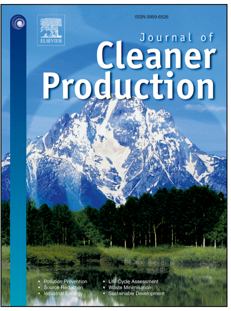

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Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall

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Abstract

Digital fabrication represents innovative, computer-controlled processes and technologies with the potential to expand the boundaries of conventional construction. Their use in construction is currently restricted to complex and iconic structures, but the growth potential is large. This paper aims to investigate the environmental opportunities of digital fabrication methods, particularly when applied to complex concrete geometries. A case study of a novel robotic additive process that is applied to a wall structure is evaluated with the Life Cycle Assessment (LCA) method. The results of the assessment demonstrate that digital fabrication provides environmental benefits when applied to complex structures. The results also confirm that additional complexity is achieved through digital fabrication without additional environmental costs. This study provides 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.

Keywords

Digital fabrication, LCA, complexity, concrete, robotic construction, sustainability.

1 Introduction

The construction sector is responsible for significant environmental impacts, such as 40% of the energy consumption and greenhouse gas emissions worldwide (UNEP, 2012). But these extremely large impacts represent also opportunities for improvement, and buildings are seen by the main international agencies (UNEP, IPCC) as a key player for carbon mitigation actions (IPCC, 2014). This potential is foreseen as occurring through the implementation of new technologies, such as digital technologies (McKinsey&Company, 2016). Digital technologies are broadly used in the manufacturing industry and the direct production of elements from design information (e.g., 3D printing) has become an essential component of modern product development (Chen et al., 2015). However, digital fabrication in construction is still in its early stage, probably because the construction industry is a highly fragmented, risk-averse sector (Arora et al., 2014). Most construction firms are small, so few of them have the ability to exploit new technologies, which rely on specific knowledge. Learning is done on a project-to-project basis with professionals to develop perceptions and skills from their individual experiences (Giesekam et al., 2016). This unsystematic process of building up knowledge leads to a reluctance to use unfamiliar technologies and materials (Pinkse and Dommisse, 2009).

Finally, the benefits that digital technologies can provide are not clear. Recent publications have highlighted the potential sustainability benefits of additive manufacturing (Ford and Despeisse, 2016; Kohtala, 2015). However, most of these studies focused on small-scale processes. For instance, Kreiger and Pearce (2013) showed that distributed manufacturing through 3D printing has potentially fewer environmental impacts and lower energy demand than conventional manufacturing. Similar results were gathered by Faludi et al. (2015), who highlighted a reduction in waste and energy savings from a smaller machining effort with 3D printing compared to traditional CNC milling. Finally, Gebler et al. (2014) provided a general perspective on 3D printing technologies from an environmental, economic and social perspective. However, very few of these studies were quantitative, and Ford and Despeisse (2016) are pushing for more applied research on the environmental implications of digital fabrication. In particular, its implementation in the construction sector requires quantitative assessments that consider aspects such as the design freedom that is facilitated by additive techniques.

The objective of this study is to quantify the environmental benefits that digital fabrication can provide to the construction sector and define for which processes these construction techniques have a clear interest. Digital design and robotic fabrication developments which increase complexity in architecture yet should provide a cost effective method to deal with this structural complexity.Consequently, this study focuses on the environmental assessment of a building element that can be produced with different levels of complexity and a comparison between an additive robotic fabrication technique and traditional building construction techniques. This approach enables us to evaluate the potential environmental benefits of digital fabrication for each level of complexity.Specifically, we perform a comparative assessment of two construction processes (digital fabrication and conventional construction) for different types of concrete walls, from the simplest to the most complex.

2 From 3D printing to digital fabrication in architecture

The first three dimensional printing (3DP) technologies arrived during the 1980s to more efficiently fabricate prototypes in the product manufacturing industry. 3DP employs additive manufacturing (AM) processes to create three-dimensional objects by adding consecutive layers of material. These systems can now manufacture end products with the development of new materials and improvements in speed and accuracy based on superior hardware and computer technology (Lipson and Kurman, 2013). Nowadays, AM is used across various industries (medicine, aerospace, art, etc.), mainly for prototypes but increasingly for final products (implants, lightweight structures, jewellery, etc.). Computer-controlled manufacturing methods are fundamentally transforming many design and production disciplines, similar to the mechanisation of the textile industry or the introduction of the assembly line. The high flexibility and reduced production costs of digital technologies introduced a new era towards the mass customisation of products (Berman, 2012).

3DP has experienced rapid development in recent years, and more materials can now be used in these processes. The size of these technologies has also rapidly increased, showing the potential to build large and complex-shaped structures by printing. As interest in additive manufacturing has grown, research into large-scale processes has begun to reveal potential applications in construction (Feng et al., 2015). The development of digital fabrication in architecture starts from specific projects, in which design aspirations and technological innovations lead to the development of fabrication processes beyond conventional boundaries (Dunn, 2012). Digital fabrication processes at the architectural scale are based on computational design methods and robotic construction processes, which are typically categorised as subtractive or additive fabrication. Specifically, architecture is typically built through material aggregation (assembly, lamination, extrusion, and other forms of 3D printing) in additive fabrication processes, frequently with an industrial robot, which enables the implementation of the additive principle at a large scale (Gramazio and Kohler, 2008).

Recent developments in digital technologies and the introduction of computer-controlled additive fabrication in architecture demonstrate strong potential to construct customised complex structures (Gramazio et al., 2014). In particular, the optimisation of concrete structures through digital fabrication is currently being broadly investigated because of the large use of concrete in building construction and the labour costs from formwork preparation (Wangler et al., 2016). For example, the research project “Contour Crafting” at the University of Southern California showed the possible application of layered extrusion technologies for large-scale concrete construction (Khoshnevis et al., 2006). Similarly, Loughborough University applied 3D concrete printing to non-standard geometries to reduce the amount of material, time, waste and need for formwork (Lim et al., 2012). However, some of these technologies have limitations regarding the incorporation of reinforcement during the production process. The project Smart Dynamic Casting (SDC) at ETH Zürich overcame this problem with a novel digital fabrication process for complex concrete structures that enables the implementation of reinforcement during production. SDC uses dynamic slip-forming techniques to fabricate customised, vertically oriented shapes, which would conventionally require custom-made formworks (Lloret et al., 2014).

