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AN ENVIRONMENTAL PERSPECTIVE ON DIGITAL FABRICATION IN ARCHITECTURE AND CONSTRUCTION

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Abstract. Digital fabrication processes and technologies are becoming an essential part of the modern product manufacturing. As the use of 3D printing grows, potential applications into large scale processes are emerging. The combined methods of computational design and robotic fabrication have demonstrated potential to expand architectural design. However, factors such as material use, energy demands, durability, GHG emissions and waste production must be recognized as the priorities over the entire life of any architectural project. Given the recent developments at architecture scale, this study aims to investigate the environmental consequences and opportunities of digital fabrication in construction. This paper presents two case studies of classic building elements digitally fabricated. In each case study, the projects were assessed according to the Life Cycle Assessment (LCA) framework and compared with conventional construction with similar function. The analysis highlighted the importance of material-efficient design to achieve high environmental benefits in digitally fabricated architecture. The knowledge established in this research should be directed to the development of guidelines that help designers to make more sustainable choices in the implementation of digital fabrication in architecture and construction.

Keywords. Digital fabrication; LCA; sustainability; environment.

1. Introduction

The construction sector is a highly active industry that employs more than 111 million construction workers worldwide and is responsible of high environmental impacts (Ortiz et al, 2009). Today's increasing concern about sustainability has induced the emergence of "green design" practices in order to decrease environmental impacts in construction. However, commitments to sustainability remain weak and fragmented (Fry, 2008). Responding to the requirements of the current society, a new type of construction practice is needed. Specifically, innovative processes and technologies that recognize the importance of sustainable design and overcome the inefficiency and lack of interoperability present in the sector.

Digital fabrication processes are becoming an integral part of modern product development (Hague et al, 2003), and 3D printers are nowadays affordable for home use (Pearce et al, 2010). As interest in additive manufacturing grows, research into large-scale processes is beginning to reveal the potential applications in architecture and construction. Architectural design needs to extend beyond the form and function and engage with the management of complex systems (Fry, 2008). But their potential contribution to the improvement of sustainability in construction should be argued. The challenges of architectural scale additive fabrication are issues of size, material use, energy demands, durability, GHG emissions and waste production over the life cycle of a building and they must be recognized as priorities of any architectural project.

The aim of this study is to investigate the implications and opportunities of the development of digital fabrication to advance achievements in sustainable construction. The research focuses specifically on measuring the flow of materials, embodied energy and potential environmental impacts associated with digital fabrication processes. Comparative assessments with conventional construction processes are performed, with specific priority placed on new methods of additive fabrication and full-scale robotic construction in architectural processes. The final goal of this research is to develop guidelines that help designers to make better-informed and more sustainable choices in the implementation of digital fabrication.

2. Methodology

The Life Cycle Assessment (LCA) framework from the standards ISO 14040-44: 2006 (ISO, 2006) was selected for the assessment. LCA is well-established method, which application is increasing in the construction sector as it represents a comprehensive and systematic approach for environmental evaluation and optimization of construction processes (Cabeza et al, 2014). The objective of the evaluation was the comparison of digital fabrication and conventional construction projects. Therefore, the impact assessment was implemented in the software SimaPro 8 using the Ecoinvent v2.2 database (Hischier et al, 2010) and the method Recipe Midpoint (H) V1.06 (Goedkoop et al, 2009). But of course, to evaluate the environmental impact of a digital project, we could also use existing tools that efficiently integrate LCA in Revit such as Tally.

After an extensive analysis and classification of digital fabrication processes and technologies, two case studies were selected. Two classic building elements (wall and roof) where computational design and robotic fabrication enable additional functions embedded in the structure. We observed that many digitally fabricated projects present additional functions such as thermal or acoustic performance integrated with the structural function that give an added value to the architecture (Moussavi et al, 2006). As a consequence, exists an evident arduousness on the environmental evaluation due to the difficulty on the performance of a LCA comparison with conventional construction. Specifically, the definition of the functional unit is critical due to the difficulty on finding a conventional system that concentrates the functions integrated in the digitally fabricated structure. Therefore, for each particular case study, a detailed study to tailor the functional unit it is needed.

