Vision of 3D printing with concrete – technical, economic and environmental potentials

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Abstract

A vision is presented on 3D printing with concrete, considering technical, economic and environmental aspects. Although several showcases of 3D printed concrete structures are available worldwide, many challenges remain at the technical and processing level. Currently available high-performance cement-based materials cannot be directly 3D printed, because of inadequate rheological and stiffening properties. Active rheology control (ARC) and active stiffening control (ASC) will provide new ways of extending the material palette for 3D printing applications. From an economic point of view, digitally manufactured concrete (DFC) will induce changes in the stakeholders as well as in the cost structure. Although it is currently too ambitious to quantitatively present the cost structure, DFC presents many potential opportunities to increase cost-effectiveness of construction processes. The environmental impact of 3D printing with concrete has to be seen in relation to the shape complexity of the structure. Implementing structural optimization as well as functional hybridization as design strategies allows the use of material only where is structurally or functionally needed. This design optimization increases shape complexity, but also reduces material use in DFC. As a result, it is expected that for structures with the same functionality, DFC will environmentally perform better over the entire service life in comparison with conventionally produced concrete structures.

1. INTRODUCTION

3D printing is getting an exponentially increasing attention nowadays. In some industries, additive manufacturing and rapid prototyping are a daily reality already. In other industries, including construction industry, some showcase examples are available (e.g. Smart Dynamic Concrete, XTree, TotalKustom, WinSun), but daily practice still seems far away. This comes from the fact that construction industry is risk adverse and conservative in its practice but also because there are some technical, economic and social challenges that need to be overcome to unlock and trigger all opportunities from 3D printing in building sector. Gibson et al. [1] introduce the concepts and challenges for extrusion-based 3D manufacturing. For successful 3D printing, high-quality final properties have to be targeted, further considering that the material needs to successfully go through a “liquid” stage (fresh material flowing towards and in the print head) and a “solidification” process (transition to a rigid material supporting self-weight and subsequently added layers).

Considering the specific rheological properties of self-compacting concrete (SCC) [2], automated casting operations become more and more realistic. The development of SCC has led to the introduction of fundamental rheological research in concrete science, as illustrated by Roussel [3]. As stated by Shah in his recent ‘*future research needs*’ paper [4], “... *research in the rheology of SCC is a key to increasing SCC versatility in construction and utility in various construction types*”. This research goes beyond basic rheological parameters such as viscosity and yield stress, and needs to include complex behaviour such as thixotropy “... *because of its benefits, such as [...] timely green strength and shape stability in slip-form construction ...*”. Several approaches for 3D printing of concrete exist (e.g. contour crafting [5], D-shape [6], smart dynamic casting [7]), with the most popular and promising ones considering extrusion-based processing, producing elements or layers that have to be self-supporting.

In a first stage, the material needs to be fluid, in order to be easily pumped towards the printing unit, and in order to properly compact and fully fill the print volume during the time the concrete is still supported by the print head. However, as soon as the print head is no longer supporting the material, the concrete should be stiff enough. Significant yield stress is needed, in combination with adequate thixotropic behaviour. Well-chosen additions (e.g. clay

powders) and admixtures can help to achieve the desired level of thixotropic behaviour, without impairing the high fluidity of fresh concrete while in motion [8]. As soon as the printed concrete is in its final position, the yield stress temporarily provides enough stiffness to ensure shape stability of an individual layer, while the thixotropy should ensure the shape stability of collective layers following in the process of additive manufacturing. However, with increasing number of printed layers, further and speedier increase in stiffness and strength is needed to ensure the shape and buckling stability of the growing structural element. Therefore, the hydration process should proceed soon enough in order to provide a load-bearing internal skeleton of solid hydration products [9, 10]. The printed volume should not be prone to shrinkage cracking (plastic shrinkage is of a particular relevance here, since there is no formwork to protect the freshly placed concrete against desiccation). The final result should reach required mechanical properties (including bond to previous layers) and durability performance. The entire 3D printing process should be technically sound and cost-effective, and should be in line with modern environmental considerations. It is noteworthy that the rate of printing defines the economic potentials and should be harmoniously controlled, balancing both early strength and ability to avoid cold-joints.

This paper presents a vision for future concrete 3D printing industries. The vision includes challenging scientific and technical ideas to better control the transient phases of flowing and stiffening of the printed material, in view of obtaining targeted high-level final quality. The presented vision further includes the interesting economic potential and process aspects, as well as an appealing view on environmental benefits. The contents of the paper is based on emerging scientific results and studies, hoping to reveal a glimpse of what could be a future-proof 3D printing approach in concrete industries.

2. TECHNICAL CHALLENGES

2.1 Material choice

A major current obstacle in view of advanced 3D printing in construction industries is the very limited material palette currently available in practice. Many current showcases are not based on high-quality materials required to reach a reasonable service life in natural or industrial

96 exposure conditions. They are rather narrowly based on the technological issue of being able
97 to add layers on top of each other without premature collapse. When checking material
98 performance in some showcases in more detail, striking insufficient performance can
99 sometimes be noticed, e.g. related to shrinkage cracking as shown in **Figure 1** for the situation
100 of an early showcase of 3D printed mortar structural element with an excessive degree of
101 shrinkage cracking. It is currently well understood that shrinkage cracking has to be well
102 controlled by a combination of appropriate mix design and efficient curing measures. Current
103 printing operations normally avoid significant shrinkage cracking as shown in Figure 1.
104 Nevertheless, the issue of appropriate curing of 3D printed elements or structures, in absence
105 of formwork from the beginning, remains a technical challenge requiring further optimization.

