given their size and mass, construction works are immobile and customised to the place they stand. Furthermore, their construction and dismantling impose technical, organisational and societal challenges and constraints. They require interdisciplinary collaboration among many involved parties. The characteristics of (i) immobility, (ii) customisation of the construction works and the construction processes, and (iii) interdisciplinarity make each "final product of the construction industry", i.e., construction work, unique and different from other industries' products.

The value generated by construction works and the extent of challenges and constraints generated by their construction and dismantling depends on various criteria to be fulfilled or optimised. Six main criteria may be identified, basically extending Vitruvius' famous requirements of firmitas (structural safety), utilitas (serviceability) and venustas (aesthetics and integration) by additional criteria, which are equally important today: durability, environmental sustainability and construction efficiency (including economy). Structural safety and serviceability are generally considered rigid criteria, largely defined by design codes. Over the past decades, durability has also been ruled by codes. It may be considered a rigid criterion today, depending on the design life span of the construction work. On the other hand, construction efficiency, environmental sustainability, as well as aesthetics and integration are a matter of client preferences, material availability, or political and socio-economical tendencies. The importance attributed to these criteria is different for every construction work. Table 1 describes and elaborates the criteria, complementing them with corresponding, typical subordinate design requirements along with common measures to comply with the design criteria.

With the substantial growth of the population in the last 100 years and the correspondingly growing demand for construction works,

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**Table 1**
Description and elaboration of main criteria for construction works.

| Criterion | Typical subordinate design requirements | Typical structural concrete design measures |
|---|---|---|
| Structural safety | • Overall stability, ultimate resistance and fatigue resistance for persistent and transient limit states (dead loads, live loads, stiffness and load-bearing capacity of the foundation, wind, etc.)<br>• Overall stability and ultimate resistance for accidental limit states (fire, seismic or impact loading, etc.)<br>• Robustness | • Reinforced concrete cross-sections (dimensions, strength of materials)<br>• Choice of material (type of reinforcement, concrete strength, etc.)<br>• Detailing |
| Durability | • Resistance against corrosion due to carbonation and/or chloride ingress, chemical attack, freeze-thaw cycles, depending on the environmental exposure and design lifespan | • Minimum concrete cover<br>• Detailing (avoidance of joints, protection from chloride ingress, facilitated access for inspection)<br>• Prestressing (avoid cracking)<br>• Used material(s) (concrete mix design, corrosion-resistant steel)<br>• Ensure execution quality |
| Serviceability | • Functionality (building systems, vibrations, sealing, etc.)<br>• Appearance (prevention of excessive deflections or cracking for persistent and transient limit states)<br>• Comfort (temperature, moisture, noise, vibrations etc.) | • Minimum dimensions of slabs and walls (relevant for deflections, sound insulation, building systems)<br>• Type of reinforcement (e.g. use of prestressing steel for limiting deflections)<br>• Increased reinforcement ratio (for sealing) |
| Aesthetics and integration | • Materialisation and surface (visual texture and colour)<br>• Form, rhythm, contrast<br>• Elegance (apparent slenderness and transparency) | • Used material(s)<br>• Efficiency of structural design<br>• Ensure execution quality<br>• Customisation |
| Environmental sustainability | • Minimise resource use, greenhouse gas emissions and waste generated from construction to dismantling<br>• Minimise negative impact on flora, fauna, landscape | • Minimisation of material use (e.g. through structural optimisation or avoiding waste) and transports<br>• Choice of material (e.g. depending on local availability)<br>• Reusability of structure (optimisation of building volume)<br>• Recyclability at dismantling |
| Construction efficiency | • Construction time<br>• Direct construction cost (economy)<br>• Indirect construction cost (e.g. traffic disruptions, construction safety, water pumping, financing and renting) | • Type of construction (on-site or prefabricated)<br>• Availability and cost of chosen resources (material and labour)<br>• Optimisation of the floor area for a given building volume |

construction cost and speed have become increasingly important. The predominant focus on construction efficiency in terms of cost and time, combined with the extensive and cheap availability of raw building materials in the last decades, contrasting with increasingly expensive labour cost, has led to designs rarely pursuing efficient material use in industrialised countries. For example, cast-on-site floor slabs are hardly ever optimised in their concrete volume, e.g. through the use of voids or ribs, since the extra labour cost for design and execution typically exceeds the material savings despite the obvious benefits of lighter slabs in terms of required reinforcement and foundation capacity, as well as reduced seismic action. However, given the construction industry's enormous responsibility for climate neutrality [1], environmental sustainability has become more important, and saving materials should be an imperative design criterion for future construction works.

This study focuses on concrete structures. Reinforced concrete is by far the most used material in the construction industry worldwide [2], thanks to its versatility and the universal availability of the required raw materials at low cost. Due to its extensive use, reinforced concrete is a primary driver of the construction industry's environmental impact: worldwide cement production by itself causes roughly 6 % of the total anthropogenic greenhouse gas emissions, with the use of roughly 0.5 $m^3$ of cement per capita worldwide annually [3,4]. Given the massive share of reinforced concrete in current construction works and the lack of alternatives, particularly in infrastructure and underground construction, significant and continued improvements in reinforced concrete construction are essential to reducing the environmental impact of the construction industry to the extent possible.

Digital fabrication with concrete (DFC) has emerged in recent years as a group of digital fabrication which describes fabrication methods directly following model data [5]. Potential advantages of digital fabrication encompass (i) the possibility to tailor material properties to specific needs, (ii) the possibility of creating complex shapes without excessive fabrication cost and (iii) the direct integration of the fabrication in the overall digital design and construction process. Since these advantages of DFC allow for bespoke material-efficient fabrication without increasing labour intensity, DFC has the potential to drive the necessary reduction in the environmental impact of the construction industry while being compatible with the specific requirements of customised design and execution. The present contribution aims to explore DFC further and identify its mass-market potential with a comprehensive ideation approach to improve environmental sustainability while complying with the remaining criteria for construction works introduced above.

## 2. Research significance

To date, DFC has been used to (i) create topologically optimised structures and introduce innovative architectural elements (e.g. [6–10], shown in Fig. 1a and b), (ii) print walls for comparably small houses (Fig. 1c) and (iii) produce sculptures or furniture (e.g. see [11]).

Structures with complex geometry optimised for a specific load case showcase the potential of DFC. However, geometrically complex structures represent a niche market for signature buildings, such as museums, churches, or pavilions. While infrastructure construction works may benefit to some extent from increased geometric complexity, the vast majority of future building structures will most likely continue featuring rectangularity in plan and elevation, despite geometrical complexity being increasingly cost-efficient: rectangularity serves best to exploit optimally (i) the floor area and (ii) the limited space on earth, particularly in urban areas [12]. In order to have a relevant impact, it is thus essential that DFC becomes competitive for applications in such mass-market construction works.

Current DFC applications explicitly targeting the mass building market, such as 3D printed houses (Fig. 1c), essentially replace lightly loaded masonry walls with unreinforced 3D concrete printed walls or employ DFC as lost formwork instead of relying on traditional


**Fig. 1.** Exemplary applications of digitally fabricated concrete: (a) KnitCandela concrete shell from [6] (Photo credits: Angelica Ibarra); (b) façade mullions produced with Smart Dynamic Casting [7], curved wall produced with the Mesh Mould Technology [8], and Smart Slab produced with a *Particle-bed binding* formwork [9] (Photo credits: Roman Keller); (c) construction of a house with 3D concrete printed walls in Germany (Photo credits: PERI).

formwork. While such applications of DFC facilitate the seamless digital design-to-construction process and may be more time-efficient than conventional walls built by a mason, their environmental impact with currently used concrete mixes is even higher than that of conventional construction. Most DFC processes currently rely on concrete mixes with small aggregates and high clinker contents [13,14], resulting in performance beyond the requirements for lightly loaded walls.

Furthermore, some DFC technologies struggle to comply with fundamental design code requirements regarding structural safety (e.g. material characterisation and reinforcement integration [15]) and durability (e.g. due to concrete mixes used for printing [16]). Consequently, Bos et al. [11] summarise their analysis of the hitherto use of DFC by stating that current DFC is mainly used “showcasing its potential not necessarily already achieving it”.

Despite these current limitations, DFC doubtlessly has the potential to tackle material-efficient construction, thereby reducing the environmental impact of reinforced concrete. Used materials, construction processes, software and dimensioning approaches must be rethought (see [17]) to exploit this potential with inventions and innovations. However, fermenting such inventions and innovations often takes several decades until dominant solutions crystalise, as exemplified by the reinforced or prestressed concrete development [18]. Given the pressing need for sustainable construction, research projects should aim at accelerating the development of relevant practical applications by considering all requirements for construction works mentioned in Section 1.

This paper intends to complement ongoing relevant research (e.g. DFC material characterisation and durability) by presenting a methodology consisting of systematic reviews and an ideation process to foster possible innovations informing the long-term strategy for DFC development. This study comprehensively assesses traditional mass-market concrete construction (Section 3), both on-site as well as prefabricated, identifies and summarises their inherent strengths, and points out their challenges. This holistic analysis of traditional concrete construction reveals challenges addressable by new technological possibilities provided by DFC, thereby improving and complementing existing concrete and reinforcement technologies and approaches for its dimensioning, as well as construction processes. Current construction processes have been adapted to societal needs for more than a century and are highly efficient today. However, they need to be adapted to meet the needs of future generations.

The relevant DFC technologies are introduced in Section 4, employing the RILEM process classification framework proposed by Buswell et al. [19] to determine the individual processing and assembly operations associated with DFC technologies. Furthermore, the DFC technologies are evaluated using the same main criteria as introduced in Section 1 for traditional construction to identify inherent features. Overcoming fundamental challenges could foster the mass-market penetration of DFC.

Note that the RILEM process classification framework is closely based on Groover's classification framework for manufacturing processes [20]. This framework is adapted for this presented study to make the assembly classification broadly useful for concrete construction, including traditional construction processes. The assembly operation “Brazing and soldering” is irrelevant in this context and is suspended from the framework. At the same time, the assembly operations are supplemented with the reinforced concrete-specific processes “post-tensioning”, “casting/grouting” to fill a joint, “tying” (often used in the preparation of reinforcement cages), and “positioning”, which is only a standalone assembly operation without further joining when designing structures for eventually being loaded by predominant compression (e.g. vaulted shapes). Fig. 2 shows the employed process classification framework.

Finally, the clustered challenges and the characteristics of traditional concrete construction and DFC assist an ideation process to identify some mass-market levers of DFC. The process outlined in Section 5 served to derive two presented exemplary applications for improving the production of construction works with DFC. However, rather than exploring the abundant design space of the construction industry – which would be far beyond the scope of a single journal paper – the selected examples shall merely illustrate how relevant ideas may be derived to foster DFC innovation for the mass market. Furthermore, they indicate how traditional construction and DFC processes can work together in tackling the persistent challenges related to the societal demand for sustainable construction.

## 3. Traditional concrete construction

This section summarises fundamental aspects of traditional concrete construction. More details, including the derivation of the strengths and challenges presented in Section 3.2, can be found in Appendix A.

### 3.1. Overview

A principal decision in traditional concrete construction is whether on-site and prefabricated construction is preferable. It essentially depends on the criteria introduced in Section 1: e.g. architectonic individualism may be a reason for on-site construction, while prefabrication may be beneficial for time efficiency. Apart from these general criteria, market-specific reasons, such as tradition and, hence, missing infrastructure for one or the other production method, play an essential role.

On-site construction is suitable for all construction works. Its main steps consist of placing scaffolding and formwork (which may be identified as tying assembly operation within the classification framework introduced in Fig. 2), installing reinforcement (tying or welding assembly) and casting concrete (formative solidification) in the formwork. The members are always produced in their final orientation, e.g. mainly vertical (standing) production of columns and walls and horizontal