3. Case study: Self-shading wall

The project selected for the assessment was a self-shading brick wall modelled by computational design and constructed by an in-situ robotic arm. The research in ceramic building systems through design robotics performed by S. Andreani and M. Bechthold (Harvard University) was taken as a reference. The study researches mass-customization methods for the creation of dynamic ornamental effects that reduce thermal gain on façades with brick cladding. Custom brick shapes are used to optimize assembly configuration, creating shades on the wall surface that contribute to the improved thermal performance of the façade (Andreani and Bechthold, 2014).

3.1. SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

The case study was assessed in accordance to a cradle-to-grave analysis, including raw material extraction, digital technologies and materials production, robotic assembly and operation of the wall. The self-shading project shows specifically the potential of digitally fabricated façades to reduce heat gain during operation, therefore, this phase was included in the assessment. Two functional units were compared: 1 m^2 of self-shading brick wall constructed with digital fabrication techniques and 1 m^2 of a wall system with a similar brick masonry aesthetic and the same structural and thermal performance.

3.2. DATA COLLECTION

The material composition of the self-shading wall were plain clay bricks assembled with cement mortar joints. Additionally, 10% of the mass of brick was added for the creation of the self-shading effect. In the conventional wall, the same type of brick was considered with 1.5 cm of EPS insulation in the interior to achieve the same thermal performance as the self-shading function during the use phase (Figure 1).

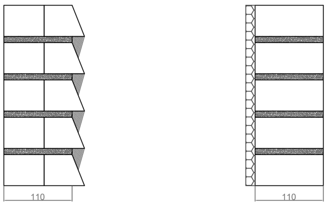

Figure 1. Self-shading brick wall and conventional brick wall sections.

For the calculation of the embodied energy, we collected production data from the "In-Situ Fabricator" robot (NCCR Digital Fabrication) and the laptop production process from Ecoinvent. In addition, the mass-customized bricks required a saw tool that attached to the robot cut them in the desired shape. The production process data of the diamond wire 500 mm saw was collected from literature (Ioannidou et al, 2014). Finally, we included the construction energy consumption of the robot and laptop computer (Deng et al, 2011).

The operation energy was calculated based on a residential cooling consumption system from the literature (Shah et al, 2008). The house reference was located in Texas (US) due to the high effectiveness of self-shading systems in hot climates. Initially, we considered 4240 kWh of cooling electricity consumption per year during 50 years of use. From the total energy demand, just a 20% corresponding to the walls heat gain was included (Department of State Development, 2015). Additionally, a reduction of the 16% of cooling energy demand was implemented due to the improved thermal effect (Andreani and Bechthold, 2014). Finally, the total operational energy considered was 559 MJ.

3.3. RESULTS

3.3.1. Environmental impact of digital fabrication process

The environmental assessment of the self-shading wall was divided in four processes: brick production, cement mortar production, digital technologies production, and electricity production. Figure 2 graphically depicts the relative contributions to the overall environmental impact of the construction of 1 m^2 of self-shading wall. The analysis reveals that the highest impact is attributed to the materials production. The energy consumption during construction remains relatively high in categories such as human toxicity, however, this factor varies depending on the electricity generation mix. Finally, the relative impact of the technologies production is negligible in most of the environmental indicators.

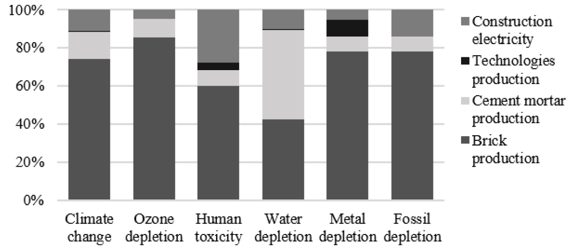

Figure 2. Relative contributions to the environmental impacts of the self-shading wall production.

3.3.2. Comparative LCA with conventional construction

Subsequently, we compared the environmental impact of digital fabrication with conventional construction. Specifically, the comparison was focused on the production and operation of the two façade systems applied to a house situated in Texas (US). Figure 3a establishes that the self-shading façade has higher environmental impacts than the conventional façade with equal structural and thermal performance. In particular, the 10% of extra brick needed for the self-shading function is potentially the largest contribution to the difference in impacts. Similarly, after 50 years of operation, the difference between the relative impacts decreases but the self-shading façade has still higher contributions (see figure 3b). The results confirmed the high influence of the production phase in the global impact of a building element.