3 Methodology

The selected method for the evaluation of the case study is the Life Cycle Assessment (LCA) framework present in the ISO 14040-44: 2006 standards (ISO, 2006a, b). LCA has been commonly used in many industrial sectors to evaluate the environmental load of processes and products during their life cycle. This method presents a comprehensive, systemic approach for the environmental evaluation, comparison and optimisation of processes (Cabeza et al., 2014). LCA has become a widely used methodology over the past 20 years to evaluate the impacts of materials, construction elements and buildings (Hoxha et al., 2017).

European regulations for the promotion of a sustainable built environment highly stress the reduction of energy during the use phase. However, the proportional percentage of embodied energy is increasing as the operational energy demand is further optimised. Recent studies such as Passer et al. (2012) agree that the operational energy is reaching the limit of reduction measures. Further optimisation of the life-cycle impacts of buildings may only occur by lowering the embodied energy of materials (Pacheco-Torgal, 2014). Consequently, we performed a cradle-to-gate analysis, including data from raw material extraction and transport, building materials and digital technologies production, and robotic fabrication (EN 15978 modules: A1-A3, A5). The operation and end-of-life stages were excluded from this case study evaluation.

The LCA method was applied in this paper to compare the differences in the environmental impacts between digital fabrication and conventional construction and to understand for which type of projects digital fabrication produces environmental benefits. This case study compared two functional units of reinforced concrete wall with equal functionality and structural performance, including 1 m^2 of wall that was constructed with digital fabrication techniques and 1 m^2 of a conventional reinforced concrete wall. Specifically, the LCA comparison was applied to different types of walls, including straight, single-curved and double-curved, to illustrate the possible levels of complexity. Finally, we tested the variability regarding the volume of concrete and steel in the structure in a sensitivity analysis to evaluate the additional benefits of digital fabrication if the process is optimised. The LCA method was implemented in the software SimaPro 8. Because of the Swiss context of this project, Ecoinvent v3.1 was used as a database (Weidema B. P., 2013). The Recipe Midpoint (H) v1.12 impact method (Goedkoop et al., 2009) was used. The selected impact categories were climate change (kg CO_2 eq.), ozone depletion (kg CFC-11 eq.), human toxicity (kg 1.4-DB eq.), terrestrial acidification (kg SO_2 eq.), freshwater eutrophication (kg P eq.), terrestrial ecotoxicity (kg 1.4-DB eq.), freshwater ecotoxicity (kg 1.4-DB eq.), water depletion (m^3), metal depletion (kg Fe eq.) and fossil depletion (kg oil eq.).

4 Description of the Mesh Mould construction technique

Contemporary architecture has evolved towards a new culture based on the integration of design, structure and materiality to create complex non-standard surfaces (Rippmann et al., 2012). However, non-standard architecture requires the planning and fabrication of complex and labour-intensive rebar geometries and formworks that are not easy to fabricate with current construction techniques. The research project Mesh Mould from Gramazio Kohler Research at ETH Zürich is a novel construction system that is based on the combination of formwork and reinforcement into one single element that is fabricated on-site. This element is a three-dimensional mesh that is robotically fabricated through bending, cutting and welding steel wires. The mesh acts as the formwork during concrete pouring and as structural reinforcement after the concrete is cured (Hack et al., 2015). The structure is no longer restricted to planarity or single curvature and can be geometrically complex and individually adapted to the forces that act on the mesh (Hack et al., 2013). Figure 1 shows one of the recent prototypes of the Mesh Mould project.

Figure 1. Prototypes of the Mesh Mould structure (Gramazio Kohler Research, ETH Zurich).

5 Case study

The Mesh Mould construction technique was selected as a case study for the following LCA evaluation because of its formal and functional flexibility, which is adaptable from conventional to highly complex architectural forms. The Life Cycle Inventory (LCI) of a wall that is fabricated with the Mesh Mould technique and the LCI of different conventionally constructed reinforced concrete walls are summarised in this section. We considered a section of 1 m^2 with a thickness of 20 cm for both types of walls.

5.1 Digitally fabricated wall

5.1.1 Concrete

The concrete in the Mesh Mould wall is more demanding than that from the conventional technique. The properties of the concrete influence the protrusion rate through the mesh and the roughness of the surface. In response to the requirements of the Mesh Mould technique, the Institute of Building Materials (IFB, ETH Zürich) developed a special concrete mixture that could be optimised for the filling and trowelling processes (Hack et al., 2015). This mix is described and compared with an ordinary C25/30 concrete in **Table 1.** The ETHZ IFB concrete was modelled in the LCI using Ecoinvent processes. The silica fume was considered a by-product from the production of ferrosilicon alloy, and the allocation of environmental impacts was performed according to an economic distribution (Chen et al., 2010). Hypothesis on costs and production scheme were taken from Grist et al. (2015). For modelling the superplasticiser, we used data from different concrete production processes in Ecoinvent database. An average from different superplasticisers was included due to the unavailability of LCA data from the superplasticiser developed for the ETHZ IFB concrete (for details, see supplementary information). The volume of concrete contained in 1 m^2 of wall was $V_{c,MM}$ = 0.2 m^3.

Flow	ETHZ IFB	C 25/30
Ordinary Portland cement	500 kg/m^3	300 kg/m^3
Undensified silica fume	43.5 kg/m^3	-
Water	169 kg/m^3	190 kg/m^3
Aggregates of grain size 0-4 mm	705 kg/m^3	790 kg/m^3
Aggregates of grain size 4-8 mm	1,008 kg/m^3	1,100 kg/m^3
Polycarboxylate ether superplasticiser	4.32 kg/m^3	-

Table 1. ETHZ IFB concrete and C25/30 concrete mix composition.

The difference in environmental impacts between an ordinary C25/30 concrete and the ETHZ IFB high-performance concrete mix was investigated in the LCA comparison, which is shown in **Figure 2**. The graph shows that the difference between the contribution to climate change of 1 cubic meter (m^3) of the two concrete mixtures is significant. The customised mixture contributes approximately 40% more CO_2 emissions than the conventional concrete. The increased amount of Portland cement (500 kg/m^3) is the main cause of this discrepancy, which nearly duplicates the amount within 1 cubic meter (m^3) of C25/30 concrete. In contrast, the analysis through the cement efficiency concept developed by Damineli et al. (2010), where the environmental impact is expressed in kg CO_2.m^{-3}.MPa^{-1}, indicates a higher CO_2 intensity in the ordinary concrete **(Figure 3)**. The ETHZ IFB mix presents a compressive strength of 60 MPa, which duplicates the strength of the C25/30 concrete. Consequently, less ETHZ IFB concrete is needed to reach the same structural performance as an ordinary concrete, producing 20% less CO_2 emissions.