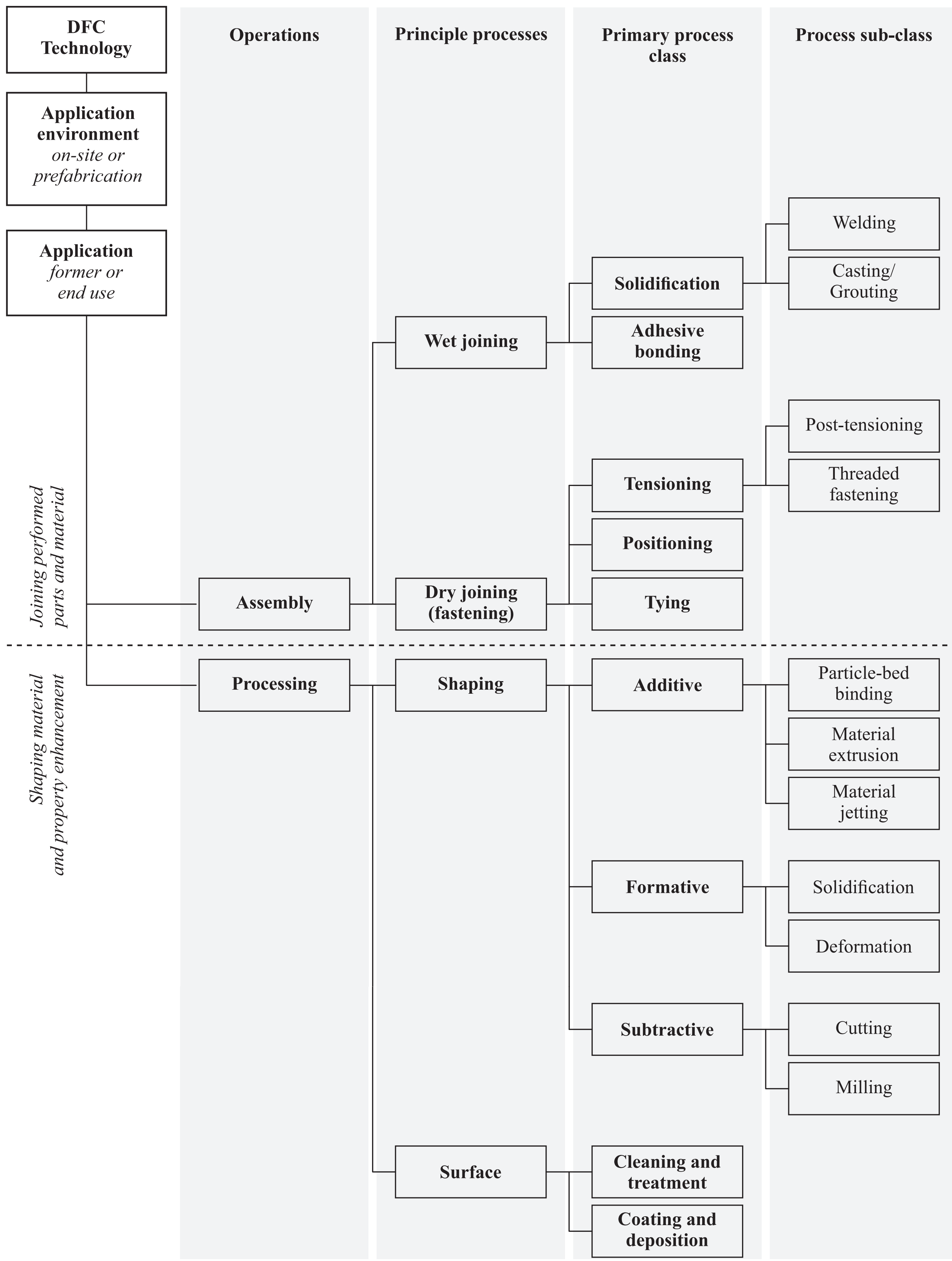


**Fig. 2.** The process classification framework for DFC technologies, adapted from [19].

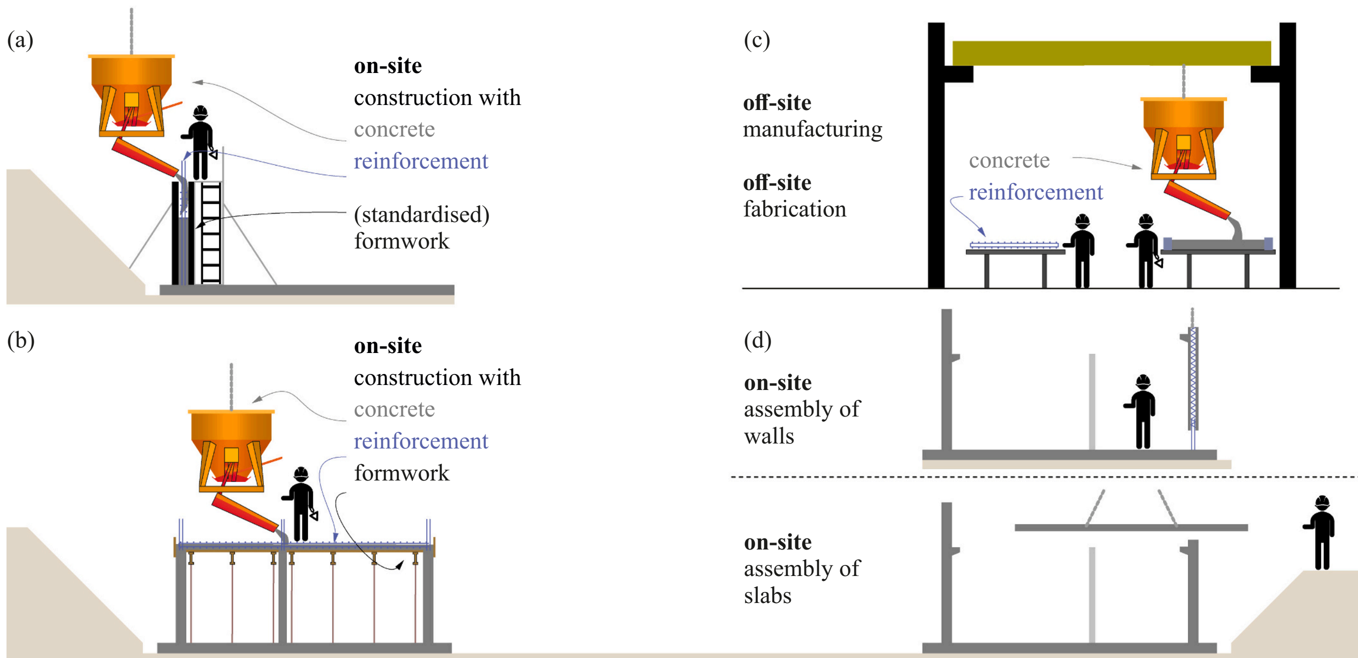


**Fig. 3.** Schematic representation of decisive work steps of traditional construction: a) and c) representing cast-on-site construction; b) and d) representing prefabricated construction.

(lying) production of slabs (Fig. 3a and b). Whereas double-faced formwork is typically required for vertical production (walls), single-sided formwork is sufficient for slabs unless they are heavily inclined, which may require using counter formwork. However, until the concrete has hardened, the top side of slabs – as any free concrete surface – needs to be protected from evaporation by covering or applying a curing agent. The formwork is typically removed after 24–48 h for vertically cast elements and after 3–7 days for horizontally cast elements, respectively; in the latter case, temporary props are required to avoid excessive creep deflections.

Prefabricated construction is mainly used for three reasons in structural concrete:

- mass-production of industrialised elements (with multiple uses of the same formwork, reason for the most extensive use of prefabricated construction) [21];
- production of unique and/or complex units with high demands on the form, surface quality and/or tolerance [21];
- (partial) prefabrication due to (temporal or spatial) constraints [22].

Apart from shafts and slender columns, precast elements (including walls) are preferably cast in a factory in a horizontal (lying) position, which minimises the necessary formwork area and the effort for compaction (Fig. 3b). Vertical battery casting (walls or slabs) and long pretensioning beds (typically 100–200 m long for Hollow-Core Slabs or T-beams) may be exploited for highly industrialised production series. Bridge segments are often precast in heavy steel forms suitable for multiple uses, match-casting the segment joints – i.e., using the previously cast element as stop formwork for the next one – to obtain precisely matching surfaces and dimensions.

Typical precast concrete needs 6–12 h for curing and hardening until the formwork can be removed, or elements produced in pretensioning beds may be detensioned and sawn to the desired length and angle; note that the hardening process is often accelerated by steam curing. Subsequently, elements are stored, transported to the site and assembled (including mounting and joining, Fig. 3d). Transport limitations typically limit the width of members to 2.5–3.0 m. Various assembly operations, given in the classification framework introduced in Fig. 2, find application in the modern precast construction industry. The most frequent wet joining methods are casting or grouting between adjacent elements, while the most frequent dry joining methods are post-tensioning or threaded fastening.

In addition to the prefabrication of complete elements, parts of structural members constructed on-site such as reinforcement cages or elements for composite structures, as well as formwork, may be prefabricated.

### 3.2. Features

The evaluation of traditional construction methods presented in Appendix A.1 identifies features (strengths and challenges) for both studied traditional construction, on-site and prefabricated construction. The following summary of these features serves to identify opportunities for improvement with DFC.

Features attributed to traditional on-site construction are:

- Monolithic construction:
  - facilitates (i) the construction of robust structures and (ii) optimising structural resistance by two-way and statically indeterminate loadbearing systems;
  - requires (i) increased reinforcement contents due to internal stresses, specifically for members and structures with severe exposure and (ii) increased formworking efforts to provide continuous reinforcement across construction joints.
- On-site works concentrated at the final location of the construction work:
  - facilitate (i) an optimised supply chain to cast large concrete volumes, (ii) the integration of building systems installation in slabs (optimisation of the overall construction height possible), (iii) freedom of geometry in plan and (iv) freedom to flexibly introduce a camber;
  - require (i) over-strength concretes due to the environmental exposure of construction works, (ii) the production of members in their final orientation, necessitating wall thicknesses exceeding those statically needed to ensure sufficient compaction, (iii) efforts for curing of the fresh concrete to avoid early age cracking and

excessive shrinkage, and (iv) a high labour intensity on-site with a corresponding demand for construction efficiency, preventing optimisation of members in terms of concrete use.

Features attributed to traditional prefabricated construction are:

- Segmented production in off-site controlled environmental conditions:
  - enables (i) concreting in best (often lying) position for virtually all members, (ii) controlled and possibly accelerated curing of concrete, (iii) an increased surface quality and (iv) the reduction of safety margins in terms of concrete strength and tolerances for members dimensions, respectively;
  - requires (i) the transport and assembly of elements to the site implying limiting weight and dimensions of prefabricated elements, (ii) on-site execution of toppings (if required) and connections (possibly with extra formwork for lap splices) and (iii) efforts to provide watertight joints.
- Mass production:
  - enables (i) fast production of industrialised elements in simultaneous (repeatable) work steps and (ii) the optimisation of each work step with the help of elaborate tools and machinery (e.g. to facilitate the reduction of concrete volume with the creation of voids as applied for Hollow-Core Slabs);
  - requires (i) one-time-use formworking for non-regular and variable geometries (e.g. vault or controlled camber) and impedes (ii) time demanding local adjustments of the concrete performance, e. g. for concrete performance grading.

### 3.3. Cost structure and material use of reinforced concrete buildings

Three recently erected traditional concrete construction works were analysed regarding cost and material use. Two buildings were cast on-site in two different regions in Switzerland, while one building, mainly consisting of precast elements, was erected in Denmark. The two Swiss buildings were studied based on the plans, the successful bids and schedules, while the Danish building was studied based on (i) the plans in terms of material use and (ii) information in terms of cost from the design engineer. Appendix A.2 presents details of the analysis. Fig. 4 shows the cost structure of two cast-in-situ buildings in Switzerland, while Table 2 presents the corresponding share of foundations, vertical members and floor members in terms of their cost, required construction time and material use for the two cast-on-site buildings, and in terms of their material use of the precast building, respectively.

From this analysis of specific buildings, the following conclusions may be drawn:

- Formwork, concrete and reinforcement account for roughly 75 % of the cost for the basic structure (formwork with the lowest contribution).

**Table 2**
Cost, required construction time, and material use for foundations, vertical members, and horizontal members of two cast-on-site buildings and material use of a precast building. Note: total cost refers to the cost of installation, formwork, reinforcement, concrete, masonry, and miscellaneous (see Fig. 4).

| | Foundations | Vertical members | Horizontal members |
|---|---|---|---|
| (a) | 3-Storeys above ground, cast-on-site building for office use | | |
| Share of total cost | 16 % | 11.5 % (walls) and 3.5 % (columns) | 41 % (floor slabs) |
| Construction time | 35 working days | 159 working days | 165 working days |
| Share of total concrete volume | 28 % | 11 % (walls) and 0.6 % (columns) | 58 % (floor slabs) |
| (b) | 8-/4-Storeys above ground cast-on-site building for residential and business use | | |
| Share of total cost | 11 % | 24 % (walls) and 1 % (columns) | 39 % (floor slabs) |
| Construction time | 66 working days | 165 working days | 209 working days |
| Share of total concrete volume | 19 % | 24 % (walls) and 0.3 % (columns) | 57 % (floor slabs) |
| (c) | 5(+1)-Storeys above ground, precast building for residential and business use | | |
| Share of concrete volume | 24 % (cast-on-site) | 14 % (precast walls), 2 % (precast columns), 7 % (precast façade), and 1 % (precast parapet) | 40 % (precast slab elements) 7 % (cast-on-site floor slabs) 5 % (precast beams) |

- Foundations are comparably quickly produced but contribute considerably to the total cost and material use.
- The material use of slabs above ground and foundations are closely related because the slab self-weight directly influences the demand on the foundations. The foundation share of the total material use may be estimated at roughly 20–30 % for typical three- to eight-storey buildings.
- Walls and columns contribute considerably to the construction time (in the same order of magnitude of slabs). However, they have a subordinate relevance in terms of the total cost and, even more pronouncedly, in terms of their concrete volume share.
- Slabs are highly relevant for cost, construction time and material use, independent of the type of construction. Interestingly, even the Hollow-Core Slabs are responsible for 40 % of the complete concrete volume in the Danish building, despite that they were highly optimised regarding material use (44 % of a solid slab of equal thickness) and cover 85 % of the total slab area; this may partly be explained by the relatively long spans of the Hollow-Core Slabs.

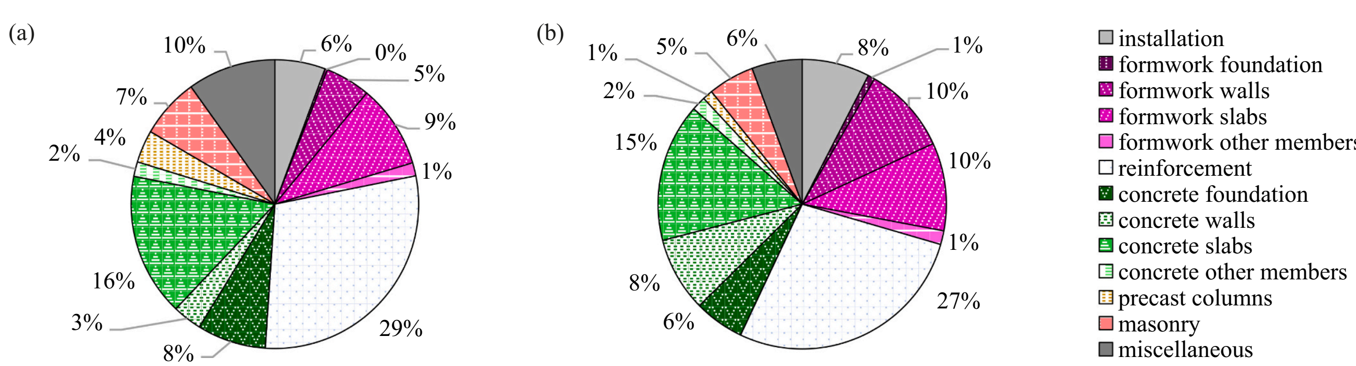


**Fig. 4.** Cost structure of two cast-in-situ buildings in Switzerland: (a) Three-storey office building; (b) eight-/four-storey residential building.