Figure 1: Excessive shrinkage cracking in an early showcase 3D printing mortar element, as
an example of 'bad practice' (Courtesy G. De Schutter)

The current focus on material properties (mechanical, durability) is still limited, although
several groups recently initiated major research steps in this respect. The challenge still seems
to be the transformation of available high-quality cementitious materials, specifically also
concrete materials complying with valid structural concrete codes, to printable materials, so
that we can move from formwork-based technologies to more automated additive
manufacturing approaches. Fundamental approaches are followed to modify the mix design

e.g. in view of modifying the particle clustering and structural build-up at micrometer level [11]. Intense work on admixture development to get the desired material performance has been done recently [10]. The detailed control of rheological properties allow to develop a structural buildup of the building element when material is combined with the right technical set up to support and adapt itself to material evolution [9]. Although these developments are promising and have already been implemented on the field, they are quite sensitive to the physico-chemical composition of the mix. A change in the cement type, or aggregate nature might require a new adaptation of the concrete mix design and admixture type. This hinders the scale up possibilities as it is not straightforward to transfer knowledge and development. However, a more robust approach is to actively control rheology and stiffening in real time during production.

2.2 Active control of rheology and stiffening

The problem while placing concrete is that the rheological properties cannot be actively adjusted during the casting process. Based on mix design and mixing procedure, the concrete will show its particular rheological behavior, only further influenced by environmental conditions and duration of the casting process.

A fundamentally new way will be to actively control rheology and stiffening of the fresh cementitious material, as currently studied in the ERC Advanced Grant 'SmartCast' project [12]. The main objective of 'SmartCast' is to develop concrete with actively controllable rheology and stiffening, in order to automate and optimize concrete casting operations. The ground-breaking idea to achieve the main objective of active control, is to modify concrete by adding special polymers responsive to externally activated electromagnetic frequencies or other types of trigger signals. While special responsive polymers are currently being developed, the principle of Active Stiffening Control (ASC) and Active Rheology Control (ARC) can already be demonstrated with available materials. The following initial results illustrate the concepts using magnetic particles and magnetic fields. A responsive paste ingredient might contribute to the paste stiffness by aligning itself with the magnetic field lines, forming a more rigid or entangled structure. In case of magnetic particles, a rigid network structure is

expected to contribute to the shear resistance of the paste, making this particle-field combination a prime method to arrest paste flow.

The feasibility of this method depends on the relation between the applied magnetic field strength and the dosage of magnetic particles. It is unclear how the dosage affects the immediate rheological response to the field and whether there are any lasting effects due to earlier magnetization periods. To that end, two pastes were prepared of CEM I 42.5 N (W/C 0,35) with and without an additional 5% (of cement weight) of magnetic particles (FeO). The pastes were both exposed to the same series of subsequent magnetic field strengths (i.e. 0T, 0.34T, 0.76T, 0T) without leaving the rheometer. The equipment used was a rotational rheometer (MCR 301, Anton Paar, Graz, Austria) combined with its magnetic rheological cell (MRD 70/1 T). In the cell, a typical parallel plate (20mm diameter) measurement can be performed while the strength of a vertical magnetic field can be varied. A gap width of 1mm was maintained between the plates and the temperature was kept constant at 20°C. Drying of the cement paste was prevented by sealing the exposed side of the paste with a lightweight silicon oil (10 mPas). The tests started when pastes were at the age of 15 minutes after mixing.

In **Figure 2** the storage modulus is shown for the cement pastes with and without 5% of magnetic particles. The magnetic field strengths were subsequently applied to the paste sample, for 10 minutes each. In between each interval a critical strain was applied during a 30 second interruption. Modulus measurements were registered at the end of each 10 minutes interval. It can be observed that the addition of magnetic particles itself causes the storage modulus to increase, even for a zero field strength. This is due to the additional surface of the magnetic particles for which no additional water or plasticizer has been added to compensate for the loss in paste fluidity. Nevertheless, it can be seen that the storage modulus increases steadily for the reference paste towards a value of 1350 Pa. The enriched paste starts at a value of 27600 Pa and evolves to 82247 Pa.

Figure 2: Storage modulus for two cement pastes with and without 5% of magnetic particles, under different subsequently applied magnetic field strengths

The modulus results of the enriched paste have been isolated in **Figure 3** for better analysis. It can be observed that the modulus increase due to the magnetic field is not proportional. First, it is noted that the field strength increase from 0,34T to 0,76T has a disproportional effect compared to the first interval without field. This means that for a targeted modulus, the local magnetic field strength and global particle dosage need to be brought in line with each other. Secondly, it is remarkable that after taking away the field strength of 0,76T there is still a higher modulus value for the final interval with no field.

Figure 3: Storage modulus for cement pastes with 5% of magnetic particles, under different subsequently applied magnetic field strengths

Besides arresting flow and its usefulness for active stiffening control, it can also be wondered whether the magnetic field could contribute to active rheology control (ARC). For example, in future applications where concrete is exposed to different subsequent shear rates, it might appear useful to keep the resulting shear stress constant. In the following experiment, the enriched cement paste from above was exposed to the subsequent tests as listed in **Table 1**.

Table 1: Overview of subsequent rheological shear tests applied to paste with magnetic particles.