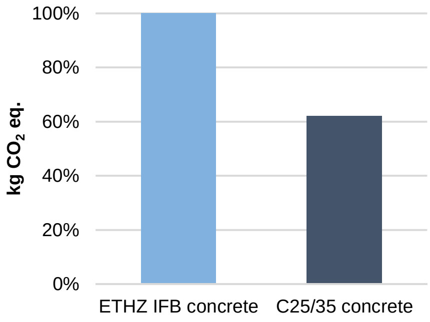

Figure 2. Comparison of the climate change impact of 1 cubic meter of C25/30 and ETHZ IFB concrete.

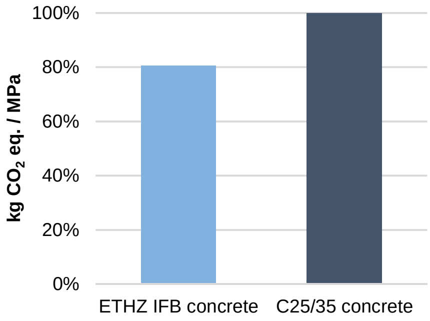

Figure 3. Comparison of the cement efficiency of 1 cubic meter of C25/30 and ETHZ IFB concrete (expressed in kg $CO_2/m^3/MPa$).

The background data source for performing the LCAs can be found in the supplementary information.

5.1.2 Steel mesh

Metal wires with a diameter of 3 mm formed the 3D mesh of the digitally fabricated prototypes. The steel was B500A, which indicates the same tension yield strength f_{yk} = 500 N/mm^2 as the reinforcements in a conventional wall but less ductile material. Conventionally, reinforced concrete walls have a minimum nominal reinforcement r_{min} = 0.3 - 0.7% of the concrete volume, depending on the structural normative (CEN, 2004). Because of constraints such as the additional formwork function, the mesh volume fraction for the digitally fabricated wall was assumed to be r_{MM} = 0.7%.Considering these data, the total steel mass of 1 m^2 of wall was calculated as follows:

$$m_{s,MM} = V_{MM} \cdot r_{MM} \cdot \rho_s = 0.2 \cdot 0.007 \cdot 7850 \approx 11\ kg \tag{1}$$

where V_{MM} is the total volume of the wall, r_{MM} is the percentage of contained reinforcement and ρ_s is the standard density of the steel.

5.1.3 Energy

The energy demand of the robotic construction process was calculated based on the construction time of a wall prototype and the power supply of the construction robot. The tool head had a theoretical building speed of 10 h per 1 m^2 (volume of 1 m x 1 m x 0.2 m). The robot "In-Situ Fabricator", which has been developed by the NCCR Digital Fabrication, is electrically powered by lithium-ion batteries with a total capacity of 5.1 kWh, which enable the robot to operate for 3–4 h without being plugged in (Dörfler et al., 2016). As a result, the energy consumption during the construction with the Mesh Mould technique (E_{MM}) was calculated:

$$E_{MM} = P_R \cdot\ T_{MM} = \frac{5.1}{3} \cdot 10 \approx 17\ kWh \tag{2}$$

where P_{R} is the power consumption of the robot and T_{MM} is the construction time of the functional unit of the wall.

5.1.4 Digital technologies

The embodied energy of the digital technologies was included in the LCI of the Mesh Mould wall, including the production of the "In-Situ Fabricator" construction robot and an attached tool for welding, bending and cutting, which are a property of the NCCR Digital Fabrication. The environmental impact of the robot production was calculated based on its material composition, which is listed in Agustí-Juan and Habert (2017). In addition, the tool head had an approximate mass of 10 kg and mainly consisted of aluminium. Because of the uncertainty in the service life of both customised digital technologies, we assumed a running time of 90,000 hours (Motion Controls Robotics, 2017). Based on the service life and the construction time, we calculated the units of the robot and the tool that were used during the construction of the project:

$$u_R = u_{tool} = \frac{T_{MM}}{T_{DT}} = \frac{10}{90{,}000} = 1.11 \cdot 10^{-4} \tag{3}$$

where $\boldsymbol{u_R}$ and $\boldsymbol{u_{tool}}$ represent the units of the robot and the bending, welding and cutting tool, $\boldsymbol{T_{MM}}$ is the construction time and $\boldsymbol{T_{DT}}$ the lifetime of the digital technologies.

5.2 Conventional wall

5.2.1 Concrete and reinforcing steel

A reinforced concrete wall with a thickness of 0.2 m, as described in the Elementaten-Katalog EAK (CRB, 2011), was taken as a reference. The conventional wall contained the same volume of concrete and steel as the digitally fabricated wall. The concrete was C25/30, which is characterised by a compression strength fck = 25 N/mm^2. The reinforcing steel was an ordinary, highly ductile B500B, with a tension yield strength fyk = 500 N/mm^2.

5.2.2 Formwork

Four walls with increasing complexity were evaluated: straight, curved, double-curved and complex double-curved. The formwork for the construction of the conventional wall varied according to the degree of complexity of the wall. The initial scenario compared two straight concrete walls, one that was digitally fabricated with the Mesh Mould technique and one that was conventionally constructed. The formwork for the conventional wall consisted of three-layered laminated boards of spruce veneers (PERI, 2015). The formwork consisted of two panels with a nominal thickness of 21 mm, and we considered 10 times reuse (Malpricht, 2010). In scenario 1, we increased the complexity of the structure for a curved wall, so no formwork reuse was assumed. Additional softwood boards were used to support the facing of the three-layered panels and control the deformation of the concrete surface. In scenario 2, the complexity of the wall was increased compared to the previous scenario, this time considering a double-curved wall. In this case, the varying loads from the different physical states of the concrete were difficult to control and led to a higher use of softwood to stabilise the facing of the formwork. Double-curved wooden moulds can be fabricated (Weilandt et al., 2009), but these designs are labour intensive and have some formal limitations. Finally, the scenario with the highest complexity was a complex double-curved wall with a free-form polystyrene formwork, similar to the structure in **Figure 4**.