Evidently, these findings must be used with care and cannot be applied to cases differing strongly from those of the studied buildings and building types, such as sites with soft soil requiring pile foundations. Furthermore, it should be noted that the concrete volume for walls in Table 2 does not consider all walls within the corresponding buildings: a substantial portion of the walls are masonry walls. Still, the results are highly useful for identifying levers for digital construction. They particularly underline the relevance of slabs, especially when considering that most overall used concrete volume is deployed construction (about 75 % in Switzerland [23]). Note that also other researchers performed such studies, e.g. to determine the embodied carbon of different building elements [24].

## 4. Digital fabrication with concrete

Digital fabrication with concrete (DFC) encompasses various fabrication technologies. In this section, fundamental aspects of DFC processes are summarised. More details, including an evaluation of the strengths and challenges considering the criteria defined in Section 1, can be found in Appendix B.

### 4.1. Overview

The most prominent DFC is doubtlessly 3D printing with extruded concrete (referred to in the following as *3DCP*) [11], which has already found widespread application in industry. Further, currently less known DFC technologies include 3D printing with sprayed concrete, *Eggshell*, *Mesh Mould*, *Smart Dynamic Casting*, *KnitCrete*, *Flexible Mould*, and several applications of *Particle-bed binding*. DFC technologies commonly abandon traditional formwork while promising to tailor the construction material and create structurally optimised material-efficient shapes. Their intended applications range from on-site producing complete members or parts thereof to prefabricating (i) complete elements or parts thereof, (ii) temporary formwork, or (iii) stay-in-place formwork (also [25]).

The technologies suitable for fabricating temporary or stay-in-place


**Fig. 5.** Fabrication operations of DFC technologies: (a) *3DCP* [32], (b) 3D printing with sprayed concrete [33], (c) *3DCP* Formwork before casting concrete [34], (d) Eggshell Formwork production with contiguous concrete casting [28], (e) Mesh Mould reinforcing mesh fabrication [8], (f) Smart Dynamic Casting [29], (g) concrete application on coated knit for the KnitCrete technology [6], and (h) Funicular Floor element with timber and EPS formwork after casting [31].

formwork in a digital process can be grouped within “digital formwork”. Digital stay-in-place formwork and temporary formwork may be cementitious or non-cementitious. Compared to traditional formwork, digital formwork technologies promise to offer new possibilities in form and material optimisation or reduce the formwork waste inherent to curved shapes.

Fig. 5 shows several DFC technologies during fabrication. *3DCP* (Fig. 5a and c) is an additive shaping process based on concrete layer extrusion and serves for producing complete or parts of members or digital cementitious formwork (e.g. [26]). 3D printing with sprayed concrete (Fig. 5b) is an additive shaping process based on concrete material jetting in layers (e.g. [27]). Its use mainly involves the production of complete reinforced concrete members and elements. *Eggshell* (Fig. 5d) is a fused deposition modelling process and describes a technology where a thin, recyclable thermoplastic shell is additively shaped and used as formwork [28]. In the *Mesh Mould* process, a robotic tool head bends, cuts and welds a steel mesh to create a semi-permeable formwork (Fig. 5e), eventually filled with concrete before adding a cover layer [8]. *Smart Dynamic Casting* (*SDC*) [29] includes continuous slip forming with a small formwork including multiple degrees of freedom to cast varying shapes in a formative solidification process (Fig. 5f). *KnitCrete* employs a flexible integrated formwork created by knitted textiles [30] brought to shape using a cable-net falsework and an external scaffolding frame. After applying a cement-paste coating, concrete is applied to the coated knitted formwork (Fig. 5g). Many other materials have been used to create formwork directly following model data, such as CNC-milled expanded polystyrene (EPS) pieces (Fig. 5h, showcasing the *Funicular Floor* system [31]).

Appendix B.1 explains these DFC technologies and their inherent operations and characteristics in more detail. Figs. 1 and 6 show various final products of DFC technologies. Further comprehensive reviews on these DFC technologies, their applications, strengths, and limitations have been worked out lately. Wangler et al. [16] provided an overview of available technologies and focus on fresh and hardened state challenges. Bhardwaj et al. [35] focused their DFC review on the need for infrastructure construction. Bos et al. [11] systematically discussed the design, manufacturing and lessons learned of eight realised *3DCP* projects (six buildings, one bridge, a set of street furniture). Several reviews and outlooks exist for challenges related to the inclusion of reinforcement in DFC processes [15,33,36–38]. Hawkins et al. [39] summarised flexible formwork technologies. Lloret et al. [29] reviewed the processes of Smart Dynamic Casting, Eggshell, and counter-pressure casting.

### 4.2. Features

It is commonly agreed that DFC provides opportunities to produce material-efficient building members with an inherent geometric complexity while avoiding unnecessary formwork waste. The low effort to produce geometric complexity with DFC allows adapting to specific loading conditions, spans, support conditions, building systems and material performance (e.g. for ribbed floor slabs, as elaborated by [43]). Accordingly, several DFC technologies enable the elimination of some process-dependent constraints for traditional construction (derived in Section 3). Such constraints are the minimum thickness requirements for cast-on-site walls to enable proper concrete compaction, the formwork effort for producing ribbed, cambered, or vaulted slab systems, or the need to use concrete with increased strength in prefabrication to ensure time-efficient use of formworks. Furthermore, Lydon et al. [44] showed the combination of structural and functional demands to have a high potential for material-efficient construction.

On the other hand, the various existing DFC processes face fundamental challenges specific to the applied process and application. Appendix B.2 evaluates these challenges by considering the main criteria for construction works introduced in Section 1. The fundamental aspects when addressing mass-market applications are summarised below:

- Meeting structural safety requirements defined in pertinent design codes impose several challenges to digital fabrication and its design:
  - *3DCP* and particle-binding processes feature material anisotropy inherent to the production in layers (weak interfaces between layers). The anisotropic material behaviour affects the load-bearing behaviour of printed concrete under all loading conditions [45], but particularly under tension and shear (with respect to the layer surface). Accordingly, design provisions accounting for the concrete tensile or shear strength cannot be applied to elements additively shaped by *3DCP* or particle-binding.
  - Reinforcing bars or reinforcement cages across layers challenge the use of additive shaping processes [36]. Their integration in the fabrication process has been shown feasible when using 3D printing with sprayed concrete (Fig. 5b). However, the current design of concrete structures fabricated by *3DCP* and *Particle-bed binding* technologies highly relies on compression-only solutions, using post-tensioning or exploiting vaulted geometries. Even when using *3DCP* as digital cementitious formwork, the geometrical possibilities to integrate and connect reinforcement cages after printing are limited. Note that reinforcement across layers is not necessarily required for the lying additive fabrication of walls or slabs (the code compliance of such elements remains to be checked with the reduced shear strength of layer joints).
  - Fire exposure will become an increasingly important design criterion when working with slender concrete structures (e.g. ribbed slabs).
  - Members of printed and subsequently added cast concrete rely on the bond between the two concretes. However, the rough surface of additively shaped formworks boosts the risk of entrapped air while conducting an on-site casting process.
- Lately, concerns have been raised regarding durability for technologies using high paste content mortar with early exposure to the

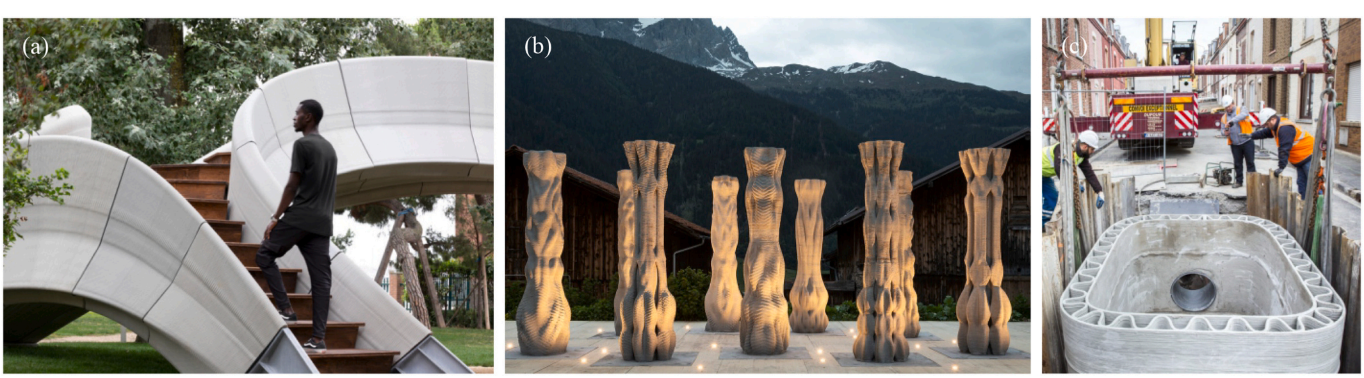

**Fig. 6.** Exemplary applications of *3DCP*: (a) Striatus – *3DCP* footbridge [40] (Photo credits: Studio NAARO); (b) *3DCP* Concrete Choreography described in [41] (Photo credits: Benjamin Hofer); (c) *3DCP* stormwater collector [42].

environment without curing. This challenge is especially relevant when reinforcing steel is used within or near this mortar for structures exposed to the environment.
- Additively shaped stay-in-place formwork may serve to optimise the form of building members. However, the need for the proper embedment of reinforcing steel in the concrete volume cast within the formwork may antagonise attempts to reduce the overall material volume.
- Technologies applying high paste mortar counteract the attempts of reducing the environmental impact with optimised geometries. Even though successful research has been leading to a decreased environmental impact of printed material [14], it will always have a higher environmental impact than cast concrete due to the exigencies for pumpable and printable materials [13].
- The fabrication of many DFC technologies is often envisioned in the prefabricated environment. However, DFC technologies are still remarkably slower (at least an order of magnitude) than traditional mass-market construction because formwork is not time-relevant and labour-intensive in mass-market prefabrication. Currently, DFC is only time-competitive towards the traditional production of bespoke elements with high demands, e.g. on their form. It should be noted that most of the discussed technologies are matters of ongoing research. Hence, numbers should be taken as information on the order of magnitude rather than accurate values.

Accordingly, many DFC technologies still face substantial technical and organisational challenges before the products comply with the current construction mass market requirements. These challenges are especially relevant when producing complete building members with DFC, implying the current need to explore DFC solutions supporting, rather than substituting, traditional construction.

## 5. Ideation of new opportunities for DFC

This section explores the opportunities of DFC to tackle challenges of traditional concrete construction derived in Section 3. The exploration employs a structural engineering-centred ideation process inspired by the morphological approach [46], using a systematic variation of influencing parameters for the relevant properties (*property-specific parameters*) and operations (*operational-specific parameters*) to process or assemble a member, an element, or a part thereof. While other ideation methodologies may be applied, the authors are convinced of the necessity to rely on a holistic background analysis of (i) the essential requirements for construction works and their (de)construction (Section 1) and (ii) the strengths, opportunities, and challenges of traditional construction processes and DFC (Sections 3 and 4). This background sharpens the focus for identifying relevant practical challenges, referred to *key aspects* below. The section concludes by presenting selected ideas developed with this framework and considered appropriate to build sustainable future construction works.

### 5.1. Ideation methods

Material or surface properties may be described as property-specific parameters using (i) mechanical models for the corresponding behaviour, such as the shear transfer across structural connections, or (ii) available types of formwork, reinforcement and concrete. For example, many types of concrete with inherent properties are available on the market, e.g. differing in strength, specific weight, aggregate size, hardening time, hydration heat, or shrinkage.

Furthermore, various operations may be chosen as operational-specific parameters during construction. The classification framework introduced in Section 2 can be used to determine possible operational-specific solutions. The classification framework allows breaking traditional and DFC construction technologies into individual operations and, hence, entails various processing and assembly operations applicable in a morphological approach. Typical operations include the provision of formwork (e.g. through a conventional rigid formwork, an additive shaping process, or a flexible formwork), reinforcement (e.g. positioned on-site or prefabricated cages) and concrete (e.g. cast or printed). Operations may be carried out serially as subsequent operations, simultaneously or contiguously in alternating work steps, according to Buswell et al. [19].

The variation of these property-specific and operational-specific parameters leads to several possible solutions in the design space. A morphological box, as shown in Fig. 7, may combine these solutions in the design space as “specification of the design space” (horizontal box direction) with the operational flow to construct a piece, element, member, or structure (vertical box direction). Specifications defined through the used classification framework and used in a morphological box are marked in matching colours in Fig. 7. Possible solutions are identified by lines connecting the chosen characteristics.

To exemplify the ideation process, Fig. 7 includes a possible design solution, shown as a grey line combining chosen specifications within the operational flow. Theoretically, many design solutions result from choosing different specifications, even though some combinations are invalid (e.g. combining traditional formwork with cast concrete in a simultaneous process is impossible).