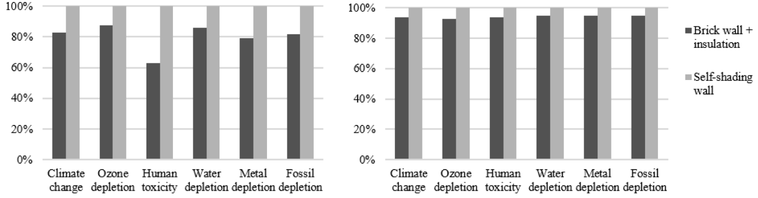

Figure 3. (a) Comparison of environmental impacts of walls production. (b) Comparison of environmental impacts of walls production and operation.

3.4. DISCUSSION

The previous results showed a clear environmental disadvantage in the use of digital fabrication processes for the production of brick façades. The reason may be attributed to the need for material optimization in the design. However, an important factor in the comparison was the additional thermal function represented by the self-shading effect and compared with the insulation in the conventional system. The environmental impact of the EPS is very small compared to the impact of the 10% extra brick used for the creation of a self-shading effect (calculations based on Ecoinvent database). Therefore, the integration of additional functions in digital fabrication did not provide environmental benefits because the equivalent function in the conventional wall had a low environmental impact.

4. Case study: “The Sequential Roof”

The second digital fabrication project selected was “The Sequential Roof” (Gramazio Kohler Research, ETH Zürich, 2010-2015). This wooden structure consists of 168 single trusses that compose a 2,308 square meter freeform roof design. The structure composed by 100-150 cm timber slats have been robotically assembled to create large-scale load bearing structures. The project demonstrates the potential of combining digital fabrication technology applied at full architectural scale with a local and natural building material. The mechanized assembly of the wood structures makes possible a reduction on the construction time from manual assembly and it has a potential interest with regard to the use of recycling waste wood (Gramazio Kohler Research, 2014).

4.1. SYSTEM BOUNDARIES AND FUNCTIONAL UNIT

The case study was assessed in accordance to a cradle-to-gate analysis, from the extraction of raw material up to the construction site. The Sequential Roof integrates finishing and acoustic functions to the structural function, allowing the elimination of additional elements such as hanging ceilings. Therefore, the assessment was focused on the production phase. Two functional units with similar structural and functional factors were compared: 1 m^2 of computationally designed and robotically assembled wood roof and 1 m^2 of conventional wood roof structure with hanging ceiling.

4.2. DATA COLLECTION

The Sequential Roof is composed by 384 m^3 of C24 fir/spruce wood robotically assembled using in total 815,984 nails (see Figure 4). The digital manufacturing process of the 168 trusses has been carried out by a special robot in the manufacturer factory. Due the lack of data from this robot, the embodied energy of two robotic arms and a desktop computer (Williams and Sasaki, 2003) were considered for the assessment. Finally, the energy consumption of both technologies during 12 hours of production.

Figure 4. Section of "The Sequential Roof" (Architektur und Digitale Fabrikation, ETH Zürich).

The conventional roof structure was formed by conventional Glulam spruce beams and joists. The joists were connected to the beams with galvanized steel hangers. The wood structure was covered by 19 mm of waterproof particle board attached with steel nails. In addition, a hanging ceiling finished the structure and protects acoustically. The ceiling was composed by laminated wood boards, 5 cm of rock wool acoustic insulation and a hanging structure of galvanized steel.

4.3. RESULTS

4.3.1. Environmental impact of digital fabrication process

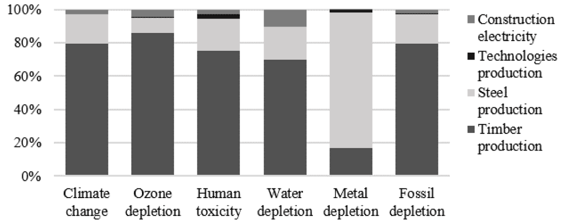

Figure 5. Relative contributions to the environmental impacts of The Sequential Roof production.