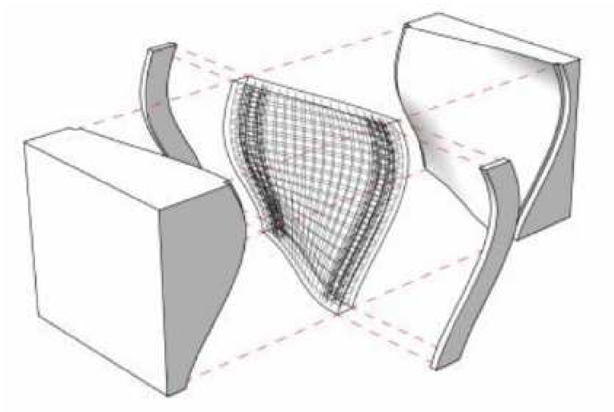

Figure 4. Sketch of a double-curved wall with a conventional foam formwork (Hack et al., 2014).

This system consisted of polystyrene blocks that were cut according to the desired form and covered by a 5-mm layer of epoxy resin. The data inventory of the formwork production included the material and the energy demand for wire cutting the blocks. Additionally, we included 30% of waste polystyrene, produced during cutting of EPS blocks into complex formwork shapes (Kaftan and Stavric, 2013). The energy demand of the formwork production was calculated based on the speed (1,500 mm/min) and power (600 W) of a 2-axis wire-cutting machine. Finally, we considered the landfill deposition of the polystyrene after use. The LCI of the formwork in each scenario is summarized in **Table 2**.

Scenario	Structure	Formwork reuse (times)	3-layer laminated board [m^3]	Softwood board [m^3]	EPS foam slab [m^3]	Epoxy resin [m^3]	Energy [kWh]
0	Straight wall	10	0.0042	0	0	0	
1	Curved wall	0	0.042	0.105	0	0	
2	Double-curved wall	0	0.042	0.320	0	0	
3	Complex double-curved wall	0	0	0	0.52	0.01	0.013

Table 2. Life Cycle Inventory of the formwork for the conventional wall in the different scenarios.

5.2.3 Manual labour

The construction of a conventional wall system involves manual labour. However, energy requirements and emissions that are related to human life are usually not included in environmental analysis. Some studies have included it and conclude that the environmental impact is anyhow negligible compared to the impact of construction work (Alcott, 2012).

6 Results

The results of the Life Cycle Assessment are presented below. The digitally fabricated wall is analysed in detail and compared to a conventional structure with the same functional unit.

6.1 Assessment of the digitally fabricated wall

The environmental assessment of the wall that was constructed with the Mesh Mould technique is illustrated in **Figure 5.** The concrete production process has a relative impact of more than 75% for Climate change because of the energy-intensive transformation process of the clinker for the cement production and simultaneous release of CO_2 during calcination. Moreover, the concrete has a contribution of approximately 60% to the environmental impact in indicators such as terrestrial acidification, fossil depletion and water depletion. Specifically, the impact of the concrete in the first indicators is caused by the burning process of fossil fuels during clinker production and the water is depleted during gravel production. On the other hand, the reinforcement has a dominant impact for freshwater eutrophication (63%), human toxicity (57%), freshwater ecotoxicity (61%) and metal depletion (89%). The pollution in the steel production for these impact categories is primarily related to the release of heavy metals to the atmosphere during steel recycling (Gomes et al., 2013). In contrast, the embodied energy of the digital technologies has a negligible relative impact, with a contribution of approximately 2% to freshwater eutrophication, human toxicity, freshwater ecotoxicity and metal depletion. Finally, the influence of the electricity production to fulfil the energy demand during construction is small in most of the midpoint categories, with a maximum contribution of 20% in ozone depletion. The results of the LCA indicate that the environmental performance of the Mesh Mould wall primarily depends on the use of materials. Therefore, an additional analysis to determine the environmental potential of an optimised design is conducted in the sensitivity analysis.

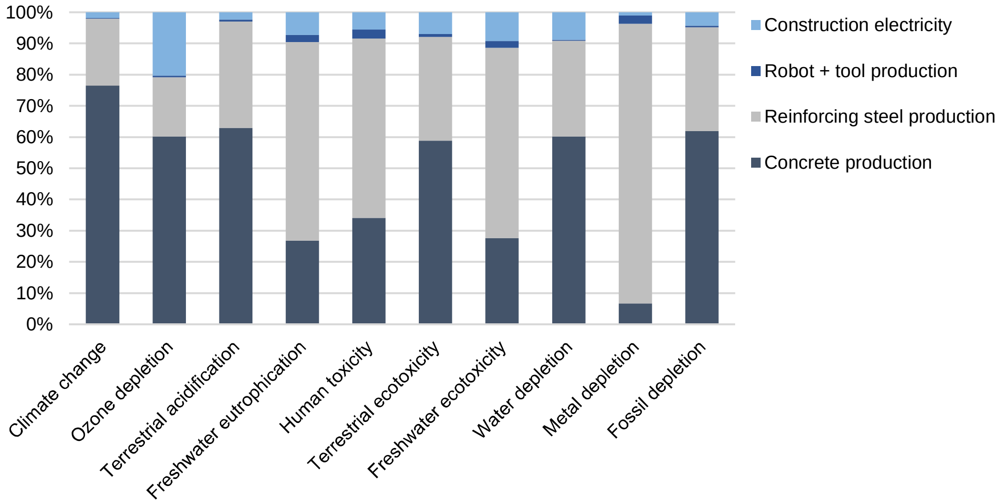

Figure 5. Relative contribution of the individual processes to the environmental impact of a wall that is constructed with the Mesh Mould process.

6.2 Comparison of conventional and digital fabrication techniques

The LCA comparison of the digital fabrication and conventional construction processes for four types of walls is graphically depicted in **Figure 6.** This figure includes an analysis of the climate change and human toxicity indicators with an increase in the walls' complexity, which is represented by the four scenarios in Table 3. The results present variability that depends on the midpoint category and considered scenario. For a straight wall, the environmental impacts of the conventional wall are lower than the Mesh Mould wall. For a single-curved wall, the contribution to climate change of a conventional wall is lower than the digitally fabricated one, while the human toxicity is similar for both (6% difference). For the double-curved wall, the CO_2 emissions from the Mesh Mould wall are still 8% higher than the conventional wall constructed with plywood formwork. In contrast, the human toxicity indicator in the same scenario is 19% higher in a double-curved conventional wall than in the Mesh

Mould wall. The results prove that the environmental performance of the conventional wall decreases with increasing structural complexity. The difference in environmental impacts between a single-curved and a double-curved wall is mainly attributed to the increase in softwood boards to contain the additional forces from the increased structural complexity of the structure. Finally, for a complex double-curved wall, which implies the use of polystyrene formwork in the conventional technique, the Mesh Mould construction process allows savings of 38% for climate change and 31% for human toxicity factors.

