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ENVIRONMENTAL IMPLICATIONS AND OPPORTUNITIES OF DIGITAL FABRICATION

I. Agustí-Juan[1]*, G. Habert[1]

[1] ETH Zürich, Zürich, Switzerland
*Corresponding author; e-mail: agusti@ibi.baug.ethz.ch

Abstract
Society's increasing concern for sustainability aspects is inducing the emergence of digital technologies to overcome the inefficiency and reduce environmental impacts in product manufacturing. As the use of digital processes such as 3D printing grows, innovative applications into large scale processes are emerging. The combined methods of computational design and robotic fabrication are demonstrating a large potential to expand architectural design and transform conventional construction processes. But, the most impressive impact may be their contribution to the improvement of sustainability in construction. The challenge of digital fabrication at building scale is to achieve efficiency in parameters such as material use, energy demands, durability, GHG emissions and waste production over the entire life cycle of a building. The goal of this paper is to investigate the environmental implications and opportunities of digital fabrication in construction. The research focuses specifically on measuring the flow of materials, embodied energy and potential environmental impacts associated with digital fabrication processes. With this objective, the case study of a wooden roof digitally fabricated is presented. The project was assessed according to the Life Cycle Assessment (LCA) framework and compared with a conventional wooden roof with similar function and structural capacity. The analysis highlighted the importance of material-efficient design to achieve high environmental benefits in digitally fabricated architecture. This research is the initial step towards the establishment of a knowledge base and the elaboration of guidelines that help designers to make more sustainable choices in the implementation of digital fabrication in construction.

Keywords:
Digital fabrication; LCA; Sustainability; Environment; Material efficiency

1 INTRODUCTION

The construction sector is the responsible of high environmental impacts, such as high energy consumption, solid waste generation, GHG emissions and resource depletion [1]. Responding to the society requirements, a new type of construction practice is needed to overcome the inefficiency and lack of interoperability and promote sustainable design practices.

The potential to fabricate elements directly from design information has transformed many design and production disciplines [2]. Specifically, 3D printing processes are becoming an integral part of modern product development [3]. As interest in additive manufacturing grows, research is beginning to reveal potential large-scale applications in architecture and construction [4]. But their potential contribution to the improvement of sustainability in construction should be argued. The challenge of architectural scale additive fabrication is more than simply "scale up" 3D printing. The issues of size, material use, energy demands, durability, CO_2 emissions and waste production over the life cycle of a building, must be recognized as the priorities of any architectural project.

The goal of this study is to investigate the impacts and opportunities 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. The methodology of assessment focuses on the LCA comparison of digital fabrication with conventional construction, with specific priority placed on methods of additive fabrication and robotic construction processes at architectural scale. Comparative assessments with conventional construction are performed, with priority placed on new methods of additive fabrication and full-scale robotic construction in architectural processes.

2 METHODOLOGY

The methodology selected for environmental assessment was the Life Cycle Assessment (LCA) framework present in the standards ISO 14040-44: 2006 [5, 6]. LCA method has a well-established use in different sectors and its application is increasing in the construction sector as it represents an appropriate approach for environmental evaluation and optimization of construction processes [7]. The LCA was implemented in the software SimaPro 8 using the Ecoinvent v2.2 database [8] and the method Recipe Midpoint (H) [9]. The selected impact categories considered were climate change (kg CO_2 eq.), ozone depletion (kg CFC-11 eq.), human toxicity (kg 1.4-DB eq.), water depletion (m^3), metal depletion (kg Fe eq.) and fossil depletion (kg oil eq.).

The method was focused on the comparison of digital fabrication with conventional construction with the same function. From the different projects classified, we selected for this study a case study of a building element where digital fabrication enables additional functions embedded in the structure. The integration of these functions adds 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 is needed.

3 CASE STUDY

The project selected for the assessment 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 recycled waste wood [10].

3.1 System boundaries and functional unit

The life cycle of the case study was focused on the production phase in accordance to a cradle-to-gate analysis, from the extraction of raw material up to the construction site. “The Sequential Roof” integrates additional finishing and acoustic functions in its wooden structure, allowing the elimination of additional elements such as hanging ceilings, which typically perform these functions in conventional roofs. Considering these characteristics, the two functional units compared were 1 m^2 of this computationally designed and robotically assembled wooden roof and 1 m^2 of conventional wooden roof structure with hanging ceiling. Both elements shared the same structural capacity (15 meter of span), wooden aesthetics for interior finishing and similar acoustic properties.