	First 30 seconds	Second 30 seconds
Test 1	15 s ⁻¹ 0 T	15 s ⁻¹ 0,17 T
Test 2	15 s ⁻¹ 0 T	7 s ⁻¹ 0,17 T
Test 3	15 s ⁻¹ 0 T	7 s ⁻¹ 0,34 T

The resulting shear stress measured for each of the above tests is shown in **Figure 4**. It is clear that the shear rate of 15 s⁻¹ in the first half of each test is sufficiently high to homogenize the sample. At the end of the first half of all tests, the shear stress has a value between 58 and 68 Pa. For the second half of Test 1, the magnetic field was raised from 0 to 0,17 T. This causes the shear stress to increase to a value around 200 Pa. In the second half of Test 2, the same was done except that the shear rate was now lowered from 15 s⁻¹ to 7s⁻¹. It can be observed that the shear stress is now at the level of 160 Pa. So, a decrease in shear rate of approximately 50% (0,15 to 0,7s⁻¹) reduced the shear stress with 20% (-40 Pa), demonstrating the lower impact of the current magnetic field strength. In order to compensate for this shear rate effect, the magnetic field strength was increased in Test 3. For the same shear conditions as Test 2, it can now be observed that the shear stress in the second half of Test 3 reaches again the level of 200 Pa, just like for Test 1. So, it appears to be possible to maintain a constant

shear stress by compensating for different shear rates through adjusting the magnetic field strength.

Figure 4: Resulting shear stress for the tests listed in Table 1.

Based on the above initial results, some preliminary evidence was found for the contributions a magnetic field could deliver to active stiffening control and active rheology control. As a concept, magnetic fields combined with responsive particles remain promising in both the areas of flow arrest and shear stress increase. Future work will refine this influence but also explore techniques to lower the shear stress and to enhance flow.

2.3 Mechanical and durability performance

While 3D printing is offering a totally new production method, fundamental scientific knowledge on cementitious materials is not becoming outdated. On the contrary, it will even become more important in view of well understanding the consequences of the different production conditions compared to traditional formwork-based casting operations. Bulk material properties (intrinsic strength and durability) will follow the same fundamental material laws. However, in a 3D printed structure or element, the role of interfaces will become increasingly important. Between successive layers, an interface zone is present, with qualities depending on time delay between deposition of layers. These interfaces will

influence mechanical performance, most prominently the bond behavior [13, 14], as well as transport and durability behaviors. The anisotropic nature of 3D printed concrete is challenging current approaches for structural and durability design, as well as current practices for performance testing [15, 16, 17].

Current structural and durability design codes consider the concrete as a homogeneous material. For 3D printed concrete elements, this is no longer the case, due to the layered concept with more porous and weaker interfaces, and anisotropic behaviour. Structural design will have to consider the layered structure, requiring new design models, e.g. for shear loading. The structural design models will further have to consider that reinforcement will most probably no longer be provided in the traditional way, introducing new reinforcement concepts (see section 2.4 for a more detailed discussion on reinforcement of 3D printed structures) and thus requiring new methodologies for dimensioning as well as for estimating deformations and crack widths.

As the deformation of the new layer is also (partly) restrained by the previous layer, and since traditional curing procedures do not fit the new production technics well, shrinkage stresses and cracking as well as their mitigation become increasingly important. New developments, including new ways of providing reinforcement to the structural element, will have to be provided, possibly going far beyond our current practices, as topological optimization (see higher) will probably not enable to use solely unreinforced concrete.

The classical concept of cube or cylinder testing as the basis for compliance testing will no longer hold, as moulded cube specimens cannot be prepared in the traditional way, and would moreover not be representative for 3D printed concrete. Durability indicator test methods, such as air permeability tests [18], will need to be reassessed for application on the surface of a 3D printed element, due to its layered structure. Due to the porous interlayer zone, the air flow while performing an air permeability test will follow preferential paths, impairing the basic assumptions for the interpretation of the obtained pressure decay measurements.

In summary, in case of 3D printed concrete based on the principle of additive manufacturing, current structural and durability design codes will have to be revised to consider the

anisotropic behaviour (mechanical as well as transport behaviour). In addition, current concepts of compliance control or performance testing will also require updating. On the short term, the lack of appropriate design codes and performance testing protocols will hinder the breakthrough of digital manufacturing in concrete industry.

2.4. Integration of reinforcement

Integration of vertical reinforcement in 3D printed concrete elements is a critical challenge to which no satisfactory solutions are available yet. This will be a prerequisite to fully utilize the geometrical freedom and topological optimizations as well as to broaden the application spectrum of digital fabrication with cementitious materials. Multiple research groups, relying on different approaches, have been investigating this aspect [19]. Six major opportunities can be listed here:

- a) Producing only permanent formwork with 3D printing and placing conventional reinforcement which will be enveloped by vibrated 'infill' concrete, following conventional casting process; the (part of) horizontal reinforcement can be placed between the layers in the process of 3D printing, this holds true also for the other production methods (see b to f). This technology was implemented e.g. by *Win Sun* [20] and *apis cor* [21];
- b) Extruding concrete with dispersed short steel or polymer fibers in which fibers not only work as a dispersed reinforcement but also as shrinkage reducers and early strength enhancers;
- c) Enveloping with two or more nozzles (extruding around) vertically placed steel reinforcement (technology implemented e.g. by *HuaShang Tengda Ltd.* [22]. In this approach no formwork as such is involved (nor conventional or 3D printed) and enveloping concrete must be self-stable after extrusion – both these aspects differentiate c) from a);
- d) Automated free forming of complex steel reinforcement in which concrete is placed subsequently (e.g. Mesh Mold approach of ETH Zürich) [23];
- e) Autonomous vertical placement of reinforcing elements which are positioned and 'connected' dynamically after individual layer extrusion (e.g. Khoshnevis [5]);
- f) Multi-arm printing of both concrete and reinforcement, at best, in parallel.