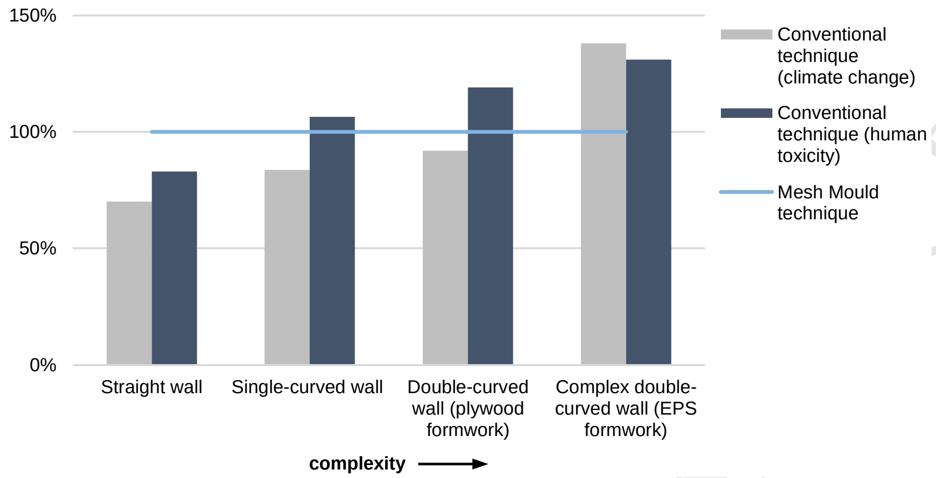

Figure 6. LCA comparison of a Mesh Mould wall (no formwork required) and a wall that is constructed with conventional techniques (formwork). The scenarios represent the increasing complexity of the walls.

The relative contributions from the production processes of a complex double-curved wall with polystyrene formwork to the different impact categories are depicted in **Figure 7**. We can observe the high impact of the epoxy resin for the formwork covering, which is responsible for 45% of the climate change emissions, 64% of terrestrial acidification, 60% of water depletion and 69% of fossil depletion. Moreover, the production of the polystyrene mostly influences the ozone depletion indicator (17%). Finally, the landfilling of the formwork after one reuse highly contributes to ecotoxicity. On the contrary, the environmental impacts of the Mesh Mould contruction process do not change with rising demands of the form, so the environmental potential is growing with the required effort in the conventional technique. Therefore, the digital fabrication method becomes more interesting the more unique and complex the architectural forms are.

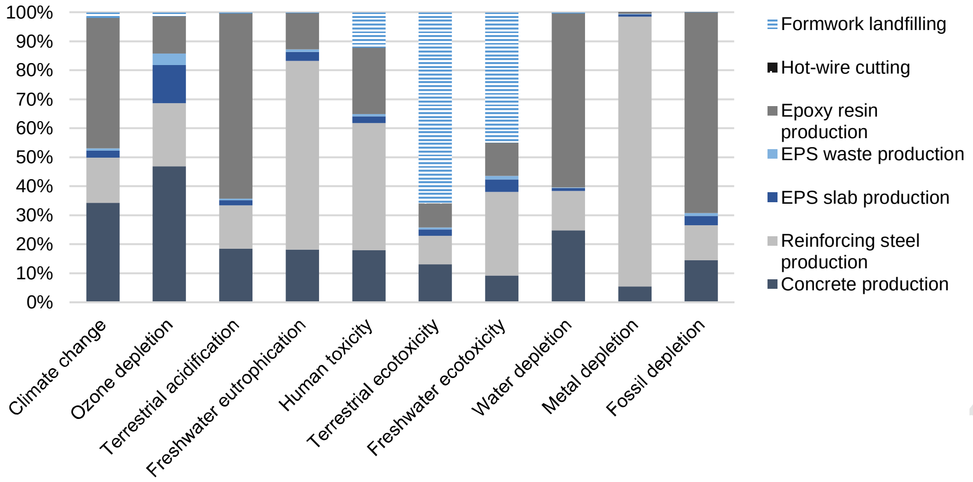

Figure 7. Relative contribution of the individual processes to the environmental impact of a complex double-curved wall that is constructed with conventional techniques.

7 Sensitivity analysis

The results show that the digital fabrication process induces greater environmental impacts than the conventional technique for walls with low degrees of complexity (scenarios 0 and 1). The Mesh Mould construction process is a research project that is still in its optimisation phase. As a result, the LCI of the digitally fabricated wall contains some assumptions, mainly at the material level, during the comparison with conventional construction. In this section, the uncertainty on the concrete and steel volume in the Mesh Mould wall is graphically depicted to further analyse when digital fabrication produces environmental benefits compared to conventional construction.

7.1 Concrete

In the initial comparison, the Mesh Mould wall was conservatively considered to have the same dimensions as a conventional wall built with C25/30 concrete. However, the compression strength of the ETHZ IFB concrete is higher based on the greater amount of cement, which could be used to reduce the thickness of the structural element. In published case studies, the use of high performance concrete has already been efficiently used to reduce thickness of structural elements such as bridges and provide an environmental benefit (Habert et al., 2012). Moreover, the difficulty of positioning the rebars and the formwork before pouring the concrete inside a tight building element is here potentially overcomed with digital fabrication techniques. Consequently, this section quantifies the minimum wall thickness that is compliant with structural requirements to improve the environmental performance of a straight wall that is constructed with the Mesh Mould process. In the following analysis, the break-even-point is approached by continuously reducing the thickness of the Mesh Mould wall. The maximum thickness of the digitally fabricated wall can be distinguished when the contribution from both construction elements to the impact categories is equal. The calculation approach for the Mesh Mould wall is based on adjusting the concrete volume to the variable thickness of the wall without modifying the other parameters. **Figure 8** compares the CO_2 emissions for wall thicknesses between 10 and 20 cm to those of a 20-cm-thick conventional concrete wall.

