Early-design integration of environmental criteria for digital fabrication

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ABSTRACT: The building industry is a traditional sector, with high environmental impacts and low productivity compared to other industries. Current research in digital fabrication is beginning to reveal its potential to improve the sustainability of the sector. However, evaluation methods are needed to quantify the actual reduction of environmental emissions compared to conventional construction. The Life Cycle Assessment (LCA) method is commonly employed for environmental evaluation of buildings. However, research on the integration of LCA in CAD and BIM software are only partially applicable to digital fabrication, because of differences in the design process. This study presents a design-integrated method for simplified LCA with the aim of integrating environmental criteria in the decision-making and optimization of digitally fabricated architecture. Finally, the paper presents the evaluation of the case study "Mesh Mould". The results prove the applicability of the method and highlight the environmental benefits that digital fabrication can provide.

1 INTRODUCTION

The construction sector is responsible for high environmental impacts, such as 40% of the global energy consumption, 38% of greenhouse gas emissions and one third of global resource consumption. Nevertheless, these large impacts represent an opportunity for improvement, and buildings are seen as a key player for carbon mitigation actions (UNEP-SBCI, 2012). Current environmental strategies focus principally on the optimization of energy consumption to lower environmental impacts during the use phase of buildings. Specifically, European regulations such as the European Directive 2010/31/EU (European Parliament and Council, 2010) focus principally on energy efficiency. These normative have successfully reduced the operational primary energy demand of new buildings over the last 40 years (Fig. 1). Nevertheless, according to Passer et al. (2012), operational energy optimization measures have reached the limit. Furthermore, the use of energy efficient materials and building operation technologies has increased the contribution of energy embodied in the construction and disposal of buildings. Figure 1 shows the shift in the ratio of embodied and operational energy demand, reaching nearly 100% of embodied energy in nearly zero-energy buildings (NZEB) buildings. This clearly shows the need for optimizing the embodied energy of buildings during design.

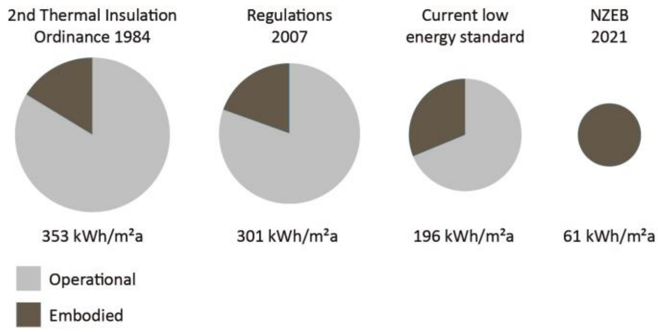


Figure 1. Proportion of operational and embodied energy in the primary energy demand of residential buildings in German energy standards for a reference study period of 50 years (Hollberg & Ruth, 2016).

The Life Cycle Assessment (LCA) framework present in ISO 14040-44 standards (ISO, 2006) has become a widely used decision support tool for the selection of appropriate materials and technical solutions to reduce environmental impacts (Ingrao et al., 2016). Several computer-aided tools based on the LCA framework are available for the environmental evaluation of construction materials and buildings (e.g. SimaPro, Gabi and OpenLCA). However, LCA is not always conducted during the architectural design and in the few cases that is applied is usually for post-design evaluation, for example for sustainable building certification. Some factors that difficult the adoption of LCAs in architectural practice are the complexity of the method or the lack of tools integrated in the design process (Hollberg & Ruth, 2016). To environmentally improve building design, LCA must be applied during early design stages, when decisions have high influence on the project and changes can be realized with minimum additional costs, as shown in Fig. 2.

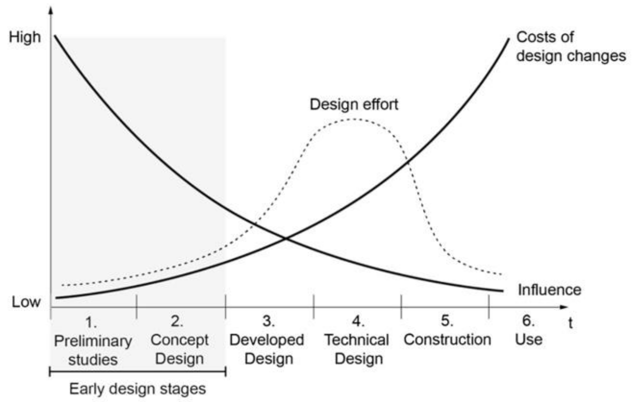


Figure 2. Stages in the architectural design process, based on Paulson Jr (1976).