Some of the above presented approaches have currently a limited applicability for DFC (e.g. a and c) or do not address the critical vertical reinforcement (e.g. b). The other approaches are not yet fully developed nor validated at large scale (d to f). Such challenges must be addressed in order to pave the way for large-scale industrial implementation of DFC for structural and complex structures. The authors envision a process or combination of processes where both reinforcement and matrix material are placed/printed in parallel in a seamlessly integrated digital fabrication process. **Figure 5** shows an example of 3D printed vertical steel reinforcement as produced and tested at the TU Dresden. The specially adjusted gas-metal arc welding technique was used with fully automatic, adaptive process control which enabled the production of steel reinforcement bars with adequate geometrical precision and geometric freedom at reasonable production speeds. The 3D printed steel bars exhibited approximately 20 % lower values of the yield stress and tensile strength in comparison to conventional reinforcement bars. However, in contrast to the conventional bars they showed pronounced yielding and higher strain capacity. The bond to printable fine-grained concrete was comparable with the bonding performance of conventional steel.

Figure 5: 3D printed steel reinforcement specimens from TU Dresden (Courtesy Martin Hertel)

2.5 Applications and 3D printing technical opportunities

Digital fabrication has been applied to 3D freeform architectural design and model prototyping for many years, some of such applications of digital fabrication and the companies involved can be referred in [24, 25, 26]. The scope of this section is limited to construction applications with cementitious materials through digital fabrication, specifically those based on extrusion. Architectural model creation and prototyping are not explicitly addressed. Pegna [27] introduced selective aggregation (or binding) of reactive bulk material (Portland cement) as a DFC technique with potential for large-scale solid freeform structures. Advances in the selective binding and binder jetting techniques such as D-Shape [28] along with applications can be found in [29]. Khoshnevis has pioneered in DFC, with Contour Crafting technology [30]. As early as 2004, Khoshnevis et al [5] had presented the idea of using Contour Crafting, to produce structures, in two process variants: a) producing outer ‘shell’ elements through automated extrusion and then filling the inner space with a conventionally casted concrete b) producing outer ‘shells’ as well as inner structure (which follows a sinusoidal path) through DFC. Complex and unique structures have also been proven to be possible applications of DFC with considerable potential. As 3D printing offers the possibility of depositing material where it is really needed, the high geometrical flexibility topology-optimized structures according to the principle “form follows force” can be produced by 3D printing which are well load bearing yet not massive. A complex truss-shaped 4 meter-high post supporting the roof of a playground at a school in Aix-en-Provence, France is an example for this (XtreeE [31]), see **Figure 6a**. Another recent example is the work conducted to find optimized shape in compression only structures [32, 33]. The recent mullions implemented in the NEST project have their shape optimized to sustain wind loads on the structure [34].

Energy efficient wall structures and multi-functional building elements are of high significance for potential applications of DFC [5, 35]. This can be achieved through a) functional hybridization b) functional integration and c) material development. On the one hand, topology optimization allows to achieve a complex structure that provides a secondary function through its shape. The implementation of this design strategy, which is called “functional hybridization” in this paper, avoids an additional building component to provide added functionality. For instance, Buswell et al. [25] reported of two wall panel designs with

same external geometry and varying internal cross-section and achieved thermal conductivities much lower than concrete block works. “Wonder bench” by Lim et al. [35] demonstrated feasibility of functional hybridization through DFC to produce light-weight, acoustic and post-reinforced structures. On the other hand, the integration of services such as plumbing or electric installations in the structure is also facilitated by digitally fabricated complex geometries. Khoshnevis [5] has conceptualized that DFC can be utilized to produce entire structures with all functions integrated such as utility conduits for installations. Finally, added functionality can also be achieved by DFC through purposeful choice of material used, e.g. cementitious materials with very low thermal conductivity such as LWAC, foam concrete, concrete with wood as additive (see **Figure 6b**) and thermally activated concrete (e.g. enriched with phase-change materials). In future settings, the smart deposition of materials with particular mechanical properties (such as high tensile strength and ductility by use of fiber reinforced cement-based composites, see e.g. [36]) could also include options for internal curing (see e.g. [37]), for self-healing [38] where needed. Usage of multiple materials, each responsible for specific function such as compression load-bearing, tensile load-bearing, insulation etc. has been demonstrated and is envisioned to offer plethora of opportunities to digitally fabricate smart structures. Multi-material structures with load bearing concrete as outer shell and insulating material as infill are also envisioned to reach marketability with DFC in near future. However, this fine intermixing of different materials raise the question of recyclability [39]. Whether multi-functionality should be achieved through a hybridization at the material level or at structural level is a fundamental question for the environmental performance of the final building element.

Figure 6: a) Complex truss-shaped structure according to the principle “form follows force” (XtreeE [31]) and b) 3D printed LWC with wood as filler [40] as an example of low thermal conductivity element, partly following earlier works [5, 25].

When the scale of the elements is concerned majority of the early examples of DFC such as Contour Crafting [30] and Concrete Printing focused on producing elements whose size is sufficient to be implemented in a pre-cast industry. However, onsite applications of DFC – e.g. with mobile 3D printers – are already proposed and are in the pilot stage currently [41, 42, 21]. The applicability of DFC for any construction process depends upon both technological fulfillments (such as the need to use reinforcement for ceilings) and economic viability. Applying DFC for cost-effective and fast construction of residential buildings has a high potential as reported by Nerella et al. [42] and Schach et al. [43]. This is also supported by the statistics here presented for Germany as an example. According to statistics for the year 2014, the construction of 163,844 residential buildings was permitted in Germany, most of them newly built [44]. When analyzed specifically from material perspective, 75.3% of the materials temporarily used for manufacturing walls of such buildings are proved to be potentially replaceable with DFC applicable materials without use of reinforcement (31.1% brick, 22.3% limestone, 18.2% aerated concrete, 3.7% lightweight concrete). One of the limiting aspect for

wide-ranging application of DFC is lack of satisfactory solutions for integrating vertical reinforcement. This issue, along with possible approaches is detailed in Section 2.4.