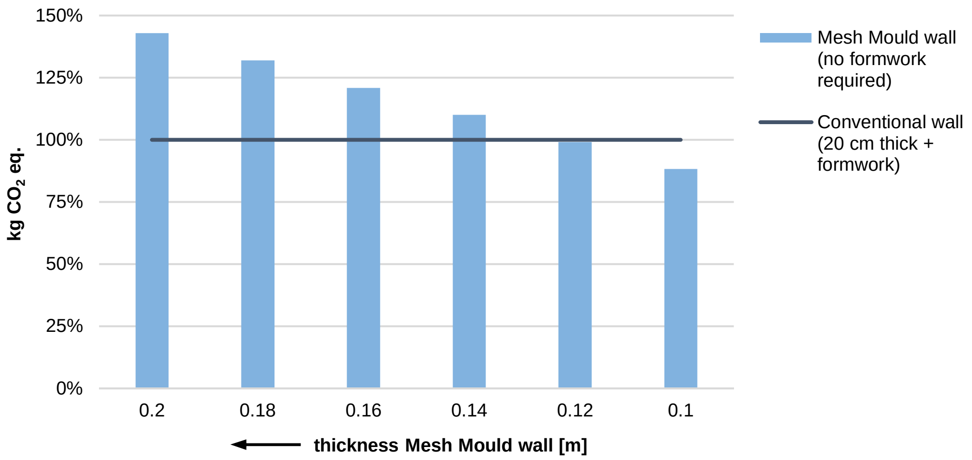

Figure 8. Comparison of the contribution to the climate change category of two straight walls: a conventionally built wall with constant thickness and a digitally fabricated wall with variable thickness.

The graph demonstrates that the CO_2 emissions of the digitally fabricated wall are 12% lower than the conventional wall when the thickness is reduced to 10 cm. The graph shows a break-even point for the climate change category at a thickness of 12 cm, which means that digital fabrication technology would be effectively performant from an environmental perspective when producing thinner straight walls than those from conventional methods. The feasibility of a Mesh Mould wall with this thickness is evaluated by calculating the slenderness criteria according to Eurocode 2: Design of concrete structures (CEN, 2004), which leads to the ratios in formulas 4 and 5:

$$\frac{l_0}{t_{wall,MM}} \leq 25 \tag{4}$$

where $t_{wall,MM}$ is the minimum thickness of a Mesh Mould concrete wall and l_0 is the effective length of the wall, which is calculated by

$$l_0 = \beta \cdot l_w = 2.4 \tag{5}$$

where l_w is the clear height of the wall (2.4 m), and β is a coefficient that represents the support conditions, which was conservatively taken as 1.0 for this evaluation. The calculation shows that a minimal wall thickness of $t_{wall,min} \geq 0.1$ m is required in the Mesh Mould wall. Therefore, the thickness at the break-even point of CO_2 emissions ($t_{MM,BEP}$ = 0.12 m) would be sufficient. Finally, a second calculation regarding the compression strength of the ETHZ IFB concrete mix is performed. A direct proportionality between the strength of the concrete and the bearing capacity of the wall is assumed, and no failure modes or load situations except compression are considered to simplify the calculation. The conventional wall has a thickness of 0.2 m and its concrete has a compression strength of f_{ck} = 25 N/mm^2. Formula 6 shows the minimum required compression strength ($f_{ck,MM,min}$) of the ETHZ IFB mix for a wall of 12 cm:

$$f_{ck,MM,min} = \frac{t_{wall,con}}{t_{MM,BEP}} \cdot f_{ck} = \frac{0.2}{0.12} \cdot 25 = 41.7\ N/mm^2 \tag{6}$$

where $t_{wall,con}$ is the thickness of the conventional wall, $t_{MM,BEP}$ is the thickness of the Mesh Mould wall at the break-even point and f_{ck} is the compression strength of the standard concrete mix. Typically, high-performance concrete has a fine fraction of a supplementary cementitious material and w/c<0.4, which enables the material to reach a compressive strength over 80 or even 100 N/mm^2. The ETH IFB mix is a high-performance concrete, which contains silica fume as supplementary cementitious material and has a water-cement ratio (w/c) of 0.34. This concrete mixture presents a minimum compressive strength between 60-70 MPa, which exceeds the required $f_{ck,MM,min}$ = 41.7 N/mm^2. In conclusion, the conducted structural analysis shows that the break-even point in CO_2 emissions for the digitally fabricated wall compared to a conventional wall is theoretically reachable and that the wall thickness can be reduced to 0.1 m.

7.2 Reinforcing steel

During the initial analysis, the volume fraction value that was assumed for the reinforcement of the Mesh Mould wall was r_{MM} = 0.7%. In this sensitivity analysis, we establish a range around the previous value with a minimum and maximum reinforcement content. On the one hand, distributing steel only where it is structurally necessary could potentially reduce the steel volume fraction of $r_{MM,min}$ = 0.5%. On the other hand, the structural performance of the wires in a bearing wall could increase the reinforcement content, with a steel volume fraction of $r_{MM,max}$ = 1.5%. **Figure 9** graphically depicts the sensitivity analysis of the digitally fabricated wall when considering the previous range of reinforcement volume fractions.

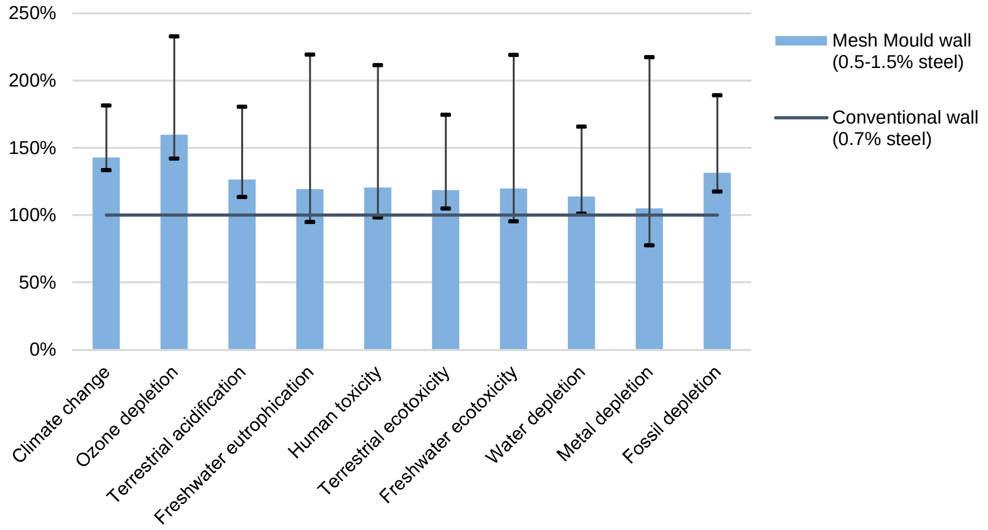

Figure 9. LCA comparison of two straight walls: a conventionally built wall with 0.7% steel volume fraction and a digitally fabricated wall with variable volume fraction of reinforcement.