Consequently, several studies have focused on the development of methods and tools for the environmental assessment of buildings during early design stages (Soust-Verdaguer et al., 2017). The introduction of Building Information Modelling (BIM) in the planning process has increased the demand for BIM-based LCA approaches. Different BIM-integrated tools and methods, such as Tally (Bates et al., 2013), aim to quantify the environmental impacts during design. However, a common problem of these approaches is the representation of results, which are not easy to understand by designers without LCA knowledge. As a response, recent studies such as Röck et al. (2017) propose BIM-integrated methods with visual feedback of the environmental performance directly on the building model. BIM-integrated tools for the environmental assessment of projects are becoming more user-friendly and design-integrated. However, they still have limitations regarding real-time assessment, visualization and optimization of building performance. Moreover, existing tools require very detailed information about the model in order to perform the assessment, which limits their application for quick comparison of design variants in very early design phases.

Simultaneously, the evolution of modern architecture towards complex geometries has promoted the use of parametric design tools. These tools, for example Grasshopper, allow changing the parameters that define the geometry and make instantaneous modifications of the model during design. Parametric design approaches present high formal flexibility and data uncertainty during early design; increasing the difficulty of LCA application. As a response, first design-integrated LCA parametric tools have been developed. For instance, the approach developed by Hollberg & Ruth (2016) or Tortuga, which aim to integrate the environmental assessment in parametric design to support the optimization of the building model. The combination of parametric design and robotic construction processes in digital fabrication provides potential to create innovative architecture. Digitally fabricated architecture is planned, assessed, and optimized during the design phase, and understanding construction as an integral part of design (Gramazio & Kohler, 2008). Consequently, environmental criteria are only relevant for project optimization if they are considered during early stages of design. However, there is a lack of tools to quantify the environmental performance of digitally fabricated architecture. In the field of digital fabrication, architects need simplified approaches to incorporate the knowledge of LCA experts together with formal and technical aspects since early stages of design. The goal of this paper is to present a simplified and visual method integrated in parametric design for environmental assessment of digital fabrication in early stages of design. The method is applied to evaluate the case study of a digitally fabricated wall to confirm its validity.

2 DIGITAL FABRICATION IN ARCHITECTURE

Digital fabrication processes combine computational design, robotic fabrication, material, and constructive processes with an architectural purpose. Construction processes are typically categorized as subtractive, formative and additive (Kolarevic, 2003). Additive fabrication processes consist of material aggregation (assembly, lamination, extrusion, and other forms of 3D printing), usually carried out by an industrial robot to enable large-scale implementation. Recent developments in additive digital fabrication in architecture demonstrate strong potential to construct customized non-standard structures (Gramazio et al., 2014). But most importantly, studies such as Agustí-Juan & Habert (2017) and Agustí-Juan et al. (2017) show the potential of digital technologies and processes to improve the sustainability of the construction sector. The analysis of digitally fabricated architecture showed that the impact of digital processes is negligible compared to materials manufacturing. Therefore, the reduction of material in any project enabled by digital fabrication reduces environmental impacts.

Novel construction processes such as Smart Dynamic Casting (Wangler et al., 2016), Mesh Mould (Hack et al., 2017) or The Sequential Roof (Willmann et al., 2016) demonstrate a big potential to save material and reduce environmental emissions compared to conventional construction. The study of different case studies highlighted the following environmental opportunities allowed by digital fabrication techniques:

– *Complexity*: digital fabrication techniques allow high structural complexity without the need for conventional construction techniques (e.g. formworks) responsible of high environmental costs.

- *Structural optimization*: computational design reduces the amount of highly industrialized material though form-finding optimization, only using material where is structurally needed.
- *Functional hybridization*: complexity can induce additional functionality in the structure (e.g. acoustic or thermal performance), which avoids an additional component to provide this function.
- *Material hybridization*: fabrication processes with hybrid materials (e.g. binder-jet 3D printing) allow material efficiency and improved performance in the structure.

3 METHODOLOGY

3.1 *Environmental evaluation method*

In a conventional design process, the architect begins with the creation of geometric variants of a building model. In contrast, in digital fabrication the final geometry is the result of the design process and interaction with digital technologies. The design process in digital fabrication begins with the definition of functional and structural parameters, without a clear geometry. Therefore, tools for environmental assessment of digital fabrication must be parametric and present results in a visual way to support real-time project optimization.