3.2 Data collection

The Sequential Roof is composed by 384 m^3 of C24 fir/spruce wood robotically assembled using in total 815,984 nails (Fig. 1). The prefabrication process of the 168 trusses was carried out by a special robot in factory. Due the lack of data from this robot, the impact of the technologies production was calculated considering two robotic arms and a desktop computer [11]. Finally, we included the energy consumed during construction, considering 12 hours/truss.

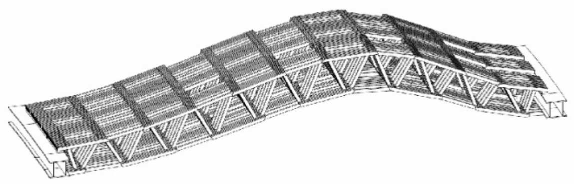

Fig.1: Section of “The Sequential Roof” (Gramazio Kohler Research, ETH Zurich, ETH Zürich).

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 water-proof particle board attached with steel nails. In addition, a hanging ceiling finished the structure and protected acoustically. The ceiling was composed by laminated wood boards, 5 cm of rock wool acoustic insulation and a hanging structure of galvanized steel. Additional roof layers such as waterproofing or thermal insulation were not included in the evaluation, as they were considered equal in both structures.

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3.3 Results

Environmental impact of digital fabrication process

The results from the environmental assessment were broken down into four processes: timber production, steel production, digital technologies production and electricity used for construction. Fig. 2 indicates that more than 95% of environmental impacts associated with the robotically fabricated roof are caused by materials production. Simultaneously, the graph shows that the impact of construction energy is lower 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 [12]. Similarly, the relative impact of the production of digital technologies is less than 2%.

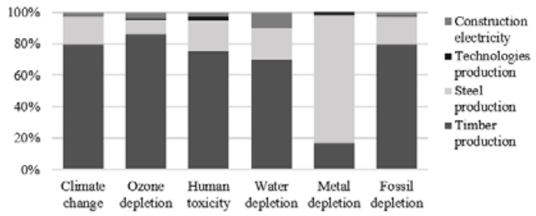

Fig. 2: Relative contributions to the environmental impacts of The Sequential Roof production.

Comparative LCA with conventional construction

Subsequently, we compared the life cycle of the digitally fabricated roof structure with the conventional system. Fig. 3 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.

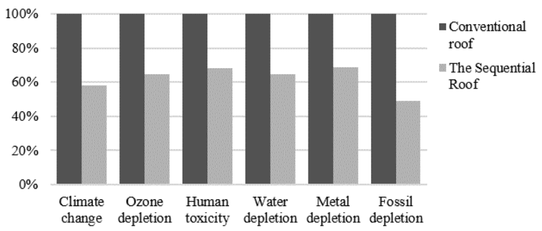

Fig. 3: Comparison of the environmental impacts of The Sequential Roof and the conventional roof structure.

3.4 Sensitivity analysis

In order to evaluate the variability of the results depending on the constructive solution, the projects were compared adapting different hanging ceiling solutions in the conventional roof. Originally the ceiling typology was composed by steel structure, rock wool insulation and laminated wood. We introduced a variation on the materiality and thickness of the last two. For the indoor layer two solutions were assessed: 16 mm laminated wood and 12 mm plywood. And the materiality of the insulation layer varied between rock wool, glass wool and cellulose fibre in 4 different thickness between 40-100 mm. In total 24 additional solutions were considered for the conventional roof and compared with the environmental impact of The Sequential Roof. Fig. 4 shows the results of the sensitivity analysis performed.

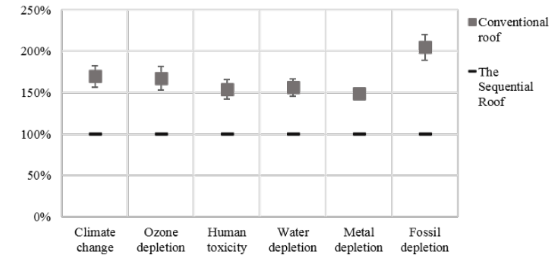

Fig. 4: Comparison of The Sequential Roof and conventional roof. Error bars represent standard deviation of the impacts depending on the hanging ceiling solution considered.

The graph locates most of the impacts of the conventional roof approximately 50% higher than The Sequential Roof. In fossil depletion the impact of the conventional roof duplicates the digitally fabricated roof due to a larger use of resources during materials production. In conclusion, the variability of the impacts depending on the hanging ceiling solution considered had a low influence on the results.