The graph reveals the great impact of the variability in the amount of reinforcement steel on the global environmental impact of digitally fabricated wall. In particular, the uncertainty between $r_{MM,min}$ = 0.5% and $r_{MM,max}$ = 1.5% results in a difference of approximately 125% in freshwater eutrophication and freshwater ecotoxicity, 113% in human toxicity and 140% in metal depletion emissions. The importance of efficient steel usage is shown in the previous results. However, the optimisation of reinforcing steel reduces the environmental impacts compared to a conventional reinforced concrete wall only in some categories such as metal depletion (23%). In categories such as climate change, the reduction in steel do not enable the Mesh Mould wall to achieve lower emissions compared to a conventionally constructed straight concrete wall. Consequently, the structural performance of walls that are fabricated with the Mesh Mould technique should be modelled and tested to minimise the volume fraction of steel but combined with the optimisation of other parameters, such as the concrete volume.

8 Synthesis

The results of the sensitivity analysis are summarised in this section. The extreme values of the individual materials represent a range of possible outcomes for the Mesh Mould case study.

Scenarios for the digitally fabricated wall:

- **Best scenario:** The optimal performance of the Mesh Mould wall is characterised by a minimal reinforcement steel volume fraction of $r_{MM,min}$ =0.5% and a lower wall thickness of $t_{MM,min}$ = 0.1 m, which is the limit from the slenderness criteria.
- **Reference scenario:** The initially considered Mesh Mould wall has a reinforcement of r_{MM} =0.7% and a wall thickness of t_{wall} = 0.2 m.
- **Worst scenario:** Buckling failure might require a wall thickness of t_{MM} = 0.2 m, and additional complications with the mesh could lead to a reinforcement steel content of $r_{MM,max}$ = 1.5%.

Scenarios for conventional construction:

- **Standard scenario:** The smallest environmental impact for the conventional method is reached in a straight wall, where the formwork was reused 10 times. The dimensions are set to t_{wall} = 0.2 m, using r_{wall} = 0.7% of steel and ordinary C25/30 concrete.
- **Complex scenario:** Conventionally, a complex double-curved wall that is constructed with polystyrene formwork and is not reusable showed the worst environmental performance. The dimensions are set to t_{wall} = 0.2 m, with r_{wall} = 0.7% of steel and ordinary C25/30 concrete.

The range of environmental impacts from the best- and worst-case scenarios and as well as the initial digitally fabricated wall compared to the complexity-dependent impacts of the conventional wall are illustrated in **Figure 10.**

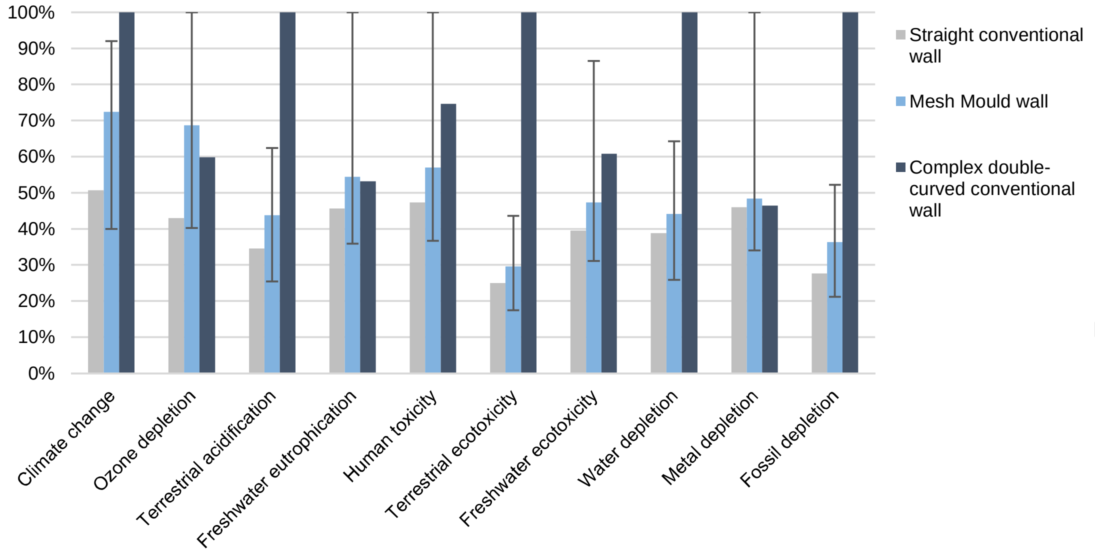

Figure 10. LCA comparison of a digitally fabricated wall with a straight and a complex double-curved wall that are constructed with conventional techniques. The error bars represent the best and worst scenarios of the wall.

The large variability in the environmental emissions of the best and worst cases of the Mesh Mould wall highlights the importance of material optimisation. The best scenario of the digitally fabricated wall reduces material usage and decreases the CO_2 emissions by 33% compared to the reference scenario. Simultaneously, the worst scenario exhibites substantially higher emissions than the reference scenario, with an increase of 52% in metal depletion. The results indicate that the best scenario of the Mesh Mould wall produces potential environmental benefits compared to a conventionally constructed straight concrete wall. Specifically, the best scenario of the Mesh Mould wall reduces the emissions by 3-13% depending on the indicator. However, the outcome of this comparison greatly depends on the material optimisation of the system. A less optimised Mesh Mould wall (worst scenario) has lower environmental performance than a conventional straight wall.

Finally, the results prove that the reference Mesh Mould system can currently environmentally compete with a conventionally constructed double-curved wall. The reference scenario of the Mesh Mould wall shows greater impacts compared to the complex conventional scenario only in three midpoint categories, but the difference is minimal (1-9%). Moreover, the worst scenario of the digitally fabricated wall can environmentally compete with a complex conventional wall in categories such as climate change, terrestrial ecotoxicity or fossil depletion. In conclusion, the complexity is an important factor to consider during comparisons with conventional construction. Contrary to conventional techniques, the impacts of the Mesh Mould process do not increase with the uniqueness and complexity of the architectural forms.