Authors opine that the construction applications of DFC will increase exponentially in near future, thanks to the wide variety of technologies under development pursuing vivid applications including: geometrically complex structures, elements with integrated functionality, topologically optimized structures and solutions for mass-customization and cost-effective mass-housing. The economic and environmental potentials of these development will be addressed in the following sections.

3. ECONOMIC POTENTIAL

In this section, process related economic and societal aspects of digitally fabricated concrete (DFC) are detailed in sub-sections dedicated to productivity, cost structure, stakeholders and applications.

3.1 Productivity

Stagnating productivity in construction industry [45, 46] is a significant concern. Construction industry in European Union constitutes 9.7% of the gross domestic product and provides 6.6% of Europe's total employment [47]. Currently, developed countries suffer from stagnating or in fact in some countries decreasing productivity (e.g. [48, 49]). The causes are numerous and include factors such as the resistance to introduce changes in a highly traditional sector, low industrialization of construction processes, poor collaboration and data interoperability, and high levels of turnover, which make it difficult to implement new methods [50]. In general, the conservative construction industry invests relatively little in research and development. This holds true also for countries with very good economic situation. Relatively low profit margins for construction companies could be the primary reason for this [49]. As a consequence, construction processes have almost not changed during the past decades.

The main significance and revolutionary potential of DFC is seen in the context of Construction Industry 4.0 since it offers a logical evolution from the already well developed Computer Aided

Design (CAD) tools to automated construction, thus making construction a fully digitalized process [51]. A reduction of construction times and the improvement of the quality and cost by the integration of digital design and construction activities can significantly increase the productivity of the sector [52]. Agarwal et al. [53] shared this vision and proposed a shift to a digital construction organization by combining existing technologies such as rapid digital mapping, Building Information Modelling (BIM), digital collaboration, internet of things, and design to construction. Digitalization of processes ranging from design to fabrication may also reduce the potential for errors and aid enhanced management of the construction process. Digital data managed through Building Information Management (BIM) will be fully utilized from planning to production and even further to maintenance, rehabilitation and recycling.

A recent study developed by García de Soto et al. [54] investigated the effects of DFC on productivity by analyzing the cost and time required for the construction of a robotically-fabricated concrete wall with different degrees of shape complexity. The results of the analysis demonstrated that additive digital fabrication provides higher productivity over conventional construction when complex concrete structures are built. The study also showed that there is no additional cost derived from robotic fabrication if the complexity of the wall geometry increases. However, the conventional construction method still outperformed the robotic fabrication method for building simpler walls. This study shows that there is a big potential to increase the productivity of DFC, as future developments in the robotics field can allow digital fabrication processes to be cost-effective also for more standard construction types [54].

3.2 Changes in the cost structure

For placing concrete, especially the ready-mix type, formworks are commonly needed. The use of formworks leads to high material, labor and machinery costs. Formwork costs amount up to 28 % according to Schmitt [55], but can be in some cases half of total concrete structure cost [56]. In addition, usage of formworks results in considerable time delays and negative environmental impact. The problematic role of formwork is even more significant in case of constructing unique objects or complex structures, where the use of formwork is on the one

hand challenging (limited geometrical freedom/flexibility) and on the other hand expensive plus time-consuming.

In case of DFC, with help of assured rheological properties and control of their evolution in time (for example using ARC and ASC), placed cementitious material can retain its shape without any formwork. This can lead to substantial cost reduction. Furthermore, quasi-unlimited geometrical freedom enabled by DFC also provides the potential that costs in case of complex structures will not increase or even decrease in comparison to the conventional construction. In other words, the costs of structures manufactured by means of DFC are expected to become largely complexity independent. Subjected to qualitative scrutiny, the four broad components of any construction process are a) labor, b) machinery, c) material as well as d) design and planning costs (3D models, BIM). In case of DFC, total labor costs will be significantly lower than that of conventional construction [43].

The costs of machinery, in principal, depend on the particular DFC approach and the applied techniques. Three major sub-processes can be identified in all DFC technologies:

- a) transporting material to the print-head,
- b) precise positioning of the print-head and
- c) extrusion or activation of parts of the desired structure's component.

Machinery used for these sub-processes varies depending on DFC technique and so are the costs. In a different perspective, the machinery used for DFC can be categorized into:

- a) unconventional construction equipment (UCE) and
- b) (adapted) conventional construction equipment (CCE).

For *transportation* process often CCE such as piston pumps can be used. For *extrusion* or *activation*, however, in general new equipment, generalized as print-head, is needed. This is however only true if the print-head has a (multi-)functional complex design, or in other words if the print-head is not a mere nozzle. In fact, for a successful industrial implementation of DFC, the print-head should have size and shape flexibility (adjustable nozzle outlet with respect to dimensions and shape), should be equipped with sensors which measure in-line the evolution of material properties for data feedback and ARC. In some techniques of DFC, print-heads should also be equipped with multiple nozzles for different materials (e.g., concrete shell and insulation infill). All these sophistications will make print heads a significant cost

factor of DFC. When it comes to the sub-process *placing*, both CCEs and UCEs are utilized already to some extent. UCEs such as multi-axial robots [57, 58, 59, 60] and gantry or portal-platforms [5] are often used for DFC. At the same time CCEs, such as truck-mounted concrete pumps with improvements to the controlling, can be used for the new technology as well as in their original function [61, 43]. The more CCEs are incorporated into machinery of DFC sub-processes the faster will be the industrial acceptance, the lower will be the total costs of DFC and also the higher will be the sustainability.