The results from the environmental assessment of the robotically fabricated roof were broken down into four processes: spruce timber production, low-alloyed steel production, digital technologies production and electricity production. Figure 5 indicates that more than 95% of environmental impacts re caused by materials production. Simultaneously, the graph shows that the construction energy impacts less than 10% in all the indicators. This fact is attributed to the production process in Switzerland, where the primary energy supply has small shares of natural gas and coal and a 22% of renewable sources (International Energy Agency, 2012). Similarly, the relative impact of the production of digital technologies is less than 2%. In conclusion, the analysis proved that the impacts of digital fabrication were negligible compared to the materials manufacturing processes.

4.3.2. Comparative LCA with conventional construction

Subsequently, we compared the life cycle of the digitally fabricated roof structure with the conventional system. Figure 6 graphically depicts the environmental benefits of The Sequential Roof production process. Specifically, the difference between the environmental impacts of both construction systems is between 30-40% in all categories. For example, in climate change the CO_2 emissions of The Sequential Roof are more than 40% lower than the conventional roof compared.

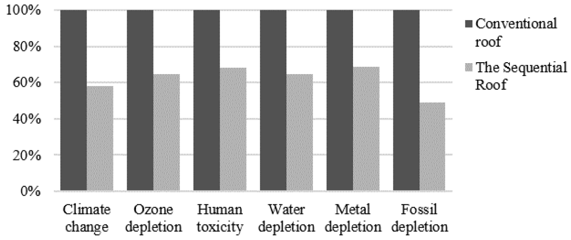

Figure 6. Comparison of the environmental impacts of The Sequential Roof and the conventional roof structure.

4.4. DISCUSSION

This case study showed clear environmental benefits in the use of digital fabrication processes during the production of wood structural elements. These benefits were mainly derived from the combination of different functions in a single element, which allowed a more efficient and material-reductive construction process. In order to prove this evidence, we carried out a study on the relative contributions to the environmental impacts of the conventional roof production (Figure 7). The analysis depicts that the hanging ceiling is responsible of approximately 40% of the impact. In conclusion, the integration of additional functions in a single digitally fabricated element provided environmental benefits because the element with equivalent functions in the conventional roof had high environmental impact.

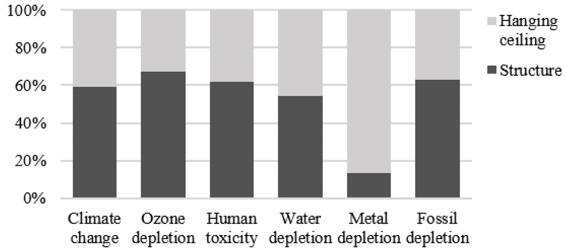

Figure 7. Relative contributions to environmental impacts of the conventional brick façade production.

5. Conclusion

Digital fabrication has fostered social and economic changes in manufacturing, but it still must mature to bring significant environmental benefits to the life cycle of buildings. This paper showed a preliminary step towards the formulation of guidelines that can help designers to make sustainable choices about implementing digital fabrication in architecture and construction. In each case study, the assessment was focused on the potential benefits that were enabled by computational design and robotic fabrication. The results of the evaluation evidenced that the largest environmental impacts depended primarily on materials production. Therefore, the most fundamental efficiency that might be brought to a project was found in material optimization during design. Nevertheless, robotic fabrication technologies and processes contributed minimally in terms of energy and environmental impacts.

Simultaneously, we observed that in many projects digital fabrication allows the integration of additional functions on the structure, such as thermal or acoustic performance that give added value to the architecture. These innovative digital construction process can contribute to achieve significant environmental benefits, elimination of waste and reduction of economic and labour costs associated with inefficient construction. However, additional functions can increase the requirement of material in the project, which might be disadvantageous from an environmental point of view. In the present study, we demonstrated that digital fabrication brought high environmental benefits when the integrated additional functions had high environmental impact. In conclusion, sustainable design in architecture through digital fabrication must focus on the functional and structural optimization oriented towards resource efficiency.

Acknowledgements

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