### 5.2. Ideation focus

Given the societal demand for sustainable construction, the construction industry urgently needs solutions for material-efficient structures, complementing the cement industry's pertinent efforts to reduce greenhouse gas emissions. While the latter have a long time horizon, material efficiency may be achieved in a much shorter term by saving formwork, concrete and/or reinforcement to the extent that the overall impact of the structure is smaller than with current solutions. The analysis of the cost structure and concrete use in typical buildings built in Europe (Section 3.3) revealed the high impact and environmental potential inherent to foundations and slabs, which together cover 70–80 % of the overall concrete volume in buildings. When using solid slabs, their share alone is 50–60 %.

The main drivers for the environmental impact of slabs are [43,47]:

- Serviceability criteria, which may be tackled by prestressing, cambering, and integrating building systems design and structural design;
- Inefficient solid cross-sections;
- Simply supported members (one-way continuous and, even more so, two-way continuous slabs are structurally efficient).

Note that the third point is closely related to the first one since structurally efficient continuous members are much stiffer than simply supported ones with equal depth.

Inefficient solid cross-sections are mainly employed on-site, while prefabricated elements commonly have efficient ribbed cross-sections, such as Hollow-Core slabs or T-beams, whose volume cannot be reduced much further. However, prefabricated mass-market solutions are mostly structurally inefficient simply supported one-way slabs. Hence, DFC technologies can outperform traditional solutions in material efficiency if they combine a similarly efficient cross-section as used in existing prefabricated mass-market solutions with a more efficient structural system, providing continuity and possibly carrying loads in two directions.

This is not a new idea: for example, Nervi [48] applied reusable prefabricated elements as temporary formwork for ribbed two-way slabs supported on columns. However, when reviving it, it must be kept in mind that even minor changes of the slab spans trigger the need to adjust the rib spacing and, hence, to produce new formwork elements. Hence, prefabricated elements are only material-efficient if they serve as a complete slab solution or structurally activated lost formwork given the

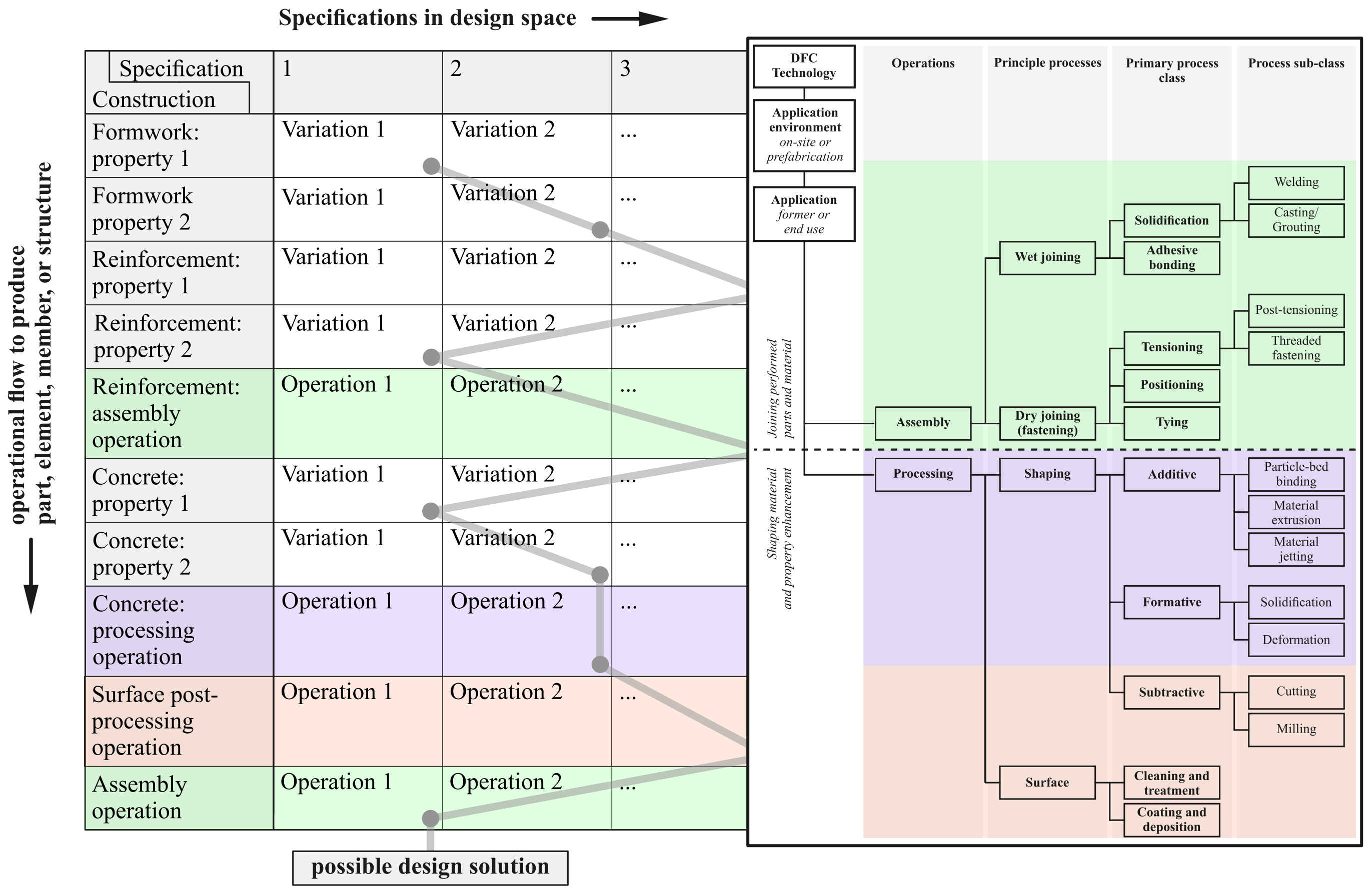


**Fig. 7.** Representation of the ideation process inspired by the morphological approach and the classification framework.

uniqueness of each construction work. Huber et al. [49] present the design and testing of an optimised ribbed slab employing 3D printed formwork. Mata-Falcón et al. [43] discuss possible DFC applications incorporating this approach, based on the technologies introduced in Section 4; they are thus not further pursued as ideation focus here.

Most DFC technologies currently rely on indoor production facilities protected from environmental exposure. Furthermore, slabs cast on-site require scaffolding and full-surface formwork due to gravity. Therefore, material-efficient and digitally fabricated ribbed slabs will be entirely or partially prefabricated. However, transport constraints limit the width of DFC elements to 2.5–3.0 m, which is considerably smaller than typical spans in building construction. Accordingly, structural connections between (i) lost formwork and cast-on-site concrete and (ii) adjacent elements are a key aspect to fostering material efficiency with partially or fully prefabricated DFC slabs. Note that connections are a persistent challenge also for traditional prefabricated construction (as evaluated in Section 3). Accordingly, the key aspect “structural connections” serves as the first ideation focus of this study.

Foundations contribute considerably to the overall used concrete volume even if slabs with optimised self-weight are used, as exemplified by the five-storey building employing Hollow-Core-Slabs studied in Section 3. The exposure of foundations exacerbates their impact on environmental sustainability: watertight and durable underground structures require a reinforcement ratio that is higher than needed for the load-bearing capacity to limit crack widths (Section 3.2). The corresponding “minimum reinforcement” for crack control often makes up for more than 50 % of the total reinforcement content for members subject to severe exposure, as frequently encountered in underground walls or infrastructure such as bridges [50], sewers, or shafts. The required reinforcement ratio increases with the concrete tensile strength, generally higher in concretes used for severe exposure conditions. While uncertainties inherent to the quantification of soil stiffness and load-bearing capacity limit the optimisation potential of foundations, Mata-Falcón et al. [18] indicated the tremendous potential of crack initiators to reduce minimum reinforcement. Accordingly, the key aspect “reducing minimum reinforcement” serves as the second ideation focus of this study.

### 5.3. Ideas

Digital fabrication will find applications with “new” features integrated into traditional construction processes. For example, set-on-demand concrete reduces the hydrostatic pressure during casting and facilitates the handling of formwork pressure and uplift. Moreover, flexible temporary supports could serve the production of a camber or water runoff in prefabricated construction without excessively investing labour and material for the formwork.

Rather than elaborating on these possibilities, this section intends to open perspectives for using DFC beyond process-oriented applications by tackling the key aspects of “structural connections” and “reducing minimum reinforcement” identified above for illustration. Note that not all suggested ideas have been tested for their feasibility yet.

#### 5.3.1. Structural connections

Table 3 presents a possible morphological box for structural connections. It describes the operational flow to produce an element, or a part thereof, with connections to adjacent parts or elements. Furthermore, it includes possible specifications to describe the operations and to define properties. In this case of structural connections, the properties are based on the provision of the design code EN 1992-1-1 [51] for calculating the shear resistance at joints between concrete cast at different times:

**Table 3**
Morphological box to identify applications with DFC technologies for structural concrete connections.

| Specification / Construction | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Formwork: property 1 | traditional rigid formwork (e.g., timber, steel, etc.) | additive shaping (cementitiuos) | additive shaping (polymer, wax) | flexible formwork (textile) | | |
| Formwork: property 2 | surface: very smooth | surface: smooth | surface: rough | surface: very rough | surface: keyed | |
| Reinforcement: property 1 | no penetrating reinforcement | traditional reinforcing steel in or between layers | traditional reinforcing steel across layers | traditional pre-stressing steel with tubes in or between layers | traditional pre-stressing steel with tubes across layers | |
| Reinforcement: property 2 | minimum reinf. content, α = 0° | high reinf. content, α = 0° | minimum reinf. content, α > 0° | high reinf. content, α > 0° | | |
| Reinforcement: assembly operation | in series | simultaneously | contiguously | | | |
| Concrete: property 1 | $d_{max} \geq 16$ mm (concrete) | $d_{max} \leq 4$ mm (mortar) | | | | |
| Concrete: property 2 | normal strength | high strength | | | | |
| Concrete: processing operation 1 | cast: in series with formwork operation | printed: in series with formwork operation | cast: simultaneously | printed: simultaneously | cast: contiguously | printed: contiguously |
| Concrete: processing operation 2 | cast: in series with reinforce-ment operation | printed: in series with reinforce-ment operation | cast: simultaneously | printed: simultaneously | cast: contiguously | printed: contiguously |
| Surface post-processing operation | no / formwork removal | cutting | milling | cleaning and treatment | | |
| Assembly operation | sequential casting or grouting | welding | adhesive bonding | post-tensioning | threaded fastening | |

$$v_{Rdi} = c \cdot f_{ctd} + \mu \cdot \sigma_n + \rho \cdot f_{yd}(\mu sin\alpha + cos\alpha) \quad (1)$$

where $c$ and μ (=friction coefficient) are factors depending on the roughness of the interface (see "Formwork: property" in Table 3), $f_{ctd}$ is the design concrete tensile strength, $\sigma_n$ is stress caused by an external normal force (defined through the general assembly operation), $f_{yd}$ is the yield strength of the reinforcement crossing the joint, and α is the inclination of the reinforcement. In the example, the produced formwork roughness may be very smooth, smooth, rough, very rough, or keyed.

Several possible solutions may be identified, including the three examples illustrated in Table 3:

- Grey line: A traditional construction process to create a construction joint with reinforcement.
- Blue line: A forming piece produced by *3DCP*. The *3DCP* process results in an undulated surface, classified as smooth according to EN 1992-1-2. Typical mortar applied in extrusion processes is used while the rest of the element is cast with standard concrete simultaneously. The connection surface is post-processed by milling to create shear keys. The elements produced in this process may be post-tensioned.
- Red line: An element or part thereof (e.g. the rib of a ribbed slab) produced using the *Eggshell* technology, printing a polymer formwork exhibiting a very rough surface. A high ratio of traditional reinforcing steel (with α = 0) is placed between the printed formwork layers contiguously during printing the formwork. Subsequently, standard concrete is used to fill the formwork. When the concrete has hardened sufficiently, the formwork is removed. The resulting surface with penetrating reinforcement can be considered equivalent to a rough construction joint in traditional construction.

Fig. 8 shows the two types of connections presented by the blue and the red line that may be produced employing DFC to substitute traditional formwork.

The idea of using *3DCP* for printing the formwork of larger elements exploits set-on-demand concretes used by most DFC technologies (e.g. [29,52]) for post-processing fitting surfaces, which today would require match-casting (implying a sequential production of adjacent elements). The fitting surfaces may be optimised in their shape specific to the loading conditions at the position of the connection, as mentioned by Baghdadi et al. [53]. Kloft et al. [54] applied fresh-state surface post-processing, preventing rapid tool wear. Fresh-state post-processing could be supplemented by hardened-state post-processing if necessary for small tolerances. Several fitting elements could be produced simultaneously when using *3DCP* and surface milling for providing the formwork.