The methodology presented in this paper focuses on the environmental evaluation of digitally fabricated building elements. The complexity of the design and fabrication process usually implies that building elements are planned individually. Furthermore, during the definition of parameters to perform the evaluation, design characteristics facilitated by digital fabrication techniques such as an increased structural complexity or functional hybridization, are considered. Consequently, the first step of the methodology is the definition of the geometry and information available in each design stage. With this objective, the digital fabrication design process is divided in four design stages. The levels of development (LOD) for conventional building elements from BIM Forum (2016) were considered as a reference. Each design stage is formed by three categories of information about the building element:

- *Geometry*: refers to the building element that is designed. The geometry evolves from a generic surface in design stage 1 to a detailed geometry in design stage 4.
- *Building element*: refers to the information related to the main function of the element. It considers the type of building element, type of material and structural function.
- *Integrated function*: refers to the information related to additional functions integrated in the element, such as acoustic or thermal insulation.

Figure 3 shows the design stages established for digital fabrication and the geometry and parameters defined in each one:

	Data inputs			
Design stages	Construction type	Geometry	Building element	Integrated function
1 Conceptual design	Digital fabrication	Surface (m^2)	Type of building element	Type of integrated function
2 Schematic design	Digital fabrication	Generic volume (m^3)	Type of material	Type of building element
3 Developed design	Digital fabrication	Defined volume (m^3)	Defined material	Defined by geometry
	Conventional construction	Standard building element (m^2)	General thickness depending on structure	Type of material
4 Detailed design	Digital fabrication	Detailed volume (m^3)	Detailed material	Defined by geometry
	Conventional construction	Standard building element (m^2)	Detailed material and thickness	Detailed material and thickness

Figure 3. Definition of design stages in digital fabrication and parameters that define the evaluation method.

The environmental assessment of each design stage is performed through a LCA integrated in the software Grasshopper, a visual scripting interface that allows the manipulation of parametrized geometry and the extraction of data from the 3D model designed in Rhinoceros. Both are common tools used in digital fabrication that allow design flexibility and real-time optimization of the model during design. In design stage 1, when the geometry is not yet defined, the selection of parameters related to the building element´s functionality allows the estimation of a reference value based on the GWP impact of conventional construction. In design stage 2, when a basic geometry is available, the user defines further parameters such as type of material to estimate the environmental impact of the digital fabrication element based on the GWP that a similar conventional element would have. In design stages 3 and 4, when a more accurate geometry is available, the quantities are taken-off automatically to calculate the GWP impact with the specific material selection. The environmental impact of digital fabrication is compared to the impact of conventional construction with the same functionality. This impact is simultaneously calculated through the definition of parameters: building element main function, material, structural capacity, and integrated functions.

The results of the evaluation provide an overview of embodied impacts of digital fabrication and conventional construction expressed in Global Warming Potential (GWP) per m^2 of building element (kg CO_2 eq./m^2). The GWP comparison of both building elements is displayed in percentage of difference between them. In addition, a real-time visualization of the environmental comparison is displayed directly on the 3D model using a color scale from green to red depending on positive or negative performance of digital fabrication. This information can be used as quantitative basis to successively optimize the environmental impact of the building element using the input parameters and the geometry.

3.2 *Environmental data*

For the evaluation, environmental data from the production of materials and building elements are collected from the Swiss databases KBOB (KBOB, 2014) and Bauteilkatalog (Holliger Consult GmbH, 2017). The data collected is organized in three different databases: building materials (kg CO_2/m^3), building elements (kg CO_2/m^2) and integrated functions (kg CO_2/m^2). Each database is divided in different levels of detail to evaluate the four successive design stages. The cradle-to-gate analysis focuses on the production stage of building elements, including data from raw material extraction, transport and building materials production (EN 15978 modules: A1-A3). The impact of the robotic construction is omitted from the analysis due to its low impact compared to materials production as showed in Agustí-Juan & Habert (2017). This simplified LCA method differs from usual environmental analysis of conventional construction elements, which only uses a database of materials (e.g. ecoinvent). In this case, each database allows the evaluation of one characteristic of digital fabrication (functional hybridization, complexity, etc.) and the comparison with conventional construction.

4 CASE STUDY

4.1 *Mesh Mould*

Contemporary architecture has evolved towards the integration of design, structure and materiality to create complex non-standard surfaces (Rippmann et al., 2012). However, non-standard concrete structures require the planning and fabrication of complex and labor-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 based on the combination of formwork and reinforcement into one single element fabricated on-site. This element is a three-dimensional mesh 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. The structure is no longer limited by the formwork and can be geometrically complex and individually adapted to the forces that act on the mesh (Hack et al., 2017).