9 Discussion

In this paper, we evaluated the environmental potential of an innovative digital fabrication process for the construction of complex concrete structures. The conducted research confirmed the environmental potential of additive fabrication, as anticipated in previous studies such as Kohtala and Hyysalo (2015). Moreover, the analysis showed that digital fabrication in complex geometries (double-curved walls) provides an environmental benefit compared to conventional construction. Digital fabrication techniques facilitate the construction of complex and slender structures without the use of conventional formworks, with associated material savings. However, does this additional complexity in the structure provide an environmental benefit? This question seems reasonable and can be addressed by examining which additional functions can support double-curved walls that are built with digital fabrication. This specific question leads to the use of complex forms in architecture. Complexity is an architecture characteristic, whose costs and value creation have often been discussed in the literature (Venturi, 1977), and we would like to raise three different possibilities to discuss the appropriate use of complexity for sustainability.

First, complexity can be seen as a consequence of a highly integrated construction process. The conventional organisation of a construction is conceived as a successive and layered process where each element and function is addressed by a different element and built at different moments by different skilled workers. This combination of functions through the help of digital technologies can save time and building materials, frequently associated with money and grey energy reductions (Agustí-Juan and Habert, 2017). This integrated design increases the complexity, which can be handled with no additional costs through digital fabrication. When digital fabrication is used to build elements that permit an integrated design, the complexity of these elements is likely justified from an environmental perspective because integrated functions can save materials and because the production of these complex elements is more efficient when digital fabrication is used. However, the choice of functions is crucial. For instance, the complex building element in this study can be understood as the fusion of structure and final layering. From a classic sustainable design perspective, these two elements are considered to have completely different service lives. The structure has a service life of 60 years, while interior finishing is thought to be changed every 15 years (Hoxha et al., 2014). If the structure must be changed every 15 years, the environmental impact drastically increases. On the contrary, avoiding the replacement of interior finishing because of its long-lasting design can save energy.

This observation leads to a second question regarding complexity in architecture as an enlightenment of the structure and more generally as an ornament. The function of ornaments has long been discussed. Rosenbauer (1947) stated that “Engineering, when it uses materials up to their functional limits approaches the economy of nature and thereby creates forms as beautiful as the forms of nature. […] Engineering occasionally produces art but we cannot assume that all art will come from engineering. We must have poets and we must have designers and their business is to embellish and adorn our lives and our culture. […] Ornament cannot be abolished as the desire for embellishment is essentially human, and humans will gratify it wherever they can”. This author also wrote that “the machine will then produce ornament willed by the designer as naturally as did the handtools of the artist craftsman. Then there will be proper and excellent ornament, differing from traditional ornament as our culture differs from those of the past. The public will buy it as the good things of the past were bought by that public, and greater numbers will be economically able to do so. This is the real manner in which the machine may raise our standard of living."

Considering this perspective and the results of this study, in which the machine produced ornaments with lower environmental impact than the same element from a conventional technique, we can consider digital fabrication as an effective construction technique to produce complex ornaments. Moreover, the function of ornaments and the inherent complexity that is related to its production is justified by the social need of ornamentation. In a recent perspective on ornamentation in architecture, Moussavi and Kubo (2006) established that "Architecture needs mechanisms that allow it to become connected to culture". The aesthetic composition of buildings is effectively related to the culture by creating affects and sensations. Even if modern design does not require ornaments, society continues demanding these additional elements to connect with the contemporary culture. In their book, the authors also showed through examples how ornaments in contemporary architecture can integrate functions (structure, visibility, etc.) behind an apparently purely aesthetic performance.

Finally, complexity can be seen as a consequence of a problem-solving attitude. Societies often solve problems by developing more complex environments and technologies (Tainter and Taylor, 2014). This can be seen as positive, for instance, studies on environmental psychology-oriented design suggest that high levels of spatial and visual complexity in the workspace foster creativity. Factors such as the creativity or productivity of employees are influenced by their aesthetic judgements of the built environment (Gifford, 2014). However, complexity both solves problems and generates them. Innovative technologies, which are intended to save energy through complex designs and controls, may consume more. The complexity of designs produces unintended interactions among components, producing further problems, and the current sustainability concerns regarding buildings are creating more complex building designs. Complexity in control systems, for example, leads to unanticipated growth in facility management. Interior environmental systems are so complex that many users cannot fine-tune the controls, so a large amount of energy is wasted (Bordass and Leaman, 1997).

Digital fabrication can facilitate the production of elements with higher complexity without increasing the environmental costs, as is usually observed in conventional construction, which could contradict the traditional observation pattern that increasing complexity, while initially effective, accumulates and induces diminishing returns, undermining the ability to solve future problems. 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 (Gershenfeld, 2012). These occasions have been so rare that they are designated with terms that signify a new era, namely, the Agricultural Revolution and the Industrial Revolution. These events were followed by great expansions in the number of humans, wealth and complexity of societies.

10 Conclusions

In this study, the environmental impact of an innovative digital fabrication construction was compared to a similar structure that was built with conventional construction techniques. The results showed that digital fabrication produces high environmental benefits compared to conventional construction when complex structures are built. In this study, we confirmed that the environmental impact of the Mesh Mould process does not grow with the uniqueness and complexity of the architectural form. Additional complexity was achieved without additional environmental costs, so the potential benefit of digital fabrication increased proportionally to the level of complexity of the structure. 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. This analysis also showed that the current Mesh Mould system can environmentally compete with conventional structures, which have a high degree of both formal and structural complexity. However, the results highlighted the need for improvement to compete at a lower degree of complexity. In this case, high thickness reduction must be achieved without compromising the structural performance. Finally, this study also raised the attention of the need to justify complexity from an environmental point of view to avoid the risk of complexifying a socio-technical system for no real mean.

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Appendix. Supplementary information

Supplementary information regarding background data and results from the LCAs can be found in appendix.

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Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall

Highlights

- LCA comparison between robotic fabrication and conventional construction.
- Mesh Mould construction process analysed from an environmental point of view.
- Environmental benefits of digital fabrication when applied to complex structures.
- Justification of complexity from a sustainable perspective.