Producing a rough joint with continuous reinforcement, a cumbersome task using traditional formwork, is straightforward with many DFC

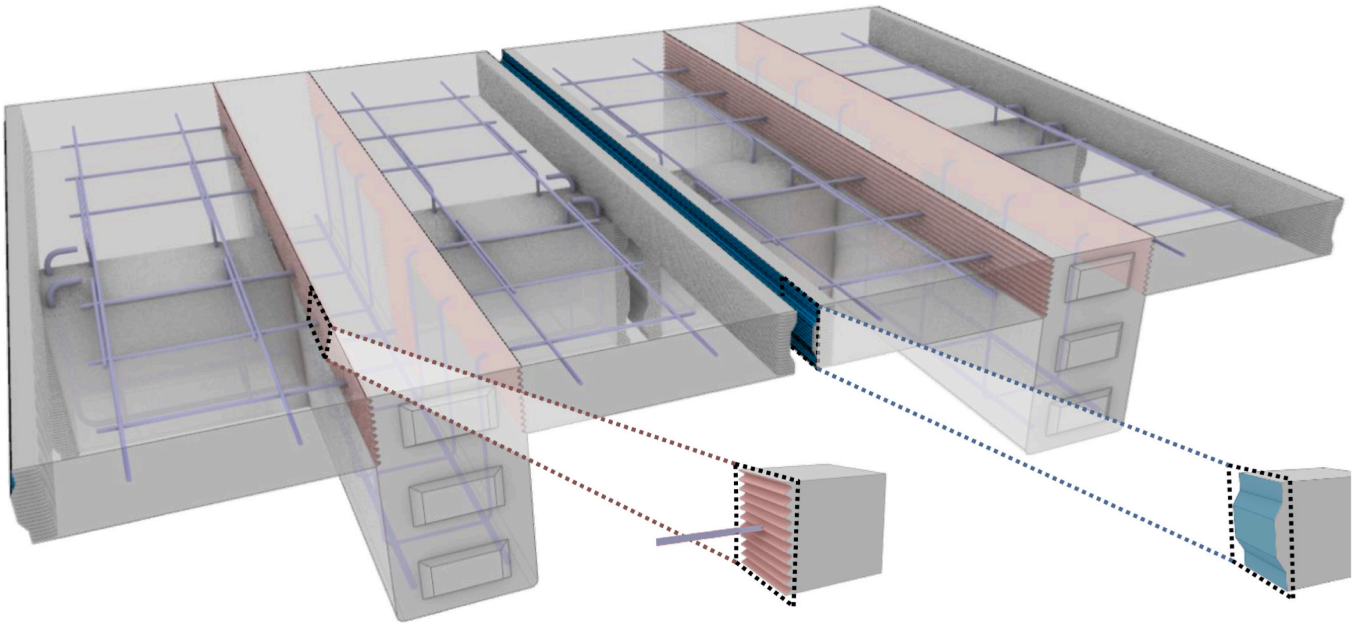


**Fig. 8.** Ribbed slab with connections produced by employing *3DCP* and the Eggshell technology.

technologies (e.g. the Eggshell technology exemplarily used in Table 3). Increasing the number of continuous reinforcing bars does not intensely increase the effort when additively shaping the formwork, as the bars may be placed on the formwork at the required distance to the surface before continuing the additive printing process. Furthermore, the rough surface characteristic of many DFC technologies (e.g. *3DCP*) may be used without further effort to ensure the shear transfer between prefabricated elements and concrete added on-site (e.g. a topping).

Further, cementitious additive shaping operations could be used to grade the concrete quality to actual needs within cast members or elements by producing a separating piece with continuous reinforcement while casting two different concretes adjacent to the piece. For example, high strength concrete could be used locally for highly loaded areas, such as short lap splices studied by Graybeal [55] for bridge construction. This concept could also be applied to connect prefabricated elements to monolithic slabs in building construction while avoiding extra horizontal formwork for lap splices. Moreover, concrete grading with tailored cement content or lightweight aggregates could reduce the environmental impact of concrete structures. In traditional concrete construction, such grading would require laborious sequential work steps with construction joints separating the parts of varying concrete quality.

### 5.3.2. Reducing minimum reinforcement

Due to internal stresses, minimum reinforcement is needed to (i) avoid brittle failures at cracking or (ii) limit crack width for water tightness or appearance. Reducing the required minimum reinforcement ratio can be tackled by systematically varying the relevant parameters. These parameters are based on the Tension Chord Model [56] to calculate the maximum crack spacing $s_{r,max}$ and crack width $w_{r,max}$ in tension ties:

$$s_{r,max} = \frac{\phi f_{ct}(1-\rho_t)}{2\tau_{b0}\rho_t} \text{ and} \tag{2}$$

$$w_{r,max} = \frac{1}{2}\frac{s_{r,max}}{E_s}\sigma_{sr0} \tag{3}$$

where $f_{ct}$ = tensile strength of concrete, $\rho_t$ = reinforcement ratio in the tension chord, $\varnothing$ = reinforcing bar diameter, and $\tau_{b0}$ = bond shear stress before yielding, where generally $\tau_{b0} = 2f_{ct}$ is assumed. The reinforcement stress at cracking $\sigma_{sr0}$, i.e. when the concrete tensile stress exceeds $f_{ct}$, is given by

$$\sigma_{sr0} = f_{ct}\left(\frac{1}{\rho_t} + n - 1\right), \tag{4}$$

with $n = E_s/E_c$ = modular ratio of the Young's moduli of reinforcing steel $E_s$ and concrete $E_c$.

Fig. 9a illustrates the effect of selected parameters on the minimum reinforcement ratio required to control the maximum crack width, which needs to be limited to ensure durability. The predictions shown in Fig. 9a rely on the Tension Chord Model, adapted for modelling crack initiators [18].

Clearly, “crack initiators”, which trigger premature cracking at values below $f_{ct}$, have the highest impact: if cracking occurs at 0.33 $f_{ct}$, the minimum required reinforcement may be reduced to a third of the standard case. Such crack initiators may be (i) weak interfaces with locally reduced concrete tensile strength, e.g. caused by additive shaping processes [18,57], or (ii) secondary loading effects (e.g. shear on the continuous reinforcement due to segmentation and misalignment of the welded loaded reinforcement, as observed in a specimen with the *Mesh Mould* technology, Fig. 9b and c).

Variations of the reinforcement layout and properties also influence the required minimum reinforcement ratio. Smaller reinforcement diameters (Ø12 vs Ø16 in the example) may cause more labour for assembly; however, they lead to a lower required ratio. Carbon fibres with higher elastic stiffness (exemplarily 300 GPa vs 200 GPa) used as minimum reinforcement would also lead to a lower required reinforcement ratio. Higher concrete strength is generally associated with a higher required reinforcement ratio (due to the increased cracking load). However, it could be exploited if tailored only locally at the reinforcement to increase the bond strength (exemplarily $2\tau_{b0}$ vs $\tau_{b0}$), again reducing the required reinforcement ratio. The same effect of increased bond strength may result from applying swelling concrete locally, causing transverse confinement of the reinforcing bar.

These possibilities to reduce the minimum reinforcement (“specifications of the design space”) may be combined with an operational flow

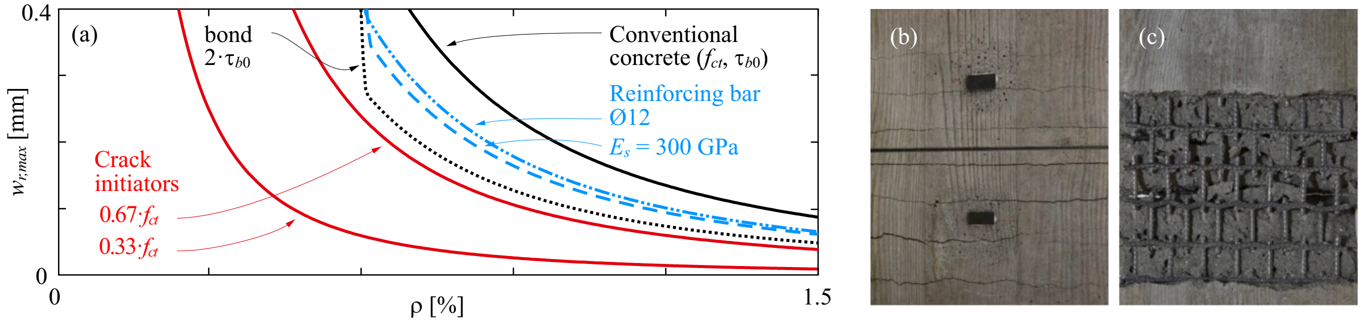


**Fig. 9.** (a) Impact of selected parameters influencing the minimum reinforcement ratio required to control the maximum crack width caused by imposed deformations (standard properties: $f_{ct} = 2.9$ MPa, $\tau_{b0} = 2f_{ct}$, Ø = 16 mm, $E_s = 200$ GPa), (b) and (c) detail of distributed bending cracks in specimen reinforced with a robotically fabricated mesh and loaded in a three-point-bending test with and without cover, respectively [8].

to develop practical applications. Possible applications may include *Mesh Mould* reinforcement to initiate cracking in foundations or walls mainly used for sealing, or provoking crack initiators by 3D printing strips with sprayed concrete for foundation slabs (or wall elements in prefabrication) before casting the rest of the volume.

## 6. Summary

Digital fabrication with concrete (DFC) is a young yet already broad discipline that provides opportunities to produce material-efficient concrete structures with inherent geometric complexity and to combine structural and functional demands. However, many DFC technologies face substantial technical and organisational challenges to be tackled before their products comply with construction mass market requirements. These challenges are especially relevant when producing complete building members with DFC. However, penetrating the mass market is paramount for making a significant contribution to the improvement of the environmental sustainability of the construction industry.

To address these issues, this study comprehensively (i) identifies the essential requirements for mass-market construction works, their construction, and their dismantling and (ii) evaluates the strengths, opportunities and challenges of concrete construction methods. This evaluation, covering traditional construction methods as well as DFC, serves to sharpen the focus for exploring the construction design space and identifying relevant practical solutions. The exploration employs a structural engineering-centred ideation process using the systematic variation of influencing parameters and a morphological approach.

Finally, selected ideas for digitally fabricated structural connections and for reducing minimum reinforcement are presented and discussed. Rather than trying to explore the abundant design space of the construction industry, these examples merely illustrate how relevant ideas may be derived to foster DFC innovation for the mass market. Furthermore, they indicate how traditional construction and DFC processes can work together in tackling the persistent challenges related to the societal demand for sustainable construction.

## CRediT authorship contribution statement

**Patrick Bischof**: Conceptualization, methodology, investigation, writing original draft, visualization, project administration. **Jaime Mata-Falcón**: Conceptualization, writing review & editing, supervision. **Walter Kaufmann**: Writing review & editing, funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

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## Appendix A. Additional information for traditional concrete construction

The following subsections cover complementary information on the evaluation of traditional construction methods. Appendix A.1 mostly coincides with the evaluation presented by Bischof et al. [58].

### *A.1. Value-driven evaluation*

This subsection evaluates traditional concrete construction based on the main criteria for construction works defined in Section 1. For each criterion, on-site and prefabricated construction are analysed, and their features, which may be considered strengths and challenges, are identified.

#### *A.1.1. Structural safety*

The structural safety of construction works comprises the overall stability and ultimate resistance at ambient temperature and fire situations, fatigue resistance and robustness. Reinforcement resisting tensile forces and its activation by bond and anchorage are essential for the load-carrying behaviour (including load redistribution), strength and robustness of reinforced concrete structures. The concrete tensile strength is unreliable, and failures governed by crack formation are very brittle. The concrete tensile strength is typically neglected; if accounted for in relevant structural verifications, e.g. for shear in members without transversal reinforcement or deviation forces of bent reinforcement, ample safety margins are provided to prevent failures by crack formation.

*A.1.1.1. On-site construction.* Reinforcement ratios and/or cross-sectional dimensions may be optimised, and sufficient robustness is usually provided through the monolithic connection of structural members creating hyperstatic systems, typically designed with reinforcement in two directions. Monolithic connections are preferred despite the increased efforts, including formwork installation and removal as well as cleaning, necessary for continuous reinforcement across construction joints, as shown in Fig. A.1a. Note that a surface retarder or mechanical roughening is may be required before cleaning in step ① to generate a rough surface for transferring shear stresses across the joint if a smooth stop formwork is used in step ②.

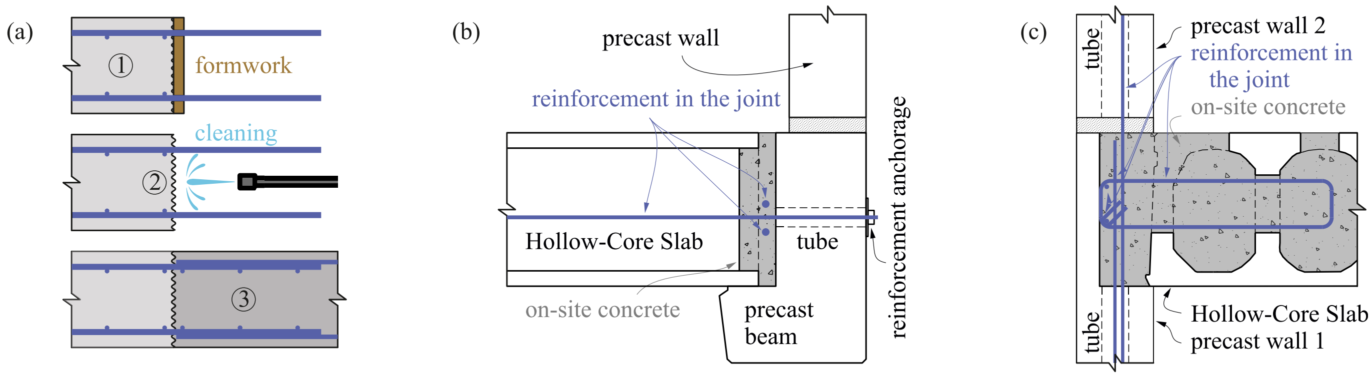


**Fig. A.1.** Details of connections in on-site and prefabricated construction: (a) Typical processing steps for an on-site construction joint; (b) typical connection of a Hollow-Core Slab to a precast beam; (c) typical connection of a Hollow-Core Slab to a wall.