This case study is selected for the following evaluation to facilitate the identification of functional parameters and comparison with conventional construction as reinforced concrete walls are commonly used in building construction. Figure 4 shows prototypes of the Mesh Mould wall. Specifically, the one chosen for evaluation has approximately 0.12 m thickness and 2.50 m high.

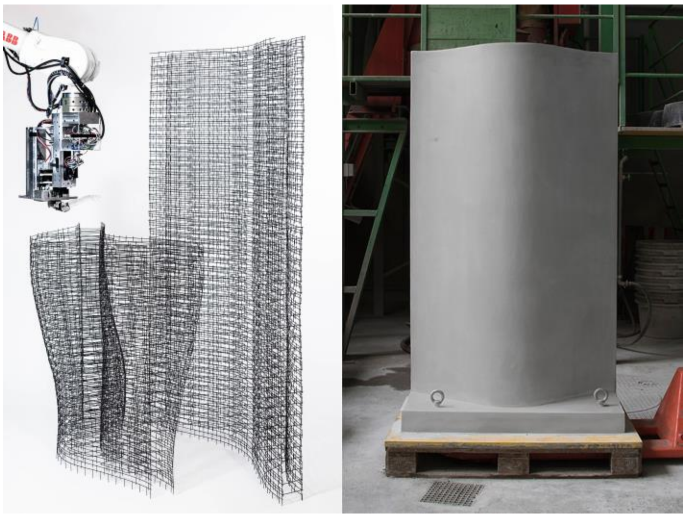
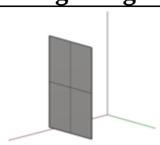
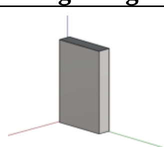


Figure 4. Prototypes of the Mesh Mould wall (Gramazio Kohler Research, ETH Zurich).

4.2 *Evaluation*

A prototype of the Mesh Mould wall developed in the design software Rhinoceros is evaluated to prove the effectiveness of the evaluation method and the usability of the Grasshopper tool. The tool is divided in four sections according to the four different design stages of the project to be evaluated. In design stage 1, the user selects the element function and the integrated function, if available. In this case study, this is an exterior wall with an integrated formwork function, see Table 1. As previously explained, the Mesh Mould method does not require conventional formworks for the construction process. Based on the median of typical conventional exterior wall solutions, the GWP impact is output as result. In design stage 2, the main material of the element is defined, which is concrete in this case. The median of GWP impacts from conventional concrete wall solutions is calculated from the database providing a more accurate result than in the first design stage.

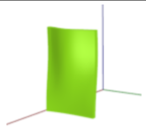
Table 1. Definition of parameters for the evaluation of the case study during design stages 1 and 2.

Data	Parameters	Design stage 1	Design stage 2
Conventional construction	Geometry		
	Building element	Exterior wall	Exterior wall: concrete
	Integrated	Formwork	Formwork: exte-

	function		rior wall

In design stages 3, when a more accurate geometry is available, the tool automatically extracts the geometrical information from the Mesh Mould wall to calculate its GWP impact based on the selection of reinforced concrete as main material. Simultaneously, the impact of the conventional building element is calculated through the definition of the exterior wall functionality, structural capacity and concrete materiality. The procedure in design stage 4 is similar to stage 3, but a complete geometry and material information are available. In this case, the type concrete and steel reinforcement are specified, see Table 2. Finally, the environmental impact of both elements is compared in percentage and visualized on the wall.

Table 2. Definition of parameters for the evaluation of the case study during design stages 3 and 4.

Data	Parameters	Design stage 3	Design stage 4
Digital Fabrication	Geometry		
	Material	Reinforced concrete	High-performance fiber-reinforced concrete, steel
Conv. construction	Building element	Concrete exterior wall: structural (0.20 m)	Concrete exterior wall (0.20 m): 105 kg/m^3 reinforced content
	Integrated function	Formwork exterior wall: double-curved	Double-curved formwork exterior wall: EPS

5 RESULTS

The results of the evaluation for each design stage of the case study are compared in Figure 5. In design stages 1 and 2, since the geometry is not yet defined, the impact of the digitally fabricated wall is estimated based on the median of impacts from conventional construction solutions. This value serves as benchmark or target value for the digitally fabricated element. We observe that the reference value from conventional construction increases from design stage 1 to 4 due to choice of a reinforced concrete wall, which CO_2 emissions are higher than other exterior wall solutions.