4 DISCUSSION

4.1 Materials production vs construction

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. The project evaluated in this paper is a clear example of the potential benefits that the implementation of computational design and robotic fabrication may bring to the construction sector. The results of the evaluation evidenced that the energy and resource consumption of robotic fabrication processes contributed minimally to the global environmental impact of the project compared to materials manufacturing process.

In the cradle to gate analysis presented in this paper, the environmental impact of the construction phase was reduced to the electricity consumption of the robot during construction. The conventional use of machines, materials and work were excluded from the LCA comparison. As previous studies have proven, the construction phase (including the use of temporary materials and equipment on-site) has a very small contribution to the life-cycle impacts of a building. For example, [13] clearly stated that direct emissions derived from on-site construction were

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relatively small (2.42%) compared to the indirect emissions embedded in the production of building materials (97.58%). Similarly, the results presented in [14], showed that the materials production accounted around a 10% in energy consumption and CO_2 emissions while the construction phase had an environmental impact around 1.5% compared to the overall life-cycle emissions. Moreover, related literature such as [15] and [16] demonstrated that GHG emissions derived from the construction phase were even more reduced in prefabricated processes.

Therefore, the environmental impact of the construction process was assumed negligible compared to the building material production. In consequence, the case studies were simplified assuming that the impacts of construction works were equal and negligible in both architectural elements compared and therefore excluded. We focused on the additional impacts induced by the use of digital fabrication and showed that these additional impacts were also negligible. In a complete LCA comparison of digital fabrication and conventional construction all impacts should be included.

4.2 Integration of additional functions

During the analysis performed in this paper, we observed that in many projects, digital fabrication allows the integration of additional functions in the structure. This integrated performance, such as thermal or acoustic functions, brings an added value to architecture [17]. These innovative digital construction process can contribute to achieve potential material savings, elimination of waste, or reduction of economic and labour costs associated with conventional construction. However, in some architectural projects, additional functions can increase the requirement of material for the primary function, which might be environmentally disadvantageous. For example, in [18] we compared a self-shading brick façade fabricated with digital technologies with a conventional brick façade. In that case study, an important factor in the comparison was the additional % of brick needed for the self-shading effect, which was equivalent to a thin layer of insulation in the conventional system. The results showed that the integration of additional functions in digital fabrication did not provide environmental benefits because the equivalent function in the conventional system had a low environmental impact.

On the contrary, the integration of acoustic and finishing functions in the structure of "The Sequential Roof" brought an important reduction of material and environmental impacts compared to a conventional roof. Even considering different materiality solutions in the conventional roof, the environmental benefits of the digitally fabricated building element were considerable. These benefits were mainly related to 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 environmental impacts of the conventional roof production (Fig. 5).

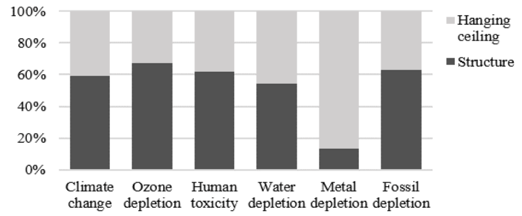

Fig. 5: Relative contributions to environmental impacts of the conventional roof production.

The analysis shows that the hanging ceiling is responsible of approximately 40% of the emissions. Therefore, digital fabrication brought high environmental benefits because the integrated additional functions were equivalent to a conventional element with high environmental impact. Even if the material requirement for the structure of the digitally fabricated product itself might have a higher material requirement as such.

5 CONCLUSION

In this paper we focused on the analysis of a case study that uses digital fabrication as an innovative construction process. A wooden roof was selected and compared to a conventional building element with a similar function. The Sequential Roof demonstrated the advantages of computational design and robotic assembly for a more efficient production of structural elements. The analysis proved that the impacts of digital fabrication were negligible compared to the materials production process. Therefore, any digital fabrication process that can save materials compared to a conventional fabrication process will allow to reduce the environmental impact. Simultaneously, the study highlighted the potential environmental opportunities of integrating additional functions in the structure of digital fabrication elements. However, the integration of multiple function allows great savings only when these functions have a large environmental impact. In conclusion, sustainable design in architecture through digital fabrication must focus on the functional and structural optimization oriented towards resource efficiency.

6 ACKNOWLEDGMENTS

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