In concrete structures, restraint stresses are caused by the hardening process of concrete (hydration heat), its viscoelastic nature (shrinkage, creep) and environmental influences (temperature). These internal stresses, occurring not only in hyperstatic systems but also in cross-sections of isostatic members, are hard to quantify analytically, and prototype testing is no valuable alternative, given the size, mass and custom nature of concrete construction works. However, restraint stresses can be ignored in ultimate limit state design when a ductile behaviour is ensured by providing a minimum amount of ductile reinforcement and using a conservative value of the concrete compressive strength, thereby enabling the application of plasticity theory in design. If sufficient ductility ductility cannot be guaranteed, e.g. when using brittle textile or softening fibre reinforcement, structures need to be strongly over-dimensioned to cover uncertainties.

*A.1.1.2. Prefabricated construction.* The assembly of precast elements and its preparation, particularly ensuring plane supports complying with the specifications, are of great importance for their efficient use and structural safety. For example, the shear resistance of Hollow-Core Slabs is vulnerable to flexible supports and short support lengths.

Precast elements usually carry loads as one-way systems and, due to transport limits, over one or maximum two spans. Hence, connection systems such as tying systems or on-site toppings and laps are often necessary for providing sufficient strength to horizontal wind and seismic loads, as well as robustness (Fig. A.1b and c show typical connections of precast elements; for more details see e.g. [59]).

*A.1.2. Durability*

The concrete mix, sufficient concrete cover, small crack widths, and tight joints are critical for the durability of concrete structures. Durable concrete mixes for structures or infrastructure in harsh environments, such as exposure to de-icing salt, generally require a clinker content higher than necessary for indoor floor slabs to increase the passivation potential for traditional steel reinforcement. The concrete cover thickness required to protect the reinforcement from corrosion and enable proper compaction of the cover (with maximum aggregate size) – which in turn ensures a high density of the cover concrete – also depends on the exposure. Clear concrete covers typically range from about 20 mm (indoor) to 60 mm (severe exposure to chlorides) today, imposing a minimum concrete dimension of usually 70–80 mm even indoor and when providing two reinforcement layers only (e.g. one vertical and one horizontal layer in a wall).

*A.1.2.1. On-site construction.* Avoiding joints while creating large monolithic construction works is highly beneficial for durability, e.g. in bridge design, where expansion joints often leak and the reinforcement in the area of joints is prone to corrosion. However, increased reinforcement ratios are required to limit crack widths in monolithic construction due to internal stresses particularly originating from restrained shrinkage. Furthermore, curing to avoid early shrinkage cracking is a challenge for on-site construction.

Air entrapped when casting slender vertical members (walls or columns), casting against counter formwork or excessive compaction may cause honeycombs, which expose the reinforcement to the environment.

*A.1.2.2. Prefabricated construction.* Joints are an indispensable prerequisite of prefabricated construction. Their proper and durable tightness is a persisting challenge in civil and structural engineering. Ultra high performance concrete (UHPC) has recently been applied for short lap splices between adjacent precast elements [55], avoiding expansion joints to be watertightened.

At the same time, cracking due to internal stresses is of lesser importance in precast elements due to the joints between elements with lengths limited due to transport. While this applies to temperature and shrinkage-induced restraint stresses, the latter are further reduced by advanced curing technologies and the age of elements at installation: only residual shrinkage is relevant.

#### A.1.3. Serviceability

Serviceability (functionality, appearance and comfort) is the most frequent reason for non-slender building members for on-site and prefabricated construction. Excessive deflections of slabs and beams may be avoided by cambering or prestressing them for permanent loads, but deflections due to live loads and vibrations are often a limiting factor. The latter is more critical in prefabrication since continuity over the supports, usually provided in on-site construction, is highly beneficial for the stiffness of beams and slabs.

When water tightness is required, e.g. for underground spaces, increased reinforcement contents result in the design of foundation slabs and on-site underground walls due to crack width limitation.

#### A.1.4. Aesthetics and integration

The rating of aesthetics and integration is highly dependent on client preferences. While on-site construction provides higher freedom to produce unique geometries, prefabricated elements are often superior in terms of surface quality.

*A.1.4.1. On-site construction.* On-site construction facilitates freedom in geometry and, hence, flexibility to adjust to the local environment. For example, the building geometry in plan can be adjusted to non-regular plots. On a smaller scale, customisation of spans and heights is facilitated, and adjustments such as small rises creating a slope for surface water runoff are easily executed by locally lifting the formwork. However, ensuring high surface quality and the specified concrete cover is often challenging, particularly due to entrapped air, e.g. when casting with counter formwork. When casting slabs on-site, the vertical space between top and bottom reinforcement is often used for flexibly installing building systems (e.g. venting and electric installation), which helps to (i) optimise the overall construction height, (ii) avoid visible installation pipes and (iii) isolate noise from these systems. However, such installations are generally accessible only with disproportionate effort in the finished construction work.

*A.1.4.2. Prefabricated construction.* Precasting allows for increased surface quality which is often asked for in unique or complex units with fair-faced concrete walls or soffits.

Although mass-manufactured products (such as Hollow-Core-Slabs) may be cut to specific lengths and angles to comply with varying two-dimensional floor plans, precasting is usually less suited for unique non-regular, variable three-dimensional geometries. For example, a vault, a camber, or a water runoff may require one-time-use formwork for the large element surfaces.

#### A.1.5. Environmental sustainability

When considering a structure, environmental sustainability is related to the grey energy use of the raw material, the transport distance of raw material and elements, waste caused by construction, the life span and recyclability/reusability at dismantling.

*A.1.5.1. On-site construction.* Process-dependent constraints of on-site construction cause inefficient use of construction materials and hence, an environmental impact superior to what could be possible when tailoring construction material explicitly according to the needs:

- Because the on-site construction process is exposed to the environment, concrete with higher strength than strictly needed is typically used. Over-strength concrete implies more binder than required, increasing the grey energy demand of the construction work.
- Traditional cast-on-site walls need a minimum thickness of approximately 200–220 mm, which is mostly more than would be strictly needed for mere static reasons, to ensure proper compaction through vibrating needles entering the space between the reinforcement layers.
- Material overuse is even more pronounced in underground exterior cast-on-site walls. Increased demands for small crack widths required for watertightness, durability, or appearance entail increased reinforcement ratios.
- Cast-on-site slabs are commonly far from being optimised in their concrete volume: solid or flat slabs are typically built rather than much more efficient systems such as ribbed slabs or waffle slabs. This is primarily due to the costly formwork (labour and material cost) of the latter.

On the positive side, the amount of formwork waste caused by on-site casting of flat uniform surfaces is typically low, thanks to reusable formwork. This advantage would be impaired if more material-efficient geometries were built on-site using conventional formwork. Furthermore, reinforcement contents and member depths can be optimised with cast-on-site solid and flat slabs thanks to hyperstatic systems.

*A.1.5.2. Prefabricated construction.* Higher-strength concretes are generally employed in precast manufacturing to enable early removal of the formwork. This increased strength is hardly ever required for the load-bearing capacity of precast elements.

On the other hand, design codes typically allow smaller safety margins on the concrete compressive strength in precasting, thanks to better and more controlled casting conditions and, hence, lower scatter. Furthermore, the required tolerances on the concrete cover and concrete dimensions may generally be reduced due to good concrete compaction (lying production and external concrete compaction equipment) and controlled casting conditions. These dimensional reductions imply reduced material consumption and, consequently, lower environmental impact with respect to the same member cast on-site.

Hollow-Core Slabs may be comparably slender, although they only span one-way and are typically simply supported, thanks to the efficient reduction of self-weight and concrete use by voids, which is more than 50 % for deep cross-sections. Even though such mass-prefabricated elements are adjustable in their length, customised optimisation is not possible: typically, few types with different slab thicknesses are available. Furthermore, heavy prestressing for standard building elements such as double-T-beams or Hollow-Core-Slabs actually causes a camber, which may require an additional concrete topping to provide a flat floor surface in housing construction.

#### A.1.6. Construction efficiency

Construction efficiency is understood to cover construction time efficiency and economy. The construction time efficiency is mainly important for the indirect cost caused by, for example, disrupted construction processes, traffic disruptions, pumping of increased water volumes, or financing. The direct cost of construction works is strongly connected to the structural design, as well as material, labour and transport costs, which depend on the local market and competition.

*A.1.6.1. On-site construction.* Formwork, concrete and reinforcement generally constitute the major part of the total cost for the basic structure (Section 3.3). Placing the formwork, installing reinforcing steel (if not prefabricated), casting concrete, and curing while concrete is hardening are serial work steps. Serial work steps are generally associated with high labour intensity and possibly lower construction efficiency. In large construction works, the serial work steps may be carried out simultaneously on different building members.

Many of the work steps of on-site construction are standardised and adapted to the mass market, such as formwork placement. For example, rectangular walls are usually formed with standard and reusable formwork elements. Furthermore, highly industrialised reusable formwork tables, enabling efficient temporary propping for early formwork removal, are commonly used for floor slabs. Also, the process of casting on-site has been optimised, covering the entire supply chain of preparing and transporting concrete by centralised ready-mix concrete suppliers. For example, casting large concrete volumes of 1000 $m^3$/day is done regularly nowadays, corresponding to concrete casting rates of 100–200 $m^3$/h (pumping or pouring). Shotcrete applications (denominated as “material jetting” in the classification framework in Fig. 2) reach a nominal spraying capacity of up to 30 $m^3$/h [60]. Hence, the single work steps carried out on-site are often highly efficient.

*A.1.6.2. Prefabricated construction.* The manufacturing of prefabricated elements has become remarkably efficient with a high level of automation and digitisation in the data processing, material supply, and machinery (e.g. see [61] for further details). For production, cost mainly consists of concrete – which is usually less expensive than on-site – and casting, reinforcing steel and the preparation of reinforcement cages, possibly some non-reusable formwork parts, and the amortisation of the plant installation including most of the formwork. The preparation of the formwork and reinforcement as well as casting can be carried out simultaneously at different places within a production site, resulting in a high degree of industrialisation. For example, the industrialised fabrication of products such as Hollow-Core Slabs is typically carried out on several beds with lengths of up to 200 m, reaching more than 500 $m^2$/day with four beds [62]. Transport distances and the plant production capacity are decisive for cost-efficiency.

To ensure a high production efficiency, only a few types of concretes are generally used in a prefabrication plant. Furthermore, concrete performance grading within one element is unusual as it requires sequential work steps separating parts of varying concrete quality by construction joints.

The assembly of prefabricated members is swift – for example, 3–4 workers can install more than 500 $m^2$/day of Hollow-Core Slabs [62]. However, on-site toppings, connections, and laps with (possibly) extra formwork interrupt a smooth construction process (Fig. A.1b and c) and are comparably expensive, i.e., about 30–40 % of the cost for the precast elements [21] (Section 3.3).

### *A.2. Cost structure and material use of reinforced concrete buildings*

As mentioned in Section 3.3, three recently erected traditional concrete construction works were analysed regarding cost and material use to gain insight into the cost structure and the material use of reinforced concrete buildings. The details of these buildings are summarised below, while the summary is provided in Section 3.3.

The first studied building was cast-on-site. It has one underground parking level and three storeys for office use above ground, each of them with a plan surface of roughly 5700 $m^2$. The building incorporates (i) a foundation slab of 300 mm depth (with deepening for columns and walls up to 1.2 m), (ii) concrete walls of 250 mm or 300 mm thickness, (iii) masonry walls (in underground parking only; room partition walls above ground level are lightweight construction), (iv) precast columns and (v) solid flat slabs of 400 mm depth with integrated post-tensioning systems for cantilevers as well as integrated venting and electric installation. The standard column grid is 8.4 m by 8.4 m.

The second studied building was also cast-on-site. It consists of an underground parking with a plan surface of 2600 $m^2$ and two parts above ground level, with eight and four storeys above ground, respectively, for residential use with stores on the ground floor. The part with eight storeys has a plan surface of 320 $m^2$, while the part with four storeys has a plan surface of 680 $m^2$. The building incorporates (i) a foundation slab of 600 mm depth, (ii) concrete walls of 200 mm to 300 mm thickness, (iii) masonry walls, (iv) cast-on-site and precast columns, and (v) solid slabs of 300 mm (eight-storey building) and 320 mm (four-storey building) depth with integrated venting and electric installation. As an exception, the flat slab above the underground parking is 600 mm deep. The standard column grid is 8.8 m by 8.8 m. The solid flat slab above the ground floor with business use is supported by columns, while the solid slabs of the residential storeys (second storey and above) are continuous over apartment-separating walls.

The third studied building was primarily precast. It incorporates an underground parking and basement rooms with a plan surface of roughly 4400 $m^2$ and six above-ground storeys incorporating a hotel, a restaurant, and shops, all with a plan surface of approximately 3800 $m^2$ (two courtyards capture an area of roughly 600 $m^2$). The foundations and some parts of the floor slabs (see below) were cast on-site; the remainder of the building was precast. The steel roof of the top storey is not considered for this analysis. After their assembly on site, the precast elements were connected on-site with minimum reinforcement ensuring the resistance against horizontal loads and the robustness of the building. The building incorporates (i) a foundation slab of 450 mm depth (with local deepening for columns and walls), (ii) precast concrete walls of 200 mm to 300 mm thickness, (iii) precast columns, (iv) precast beams, and (v) slabs of generally 400 mm depth, where 85 % of the plan surface was made with precast Hollow-Core Slabs, while the remainder was cast on-site. The span reached 14.3 m (from façade to façade).