On the one hand, the material costs for DFC can be lower than those of conventional construction due to topology optimization, avoidance of over-engineering and waste material reduction. On the other hand, they could also be higher in case of DFC due to utilization of expensive, very fine additions such as nano-clay, nano-silica and special chemical admixtures. The concretes used for DFC are by material design relatively complex (with more constituents) so that they can meet the demands of problem-free processing, high thixotropy [8], and early strengths [9, 10], additionally to the other features expected from structural concrete [19, 32]. This also has a consequence to concrete producers and practitioners in terms of mixing process (precise dosing and intensive mixing due to often high powder content) as well as storage of ingredients. It is therefore envisioned that material researchers and concrete technologists address these challenges and develop less complex yet more robust cement-based materials applicable for DFC. Best option would be that the printable concrete complies with the general specifications according to the valid codes for concrete design and construction.

The costs for the final sub-process *design and planning*, which includes 3D modelling, BIM etc. are expected to gradually decrease considering the advancements in related fields. This decrease in costs is particularly likely in case of large-scale implementation (as same algorithms and data base are used numerous times reducing costs per unit). Considering the seamless planning-to-fabrication principle of DFC construction and the use of well-proofed algorithms, planning will be more precise (low potential for human error) and less complex with respect to human involvement. The high reusability of digital data will eventually render the costs for planning in case of DFC negligible in comparison with conventional construction.

At this point in time, quantitative studies that analyze the cost structure of DFC are scarce since only a few real scale projects exist and the cost structure of prototypes may not be identical to that of large scale implementation. However, based on a real scale DFC wall constructed in the NEST building (Switzerland), García de Soto et al. [54] estimated the cost structure of this case study. Specifically, the study compared the cost structure of straight and double-curved reinforced concrete walls constructed with robotic fabrication techniques and conventionally. The allocation of the different costs (i.e., labor, material, equipment) for the different wall types and construction methods is shown in **Table 2**. We observe that the main variations occur in the construction of the conventional concrete walls, and they are caused by the high cost of the formwork needed for double-curved walls. The relative cost of materials is more than tripled when building the complex wall in the conventional way. In contrast, the variations between straight and double-curved robotically fabricated concrete walls are negligible. Therefore, this analysis shows that the cost structure of DFC processes differs significantly when compared to conventional construction. DFC leads to a small decrease in the share of labor costs which are however insensitive to the project complexity.

Table 2: Allocation of labor, material and equipment costs for different types of concrete wall construction (based on García de Soto et al. [54]).

	Labor	Material	Equipment
Straight wall / conventional	56%	23%	21%
Straight wall / robot	36%	45%	18%
Double-curved / conventional	22%	75%	3%
Double-curved / robot	38%	44%	18%

3.3 Changes in the stakeholders

DFC, similar to other revolutionary innovations, will change the stakeholders in the construction sector. IT/Tech companies will have a pronounced role by using BIM and other digital tools as a primary aspect. Furthermore, new startups and existing robotic and automation companies potentially enter and become large stakeholders in DFC. The inevitable

changes for the personnel with emergence of DFC are also noteworthy. The implementation of digital fabrication in the construction sector will potentially affect the simplest and repetitive manual tasks. As a result, the less qualified jobs may be automated (especially on-site). Recent studies argue that these kind of technologies will significantly reduce employment [62]. However, Frey and Osborne [63] showed that automation makes human jobs more specialized. The number of low-skilled workers will potentially decrease in favor of an increase of high-skilled specialized workers. As a result, highly skilled robotics, programming and concrete technology experts will be the backbone of DFC.

Figure 7 illustrates a simplified representation of the potential evolution of the construction workflow due to the implementation of digital fabrication. In a short term phase or “digitalization” phase, it is expected a partial implementation of digital technologies in construction. During the design phase, the engineering knowledge is embedded in a central software (e.g. BIM platform) allowing the architect to use this knowledge to design the building [64]. During the construction process, a digital fabrication specialist takes control of the on-site robotic fabrication, extending his/her design knowledge to the construction process. Consequently, the number of on-site conventional construction tasks decreases, and also the construction workers intended for them.

In a long term, digitalization in construction may potentially derivate in personalized construction models. A building is a complex system that cannot be conceived as a serial product, such as an automobile for example. Each building is customized according to design and construction conditions as well as stakeholder decisions. Recent developments in digital fabrication in construction facilitate the mass-customization of building elements instead of their standard mass-production [65]. Publications related to 3D printing technologies for manufacturing such as [66] suggest that the next step to mass-customization is personalization. As a consequence, the owner may become more than an informed participant, but an active responsibility-taker, administrator and coordinator of the building construction. In a future construction model, a building will be potentially designed by construction professionals like in conventional construction. However, the different designs could remain in catalogues to be selected by the client to be directly constructed or altered according to desire. Therefore, the conventional role of designers and project managers will

potentially evolve to a consultant, co-creator and collaborator, making digital fabrication technologies accessible to users and helping them during the construction process. Related research in other fields such as [67], presented the role of the designer as a communication facilitator between users and technology developers in a multidisciplinary team, understanding their needs and sharing technological possibilities.