The uncertainty on the GWP impact of the Mesh Mould wall and conventional wall is visualized through the whiskers in the graph. In conventional construction, this uncertainty is the result of considering a range of possible conventional wall solutions for the comparison with the digitally fabricated wall. Specifically, the variability is bigger in design stage 1 because all database solutions for exterior wall are considered. It decreases in successive phases due to the definition of parameters, such as type of material, until a single conventional construction is chosen as reference in design stage 4. In digital fabrication, the uncertainty is attributed to the consideration of a range of material choices to calculate the GWP impact of the wall geometry, until the final materials are specified in design stage 4.

The results clearly indicate the environmental benefits of the digitally fabricated element compared to the conventional one. In design stage 3, the uncertainty for both elements is still high, which results in the assumption that digital fabrication performs better and causes 65% less GWP. The definition of all parameters in design stage 4 allows the calculation of the final result, in which 46% of GWP can be saved through digital fabrication.

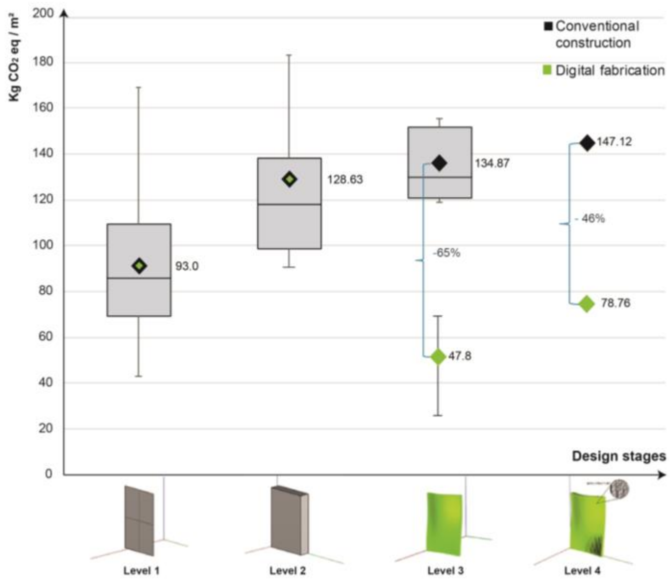


Figure 5. GWP results of each design stage of the Mesh Mould wall compared with conventional wall.

In order to validate the previous results, we can compare design stage 4 with the results presented in Agustí-Juan et al. (2017) for the same case study. This publication carried out a conventional LCA (i.e. using SimaPro software and ecoinvent data) to compare the Mesh Mould system with conventional construction. Similarly to Figure 5, the results showed an impact of 83 kg CO_2 eq./m^2 for a Mesh Mould wall with 12 cm thickness and 165 kg CO_2 eq./m^2 for a conventional wall, both with high complexity. Given the simplification of our method, which only includes material production, we can consider it valid for quick evaluation during design.

6 CONCLUSION & OUTLOOK

Digital fabrication will gain more and more importance for the design and construction of building elements. In contrast to the conventional design process, digital fabrication begins with the definition of material, functional, structural, etc. parameters and fabrication constraints, which optimization defines the final geometry. Therefore, design-integrated analysis methods need to be adapted. This paper presents a simplified LCA method to assess the environmental impact at different stages throughout the design process. The method is adapted to the level of information available and the detail of the geometry. By defining materiality and functionality, the digitally fabricated building element can be compared to a conventional one. In design stages 1 and 2, the method provides a target value for the designer, while in design stages 3 and 4 a direct quantitative comparison is provided. As such, it grants continuous feedback for the designer and provides a basis for decision-making. By incorporating a simplified LCA into the design process, the effort for designers is considerably reduced compared to a conventional LCA. Moreover, the method allows the estimation of environmental impacts in initial digital fabrication stages, which are typically not assessed because the final geometry is not available or the project data is uncertain.

The case study proves the applicability of the evaluation method. The Mesh Mould wall is characterized by the hybridization of a formwork function in the structure, which avoids the need for a conventional formwork. This environmental opportunity enabled by the digital fabrication process is reflected in the results of the evaluation. However, the method could provide more benefits when assessing other type of projects, such as digitally fabricated elements with high complexity derived from the structural optimization. Therefore, further comparative case studies should be carried out in the future to further validate the proposed method. Moreover, the method and databases should be extended to integrate further performance analysis, such as operational energy or end-of-life impacts. Finally, the tool could be adapted to evaluate the environmental impact of a complete building and give the possibility to choose the environmental indicator displayed.

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