The cost structure of the two cast-on-site buildings is subdivided into the decisive work steps for the office building in Fig. 4a and for the residential building in Fig. 4b. The total cost share (installation, formwork, reinforcement, concrete, masonry, miscellaneous), construction time and concrete volume per building member (foundation, walls and columns, slabs) are summarised in Table 2a and b for both buildings. The concrete volume per building member (foundation, vertical members, horizontal members) of the precast building is summarised in Table 2c. Note that only the cost for the structural concrete works was available (accordingly, the following percentages sum up to 100 %). Overall, the portion of the cost for producing the precast elements (incl. stairs) represents 54 %, while their assembly summed up to 25 %. The remaining 21 % were attributed to the on-site works, including the installation of the elements for the outer basement wall.

## Appendix B. Additional information for digital fabrication with concrete

The following sections cover complementary information on digital fabrication with concrete (DFC).

### *B.1. Technologies*

The technologies 3D concrete printing (*3DCP*) or *Particle-bed binding* may be used to produce members or small structures directly, while technologies such as *Mesh Mould* or *KnitCrete* are used to create formwork to produce members or small structures and consist of several working processes. Not all of these processes in DFC technologies may be computer-controlled.

*B.1.1. 3D printing with extruded concrete*

3D concrete printing (*3DCP*, with extruded concrete) is an additive shaping process based on concrete layer extrusion. It is the most used DFC technology, capturing a wide range of material and printing setups [26], and has already resulted in various applications (e.g. Figs. 1c and 6). In *3DCP*, a nozzle of typically 6–50 mm diameter [26] continuously extrudes and deposits sequential filaments to produce layered elements. The nozzle moves at a close distance to the previous layer, typically approximately corresponding to the layer height. The layer width of deposited filaments is typically 30–50 mm. However, approaches with thinner and considerably wider layers exist (e.g. 150 mm [63]). In research applications, a mortar with a maximum aggregate size in the range of 2–3 mm is usually extruded [26]. A recent industrial application uses concrete with aggregate size up to 10 mm [14,64].

The layering inherent to 3D printing influences the bond strength (i) between concrete and interlayer reinforcement, i.e., reinforcement positioned in the layer joints, and (ii) between adjacent layers. The bond strength depends on the printer-material setup (e.g. [65,66]).

The printing nozzle is generally attached to a gantry or robotic arm system. The decision of whether to use a gantry or a robotic arm to carry the nozzle influences the production speed, the degrees of freedom and the expectable resolution obtained in production (the stiffer the structure, the higher the resolution). Buswell et al. [26] mentioned typical production speeds of 50–500 mm/s; note that a higher production speed may lead to comparably lower geometric resolution for the chosen gantry or robotic arm system. A recent industrial application promises a higher production speed of up to 1 m/s with a gantry system [64].

Most layer extrusion processes produce a somewhat undulated side surface marked from the convex shape of each printed layer. Contour crafting combines concrete extrusion with surface shaping (trowelling) to create smooth surfaces [67]. Several researchers [68–70] used hybrid robots including additive and subtractive processing tools. They employed milling for creating a flat surface.

*B.1.2. 3D printing with sprayed concrete*

3D printing with sprayed concrete (also denominated as *Shotcrete 3D Printing*) is an additive shaping process, including material jetting according to the classification framework presented in Fig. 2. As in *3DCP* processes, concrete is pushed through a nozzle attached to a gantry or robotic arm system to produce layered elements [27]; however, the material is jetted instead of extruded (Fig. B.1a). Layers are typically wider than in extrusion processes (e.g. Hack and Kloft [71] sprayed 120 mm wide layers). The interlayer bond strength of additive spraying-based applications is generally almost equivalent to the printed material's tensile strength [72].

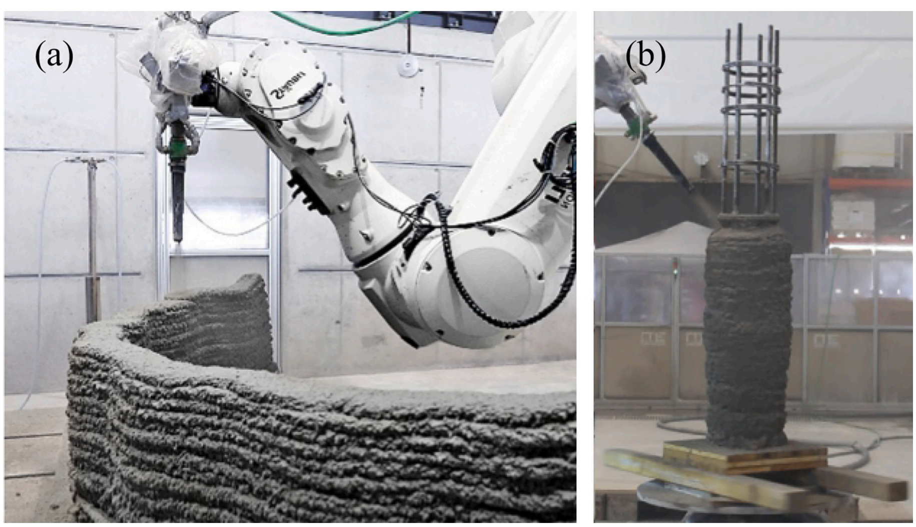


**Fig. B.1.** Exemplary applications of 3D printing with sprayed concrete: (a) Printing process [71]; (b) sprayed column [33].

Currently, spraying-based applications excel at higher production speeds than extrusion-based applications, ranging from 1 $m^3$/h [71] in the scientific environment to 2.5 $m^3$/h in recent industrial applications [73]. 3D printing with sprayed concrete allows jetting material through pre-positioned reinforcement cages – Kloft et al. [33] reported spraying ribs of 200 mm height through longitudinal and stirrup reinforcement (Fig. B.1b) as well as spraying a column with an inclined nozzle through a preinstalled reinforcement cage rotating on a platform (Fig. B.1b).

As in *3DCP*, subtractive processes have been explored for fresh and hardened state surface post-processing with trowelling [74] and with a milling tool [71] (Fig. B.3c).

*B.1.3. Particle-bed binding*

In *Particle-bed binding* (also denominated as particle-bed 3D printing), a binder is used to bind additively, layer by layer, particles provided in a bed. Unbound particles serve as support during printing and are removed after printing. Applied layer thicknesses range from 0.1 mm to 5 mm to print objects with a high degree of form freedom and a high resolution [75]; note that the resolution depends on the chosen particle size. As for *3DCP*, *Particle-bed binding* inherently produces weak interfaces between adjacent layers, whose bond strength depends on the printer-material setup. The technology, so far, has mainly been used to produce unreinforced elements. Only a few structural applications exist, such as the footbridge of Alcobenas, Madrid (Fig. B.2a).

Recent developments combine the process of *Particle-bed binding*, concrete jetting and subtractive post-processing (milling) using (i) interlayer reinforcement and (ii) particles with a size up to 36 mm [76] (Fig. B.2b and c). The use of comparably large particle sizes allowed attaining compression strengths beyond 50 MPa while simultaneously reducing the overall used clinker content compared to other applications of *Particle-bed* *binding* [76].

The main inherent disadvantage of the *Particle-bed binding* process is related to the size of typical construction industry products. The provision of the particle-bed and the removal of the unbound particles (Fig. B.2b) for typical dimensions of buildings or even elements thereof is time- and labour-demanding. Consequently, it is unlikely that *Particle-bed binding* will be used for mass-market structural elements but rather be limited to smaller parts requiring high geometric complexity.


**Fig. B.2.** Exemplary applications of *Particle-bed binding*: (a) Footbridge of Alcobenas, Madrid (Photo credits: Institute for Advanced Architecture of Catalonia); (b)–(c) example of an application with large particles, concrete spraying and milling of surfaces [76].

### B.1.4. Digital formworking

The technologies grouped here within the process "digital formworking" enable the direct transfer from digital model data to computer-controlled fabrication to create (i) a stay-in-place (lost) formwork integrated into the produced member or (ii) a temporary (reusable) formwork. Stay-in-place formwork and temporary formwork may be cementitious or non-cementitious. The reinforcement placement and casting (mostly traditional formative solidification or material jetting processes) to produce a complete element or member may be executed simultaneously or contiguously with formwork production or afterwards (in series). Compared to traditional formwork, digital formwork technologies promise to offer new possibilities in form and material optimisation, and have the potential of reducing formwork waste inherent to curved shapes.

*B.1.4.1. Stay-in-place formwork.* Parts formed by the process of 3D printing with extruded or sprayed concrete or by Particle-bed binding may serve as lost cementitious formwork, as shown in Fig. 5c for extruded concrete; other examples are available, see e.g. [77]. When employing formwork produced by 3D printing for members produced in their standing position (e.g. walls), the placement of reinforcement cages and especially their splices to already-placed reinforcement is challenging if the printed formwork is closed, which is in contrast to traditional processes where one side of the formwork is usually open and only placed after installing the reinforcement. The casting process within or on a partially prefabricated printed formwork should connect the lost formwork and the solidified concrete to activate the lost formwork for (i) being part of the complete load-bearing cross-section (e.g. as part of the compression zone in slabs) and (ii) contributing to the durability of the reinforcement against environmental exposure.

In the *Mesh Mould* process [8], a robotic tool head bends, cuts, and welds a reinforcing steel mesh to create a semi-permeable formwork (Fig. 5e). The production of the cut steel mesh is considered an assembly operation by Buswell et al. [19]. The steel mesh is filled with concrete before adding a cover layer to the mesh (this step may be considered a solidification process). In the hardened stage, the steel mesh serves as reinforcement. The first real-scale application (a double-curved wall with height 2.8 m, length 11.5 m, and thickness 125 mm) incorporated continuous reinforcement in the vertical direction while the horizontal reinforcement consisted of cut, welded pieces. The load transfer between the cut pieces in the horizontal direction generated shear stresses in the continuous reinforcement [8]. The first real-scale application revealed the following challenges:

- The on-site production of the reinforcement mesh for the double-curved wall was time-consuming (125 h for a double-curved wall of height 2.8 m, length 11.5 m and thickness 125 mm) [78]; however, the prefabrication of the reinforcement mesh could accelerate the on-site operation.
- The sufficient bond between the concrete infill and the cover layer is not straightforward to achieve.
- Finally, the surface post-processing required a considerable amount of manual labour.

The *Mesh Mould* process is currently being further developed at the NCCR dfab in collaboration with an industry partner, addressing some of the challenges mentioned above [79].

The concept of *KnitCrete* using flexible integrated formworks created by knitted textiles [30] (Figs. 1a and 5g) is most useful for curved concrete members (shells, beams, slabs) [16]. The process includes the digital fabrication of a knitted textile, which, in a second step, is brought to the desired shape in a dry joining assembly process using a cable-net falsework and an external scaffolding frame. In a third step, the textile is sprayed with a thin fast-setting cement-paste coating [80] before concrete is applied to the coated knitted formwork (solidification process). It is possible to integrate high strength continuous fibres or to guide bar reinforcement within the knitted textiles that serve as reinforcement in the hardened state [81,82]. The production of the knitted textile may be highly industrialised in the KnitCrete process, while the other operational steps (cable-net falsework and scaffolding, integration of reinforcement, coating, application of concrete on curved surface) require a considerable amount of labour.

Liew et al. [31] presented the *Funicular Floor* system, which works with a compression vault with stiffening ribs and external tension ties. They employed a CNC-milled expanded polystyrene (EPS) formwork to provide void volumes between ribs and to form the double-curved vault (Fig. 5h). The formwork for void volumes was used as permanent formwork to serve acoustic insulation, while the formwork for the vault was lost (waste) because its shape was specific to the spans of the corresponding slab. If EPS is used for creating voids, such as in the described *Funicular Floor* system, a counter formwork is needed to oppose uplift during casting (Fig. 5h).

*B.1.4.2. Temporary formwork.* *Smart Dynamic Casting* (*SDC*) [29] is a formative solidification process. It includes continuous slip forming with a small formwork with multiple degrees of freedom to cast varying shapes in the slip forming direction. The technology may be used for column-type elements (Fig. 1b) or wall-like structures such as thin folded structures [83] and allows including standard reinforcement within the boundaries of the slip formwork. The typical documented slipping rate so far applied was 10–20 mm/min [84]. A challenge of the *SDC* process is the dependency of the slip forming on variations in the (i) geometry of the element or structure and (ii) material [7]. Nevertheless, this technology is close to application in precasting practice, even if further advancements may be needed e.g. in terms of durability depending on the chosen material, Appendix B.2.2.

*Eggshell* describes a technology that uses robotic fused deposition modelling 3D printing of thin plastic formworks combined with set-on-demand concrete casting. The formwork may serve in a continuous printing and casting process with fasthardening concrete [28] (Fig. 5d). It can also work as prefabricated formwork when using standard concrete, maintaining the challenge of balancing the stiffness and strength of the formwork with the horizontal pressure arising when casting. Hence, *Eggshell* may be considered an additive printing process for the formwork with a simultaneous or subsequent casting process, including previously assembled (fixed or welded) reinforcement or cages. The removal of the printed formwork may be laborious depending on the printed surface and the formwork penetrations (e.g. penetrations of reinforcing bars). Furthermore, the *Eggshell* formwork printing speed is still low (approx. 100 mm$^2$ surface per second); however, the printing process depends on the used tools and may be further developed. Details of processes similar to *Eggshell* but using different formworks such as tensioned foils or papers are described in [29].

Various principles of double-curved concrete elements are discussed by Schipper [85], including the *Flexible Mould* technology. The *Flexible Mould* technology incorporates a mould on a flat pin-bed confined by a flexible formwork (e.g. with a rubber or extruded filaments), which is filled by concrete (formative solidification, classification according to [19]) and finally deformed by the pin bed when concrete starts to set (formative deformation, [19]). Liew et al. [86] developed a rod-net for a fabric formwork system serving the construction of the large double-curved shell-shaped roof of the HiLo unit built on-site in the NEST building at Empa.