Figure 7: Evolution of the construction workflow derived from the digitalization of the construction industry, including current, short-term and long-term state.

4. ENVIRONMENTAL POTENTIAL

The construction sector is responsible for high environmental impacts worldwide, such as 40% energy consumption, 40% solid waste generation, 38% GHG emissions and 12% water depletion [68]. Society's increasing concern about sustainability is inducing the emergence of

innovative construction processes to overcome the high environmental impacts caused by traditional construction. In particular, additive manufacturing processes have been associated with a cost-effective fabrication that lowers energy use, resource demands and CO₂ emissions over the product life cycle [69]. As the interest in 3D printing grows, potential large-scale applications are emerging in construction [35]. According to Labonotte et al. [70, 71], additive construction processes evidence a significant potential to reduce material through topology optimization, produce complex geometries without supporting structures and integrate multifunctionality in building elements, which is not possible with conventional construction techniques. However, in order to achieve a recognizably sustainable construction process, life-cycle assessments (LCA) must be performed to guide the design of 3D printed structures. This section aims to discuss the environmental opportunities of this construction technique through the review of related scientific studies.

4.1 Impact of construction vs. impact of material production

Different publications have investigated the energy consumption and environmental impacts of 3D printing processes. For instance, Faludi et al. [72] and Cerdas et al. [73] carried out Life Cycle Assessment (LCA) comparisons of additive manufacturing and conventional manufacturing. Both studies concluded that the energy consumption of additive manufacturing dominates the environmental impacts. However, most of these studies were based on the evaluation of small-scale 3D printing. The conclusions should not be directly applied to additive digital fabrication because construction processes require large amounts of material with high environmental impact (e.g. concrete), larger equipment and longer construction times. In a recent study, Agustí-Juan and Habert [74] performed an environmental evaluation of larger process where three digitally fabricated building elements and their comparison with conventional construction were studied. The results of the evaluation highlighted the low relative impact of the digital construction process compared to the impact of building materials production. Looking specifically at additive manufacturing with concrete materials, Agustí-Juan et al. [75] showed that the production of robotic arm, the production and recycling of the lithium batteries used to operate the robots as well as the electricity demand during the fabrication contribute marginally to the overall environmental

impact of a digitally fabricated wall. Moreover, the analysis confirmed that most of the impacts come from the amount and type of building materials used.

These results are not surprising as in conventional construction, published studies have already shown that the construction phase has a very small contribution to the life-cycle impact of buildings. Specifically, Hong et al. [76] and Junnila et al. [77] showed that direct emissions derived from on-site construction account for approximately 2% of the overall life cycle emissions. A common argument against the use of digital fabrication is the increase of energy consumption in construction due to robotic and high tech construction techniques. However, current studies allow to rule out this argument and push designers and material scientists to focus much more intensively on material optimization within additive construction.

4.2 Shape complexity in construction

Recent developments in computer-aided design and additive fabrication in architecture demonstrate strong potential to construct customized complex structures. However, a gap has emerged between the possibilities offered by architectural design and the reality of the building industry. Non-standard geometries in construction require the planning and fabrication of complex and labor-intensive rebar geometries and formworks that are not easy to fabricate with current construction techniques. As a result, architectural design is often constrained to standard geometries to reduce costs and enable the reuse of formworks, especially in concrete construction [70]. By integrating digital technologies and developments in material science, conventional construction techniques are modified to create novel approaches for the construction of complex [5]. In particular, the construction of complex concrete structures through additive manufacturing techniques is currently being broadly investigated because of the large use of concrete in construction and the high costs of formwork production [78]. Several published studies, such as Lim et al. [35] and [58], agreed on the potential of 3D printing with concrete to produce large-scale complex structures and save materials by reducing or completely eliminating the need for formworks. According to Labonnote and Rther [71], additive construction processes offer the possibility to produce non-standard geometries at no additional cost. The more complex the structure, the more

profitable the use of additive construction. In contrast, additive manufacturing technologies could be less cost-effective for standard construction.

Focusing specifically on digital concrete, Agustí-Juan et al. [75] analyzed the environmental performance of reinforced concrete walls with different levels of complexity constructed with additive robotic fabrication techniques and compared them with similar structures that would have been built with conventional techniques. The results of the environmental evaluation confirmed that digital fabrication brings high environmental benefits compared to conventional construction for structures with a high degree of shape complexity. As shown in **Figure 8**, the environmental impact of the digitally fabricated wall does not grow with the uniqueness and complexity of the architectural geometry. Additional shape complexity is achieved without additional environmental costs, so the potential benefit of digital fabrication increases proportionally to the degree of complexity of the architectural geometry. This result is a quantitative argument to position digital fabrication at the beginning of a new era, which is often called the Digital Age in many other disciplines. Digital fabrication can facilitate the production of elements with higher shape complexity without increasing the environmental costs. This statement contradicts what is usually observed in conventional construction, where increasing complexity leads to a higher use of resources, construction waste and delays in the construction process [79]. In that sense, this study matches the common understanding of the digital revolution as the third moment in humanity when an increase in system complexity allowed positive feedback [80].

Figure 8. Complexity-related environmental advantage of digital fabrication vs. conventional construction. The environmental impact is expressed by the percentage of Global Warming Potential (kg CO₂ eq.) per m² of concrete wall (based on Agustí-Juan et al. [75]).

Digital fabrication techniques facilitate the construction of complex and slender concrete structures without the use of conventional formworks, which are associated with high resource consumption and labor costs [81]. However, this conclusion does not mean that non-standard geometries have always an environmental advantage. **Figure 8** demonstrates that when comparing complex building elements, the one constructed with digital fabrication techniques will be more environmentally efficient than the conventionally constructed one. Nevertheless, it is essential to differentiate whether the shape complexity is used as a design strategy to reduce material or whether it has only an aesthetic purpose, which would demand more material. In order to bring environmental benefits, the shape complexity facilitated by digital fabrication techniques should be the result of an intention to optimize material use in the structure. This is usually achieved with two design strategies: structural optimization or functional hybridization.

4.3 Environmental potential through structural optimization

Novel computational approaches integrate structural optimization in form-finding design, offering new possibilities of formal expression and addressing resource efficiency in architecture [82], see **Figure 9**. Several publications have pointed out the potential of additive construction techniques to reduce the use of material through structural optimization. For instance, Wangler et al. [78] expected high sustainable benefits due to a more efficient design achieved by placing material only where it is structurally needed. Also Labonnote et al. [70] and Hack et al. [83] specified the potential of structurally optimized non-standard geometries to bring material savings and weight reduction in load bearing applications. However, the production and optimization of complex concrete structures through digital fabrication methods often relies on high contents of cement. High-performance concrete ensures early strength and buildability without the need for coarse aggregates, which usage is limited when thin structures such as the one usually manufactured by 3D printing are produced. As the environmental impact per cubic meter of concrete increases by augmenting cement content,

the volume reduction has to be even more effective [84]. For digital fabrication, the interest of high performance concrete combined with extreme volume reduction through structural optimization proves to be effective. Agustí-Juan and Habert [74] showed that approximately 50% reductions on the environmental impact of digitally fabricated concrete structures compared to conventional construction can be achieved.

However, it has to be noted that this leads to a divergence in research between conventional and digital construction. Actually, conventional concrete development relies heavily on the use of supplementary cementitious materials (SCM) to reduce environmental impact, while digital concrete development requires relatively fast setting and high performance, which is usually achieved with pure ordinary Portland cement (OPC). Both approaches seem currently diverging, but an appropriate high SCM cement with the right admixture could be developed to achieve fast setting. For instance, Marchon et al. [85] showed that alkali activators can be used in combination with specific plasticizer compatible with alkali environment in order to have the required early strength without losing the rheology control possibilities offered with plasticizers.

Figure 9. Complexity-related material optimization using computational structural analysis.

4.4 Environmental potential through functional hybridization

The second strategy to efficiently use the benefit of a higher complexity without additional cost is to use complex forms to achieve multi-functionality (**Figure 10**). Published literature on additive manufacturing applied to construction agree indeed on the potential of digital technologies to facilitate the integration of multi-functionality in building elements [25, 58]. One can distinguish two cases. First, the integration of services such as piping, insulation or

electrical facilities in the structure often requires complex geometries. Second, the complex structure can provide a secondary function through its shape, which will save an additional building component that would have provided this function. For instance Agustí-Juan and Habert [74] demonstrated the environmental benefits of functional hybridization, as a material-reductive construction process. The LCA applied to the case study of a digitally fabricated roof structure showed that the hybridization of functions avoided the construction of a suspended ceiling, which is responsible for high environmental impacts. However, the integration of functions can increase the requirement of material in the structure, which might be disadvantageous from an environmental point of view. The analysis performed by Agustí-Juan and Habert [74] showed that only functions with high environmental impact in conventional construction provide environmental benefits when integrated in digitally fabricated structures. In this case, the hybridization of functions compensates for a higher material requirement for the structural performance of the building element.

Integrated design can save building materials during production, associated with reductions in costs and environmental impacts. Nevertheless, environmental emissions are not just produced during the construction phase but also during the service life and a functional hybridization may increase the difficulty of retrofitting a building during its life cycle and increase replacement rates for building elements. The design of hybrid structures should be flexible enough to enable maintenance of certain components without influencing the service life of the whole element. Moreover, the functions integrated should be carefully chosen to avoid functions with a too short service life associated in elements that will have to last long. A reduction in the lifetime of the structure would result in high replacement rates, which increase life-cycle impacts.

Figure 10. Complexity-related material optimization through functional hybridization.

5. CONCLUSIONS

Based on emerging scientific results and studies as well as recently published information, this paper presented a threefold vision for the future of concrete 3D printing industries. The main elements of the paper can be summarized as follows.

- Although several showcases of 3D printed concrete structures are available worldwide, many challenges remain at the technical and processing level. The range of printable construction materials is very limited at this moment. Currently available high-performance and very durable cement-based materials cannot be directly processed in a printing technique, because of inadequate rheological and stiffening properties. This holds true also for concrete according to the existing design and construction codes. In future, active rheology control (ARC), active stiffening control (ASC) and other novel approaches will provide solutions of extending the material palette for 3D printing applications.
- Digitally manufactured concrete (DFC) will induce changes in the stakeholders as well as in the cost structure. At this point in time, it is too ambitious to quantitatively present the cost structure of DFC. Nevertheless, considering the different cost elements (labor, machinery, material, design and planning costs), DFC presents many potential opportunities to increase cost-effectiveness of construction processes in comparison to conventional construction methods.
- The environmental impact of 3D printing with concrete has to be seen in relation to the shape complexity of the structure. Implementing structural optimization as well as functional hybridization as design strategies allows the use of material only where is structurally or functionally needed. This design optimization increases shape complexity, but also reduces material use in DFC. As a result, it is expected that for structures with the same functionality, DFC will environmentally perform better over the entire service life in comparison with conventionally produced concrete structures.

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