Pieces created by impregnated *Particle-bed binding*, *3DCP*, or wax have been used as reusable temporary formwork [9,16,87].

### B.2. Value-driven evaluation

The DFC technologies presented above are heterogeneous in their fields of application and incorporate different strengths, opportunities and challenges: the load-bearing behaviour, the reinforcement layout and the surface of digitally fabricated concrete objects differ, while also the sensitivity to the environment and the production speed of the associated operations themselves vary. Nevertheless, the following sections attempt to cluster the strengths and challenges of DFC technologies based on the main criteria for construction works introduced in Section 1.

The fundamental constraints of traditional on-site and prefabricated construction (Section 3) also hold for DFC: on-site construction, including the installation of robots and the processing operations with robots, is exposed to the environment and bound to producing members in their final orientation, while prefabricated construction is limited in size due to transport limitations. On-site weather protection (e.g. a tent) excludes some negative aspects of the on-site construction related to the high dependency of the printing process on the environment (concrete mix, robots). However, it requires an increased effort for installation, growing with the size of a building.

#### B.2.1. Structural safety

The layering inherent to 3D printing or *Particle-bed binding* production processes (i) influences the bond strength between concrete and interlayer reinforcement and (ii) causes an anisotropic material behaviour in most printer-material setups due to reduced interlayer bond strength. The reduction of the interlayer bond strength depends on various parameters such as the type of material used, the interlayer time related to print speed and object size, or environmental conditions [45]. In *Particle-bed binding*, unbound particles at the bottom of layers may increase the anisotropy. The pressure used to apply concrete in 3D printing with sprayed concrete positively affects the interlayer bond strength, even after a considerable interlayer time [88].

An anisotropic material behaviour affects the load-bearing behaviour of printed concrete members or parts under all loading conditions [45], but particularly under tension and shear (with respect to the layer surface). Under pure tension (perpendicular to the layer joints), the anisotropy influences the stiffness; however, if the digitally fabricated member is reinforced, the ultimate load-bearing capacity remains unchanged [18,89]. Under shear loading (with respect to the layer direction), the anisotropy may cause a reduced ultimate load-bearing capacity in inclined compression fields affected by the layering [90]. Accordingly, members undergoing considerable shear loading (beams and slabs) may require additional examination or additional reinforcement when produced with DFC and when the design relies on the printed parts. Especially slabs traditionally incorporate only local shear reinforcement. It should be noted that most current DFC applications are comparably small and that the interlayer property reduction increases with object size due to the increased waiting time between two layers.

Furthermore, the anisotropic behaviour is relevant when dealing with lost formwork made of mostly unreinforced cementitious materials. If prefabricated (e.g. lost formwork serving to produce slabs), the handling of prefabricated elements is delicate during production and assembly, as its load-bearing capacity highly depends on the concrete tensile strength (see Appendix A.1.1).

The need for reinforcement inclusion in printed objects and the reinforcement activation by bonded cover concrete challenges additive processes, as pointed out by Asprone et al. [36]. Several possibilities for reinforcement placed between layers and integrated into the *3DCP* process are available [91], even though not necessarily with the same performance as cast concrete [66].

However, *3DCP* technologies and Particle-bed binding currently lack an effective strategy to implement (i) typical reinforcement cages with hoops and (ii) long continuous structural tensile reinforcement across the layers. Regarding the latter, it must be kept in mind that lap splices of reinforcing bars (nominal diameter ∅) typically require a length of 30∅ to 50∅. Hence, reinforcing bars shorter than about 200∅ (2 m for reinforcing bars ∅10 mm) are highly uneconomical and unsustainable. Only one industrial application currently implements longer reinforcing bars (only one horizontal and one vertical layer of reinforcement can be integrated) in the printing process using an approximately 3.5 m high printhead incorporating two nozzles extruding on both sides of a reinforcing mesh (elaborated in [92]).

The challenge of integrating continuous reinforcement across layers may be circumvented by using additive shaping processes such as lost formwork printing technology (Appendix B.1.4). However, digital formworking technologies impose geometrical constraints to the assembly of conventional reinforcement cages, specifically relevant for elements with complex geometry or when splicing reinforcement of an element with that of the one previously produced. Further constraints relevant for the slenderness of building members include (i) the tolerances when printing around reinforcement [93] and (ii) the minimum dimensions required for activating the reinforcement by bond when casting concrete in additively shaped cementitious formworks. Note that the joining of the lost formwork with cast concrete needs close consideration to avoid entrapped air at the rough contact surface, which would impair the bond between the two connected parts [93]. This detail becomes gradually more relevant with the increasing height of the contact surface in the casting process.

Most additively printed structures are externally post-tensioned or unreinforced and either predominantly loaded in compression (Fig. 6a) or only slightly loaded (Figs. 1c, 6b and c). The current design of digitally fabricated concrete structures highly relies on compression-only solutions and extensive experimental testing (as carried out e.g. by Bos et al. [94]) to cover all criteria to be met for construction works (Section 1). However, this limits the possible geometries and hinders mass-market application. Consequently, further research and inventions in this field are needed to exploit on-site and prefabricated digital fabrication, as also concluded by Menna et al. [15].

The technologies presented above have been used for digitally fabricating vertical members both on-site as well as in prefabrication: the façade mullions and the ribbed slab shown in Fig. 1b were prefabricated while the curved wall shown in Fig. 1b and the walls shown in Fig. 1c were fabricated on-site. However, it is anticipated that at least the industrialised digital fabrication of horizontal members will generally happen in a prefabrication environment. In this case, the challenges of traditional prefabricated construction related to transport, assembly and its preparation, as well as connecting systems, equally apply to DFC. Connection systems may be required from element to element (full prefabrication) or from prefabricated formwork to cast-on-site concrete (partial prefabrication). Stiff supports are crucial to avoid undesired, potentially harmful load redistributions, especially for ribbed solutions relying on concrete compression ribs for the load transfer. Connecting systems of traditional prefabricated construction (Fig. A.1b and c) are crucial to resist horizontal loads and provide robustness.

DFC needs to comply with standard fire safety regulations beyond the resistance to static and dynamic loads at ambient temperature. However, the implications of heating to DFC have only been studied on the material level to date [95]. Fire safety may be decisive for rib and slab thicknesses to avoid excessive heating, compromising the material optimisation potential. When exposing a slab rib with a height of 200 mm and a width of 100 mm to a standard fire (ISO 834), the average temperature after 30 min corresponds to roughly 400 °C, implying a 15–25 % concrete compressive strength reduction; after 60 min and 90 min, the temperature corresponds to roughly 630 °C and 770 °C, respectively, with compressive strength reductions of 50–60 % and 70–80 %. These concrete temperatures and corresponding strength reductions were obtained from a 2D heat transfer analysis. The reinforcement temperature and corresponding strength decay depends on the distance of its position from the surface exposed to fire. Floors with the flange or vault at the bottom and the ribs on top (as chosen for the *Funicular Floor* system presented in Appendix B.1.4) exhibit a superior fire performance than floors with directly heated ribs.

#### *B.2.2. Durability*

The research community has discussed the durability of DFC applications recently (e.g. [16,96,97]), mainly due to concerns about potential implications of the used materials and processing operations. The high paste content of mortars often used for DFC processes and the early exposure of the printed concrete to the surrounding environment may induce increased (differential) shrinkage strains if not counteracted by admixtures or curing [26]. These increased shrinkage strains may lead to significantly increased crack widths compared to traditionally cast and compacted concrete. Furthermore, challenges related to freeze-thaw resistance have been identified (e.g. [41,95,96]) and tackled [96,98]. Additionally, Lloret et al. [29] mentioned the risk of corrosion of the reinforcement related to the high accelerator content inherent to the material used for their *SDC* process, despite the passivation by the high clinker content. Hence, improvements on used materials are necessary before reinforced members produced with digitally fabricated concrete can reliably be exposed to conditions other than inside buildings at low humidity.

On the other hand, the weak interfaces inherent to additive processes have been identified as crack initiators, which could be exploited to control densely distributed cracking [18,57]. Densely distributed cracking allows substantially reducing minimum reinforcement required to provide water tightness and durability in traditional structural concrete.

#### *B.2.3. Serviceability*

Materials with high paste contents commonly undergo high creep strains [94], generally leading to increased long-term deflections, which may imply the need for deeper cross-sections or load-balancing prestressing to compensate.

New approaches to coupling acoustic insulation and energy systems with lightweight structures have been explored in collaboration with researchers of building systems [44]. Such developments foster smaller concrete volumes than typically used today to fulfil functional serviceability requirements.

#### *B.2.4. Aesthetics and integration*

The increase of production cost with increasing geometric complexity is expected to be less pronounced for DFC than for traditional construction (e.g. [16]). The freedom for geometric complexity may be understood as the freedom to create geometrically complex building members in plan, elevation, or both. As mentioned in Section 2, it may be assumed that (i) geometric complexity in plan is not a mass-market need to build material-efficient buildings in future. Nevertheless, there are many examples of aesthetically convincing solutions complying with these boundary conditions, such as the *SDC* mullions or the *Smart Slab* of the DFAB house (Fig. 1b) or the *Funicular Floor* system in the HiLo unit at Empa [31] house (Fig. 5h).

The surface quality and texture of digitally fabricated members depends on the fabrication process. The applications shown in Fig. 6 feature typical *3DCP* surfaces. Slip forming or postprocessing (milling or trowelling) on fresh and hardened concrete brings about the potential to overcome such processing limitations; however, they also involve limitations themselves. Milling will expose the aggregates (Fig. B.3a), while trowels attached to the printing nozzle may not cover all air voids (Fig. B.3b), or entail a considerable material waste (Fig. B.3c). Fresh-state post-processing may also be used for creating textures on surfaces, as shown in Fig. B.3a and c. The geometric accuracy of post-processed surfaces depends on the stiffness of the gantry, robotic arm, where applicable the formwork (e.g. in the *Eggshell* or the *SDC* process), and the toughness or viscosity of the material when milling is applied.


**Fig. B.3.** Exemplary applications of surface post-processing: (a) 3D concrete printed element with a partially milled surface [68]; (b) trowelled surface with insert of an element 3D printed with sprayed concrete [73]; (c) surface post-processing with a milling tool [71].

### B.2.5. *Environmental sustainability*

Digital formwork strategies tackle the elimination of the formwork waste currently inherent to curved shapes. For example, double-curved formworks such as the *Flexible Mould* or rod-net for a fabric formwork system introduce prefabricated solutions to provide cambers or vaults on a re-usable platform. If exploited, DFC has the potential to become an important part of the construction industry to enable the production of material-efficient reinforced concrete structures in such applications.

The use of pumpable and printable small aggregate mortars in digital fabrication is generally related to high clinker contents, causing a relatively high environmental material impact (easily 3–4 higher per volume than for standard concrete used for building construction) [13]. Recent studies show that printable and pumpable mortars could be produced with supplementary cementitious materials replacing much of the clinker, reducing the carbon footprint to less than 60 % of current DFC mixes [99]. Additionally, recent industrial applications [64,73] demonstrate the feasibility of using larger aggregate sizes. However, it should be noted that printed material will always have a higher environmental impact than cast concrete (see [13]).

Schmeer and Sobek [100] envisioned and tested the additive manufacturing of building members with gradient concrete, i.e., concrete with varying properties such as strength and weight. Such as tailoring concrete to the actual requirements would enable the overall improvement of environmental sustainability.

When using DFC to produce lost formwork, its activation as part of the structure is necessary to avoid massive cross-sections and waste its concrete volume.

### B.2.6. *Construction efficiency*

When using the typical printing speeds and filament geometries of *3DCP*, and assuming two outside filaments and a connecting inner filament, the estimated printable wall surface corresponds to 4–20 $m^2/8$ h (i.e. per workday) with a concrete volume of approximately 0.5 $m^3/8$ h. These numbers are meagre when compared to the typical construction time efficiency; the highest printing speed of 20 $m^2/8$ h for fabricating a wall corresponds to a single mason's usual working speed. However, recent industrial applications promise to reach a production speed of roughly 100–150 $m^2/8$ h and 15–20 $m^3/8$ h [64,73]. However, these numbers are still more than an order of magnitude below the ones for traditional casting or shotcrete applications (Appendix A.1.6).

Most digital formworking technologies include labour-intensive work steps, such as adding cover concrete layers and surface finishing in the *Mesh Mould* technology, scaffolding and the application of the cement-paste coating in the *KnitCrete* technology, milling and placement of EPS pieces (applied for the first application of the *Funicular Floor* system), or formwork removal in the *Eggshell* technology. The elimination of such labour-intensive work steps is a matter of further developments to foster the applicability of these technologies in the construction mass market.

A gantry system is generally stiffer, faster and more accurate than a cantilever robotic arm system, which generally offers superior geometric freedom but is also more complex to handle. While Kromoser [25] anticipated the combination of several robots, a robotic gantry system is usually exclusive to the use of one single robot and may limit the overall fabrication process. For example, a printing nozzle and a robotic arm to place inserts or reinforcement cannot be operated simultaneously from the same gantry system.

Currently, the implementation of DFC requires (i) infrastructure (robots, computational interfaces and programs) and installation efforts, (ii) for some technologies, expensive raw material, (iii) expert machine operators, but (iv) still manual labour, e.g. for the providing lintels above windows or for including inserts. However, a direct comparison to traditional construction based on direct and indirect cost today may not be valid because DFC is in a phase of development and first implementation, while traditional construction has matured for many decades.

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