Integration of environmental criteria in early stages of digital fabrication

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Abstract

The construction sector is responsible for a big share of the global energy and resource demand and greenhouse gas emissions. As such, buildings and their designers are key players for carbon mitigation actions. Current research in digital fabrication is beginning to reveal its potential to improve the sustainability of the building sector. However, quantitative assessments are needed to quantify the actual reduction of environmental emissions compared to conventional construction. To evaluate the environmental performance of buildings, life cycle assessment (LCA) is commonly employed. Recent research developments have successfully linked LCA to CAD and BIM tools for a faster evaluation of environmental impacts. However, these are only partially applicable to digital fabrication, because of differences in the design process. In contrast to conventional design, in digital fabrication the geometry is the consequence of the definition of functional and structural parameters during design and interaction with digital technologies. Therefore, this paper presents an LCA-based method for design-integrated environmental assessment of digitally fabricated building elements. The novel method is divided into four levels of detail following the degree of available information during the design process. The objective of the method is to integrate environmental criteria in the decision-making and optimization of digitally fabricated architecture. Finally, the method is applied to the case study "Mesh Mould", a digitally fabricated complex concrete wall that does not require any formwork. The results prove the applicability of the method and highlight the environmental benefits digital fabrication can provide.

1. Introduction

The construction sector is responsible for a significant amount of environmental impacts, such as 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, 2012). The evaluation of sustainability aspects in the construction sector is generally based on the optimization of the energy demand in buildings over their life cycle, which is divided in embodied (production, construction and end-of-life) and operational energy (use phase). As Passer et al. (2012) pointed out, European energy regulations focus principally on the optimization of the energy performance in buildings during operation. Consequently, the use of energy efficient materials and building operation technologies has increased the contribution of embodied energy in 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. Specifically, the Life cycle assessment (LCA) framework (ISO 14040:2006) 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).

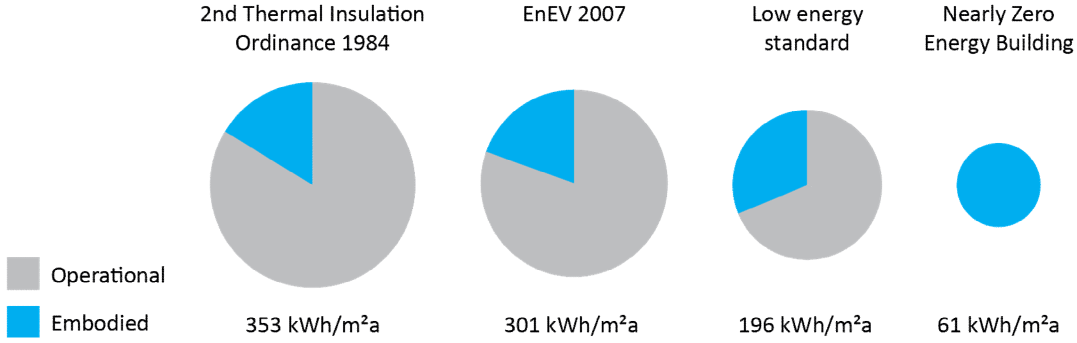


Figure 1: The proportion of operational and embodied energy in the primary energy demand of residential buildings in different German energy standards for a reference study period of 50 years (based on Hegger et al. 2012, p.2)

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). Currently, LCA is not integrated into the design process but typically used as post-design evaluation, for example for building certification schemes. To environmentally improve building designs, 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 (see figure 2).

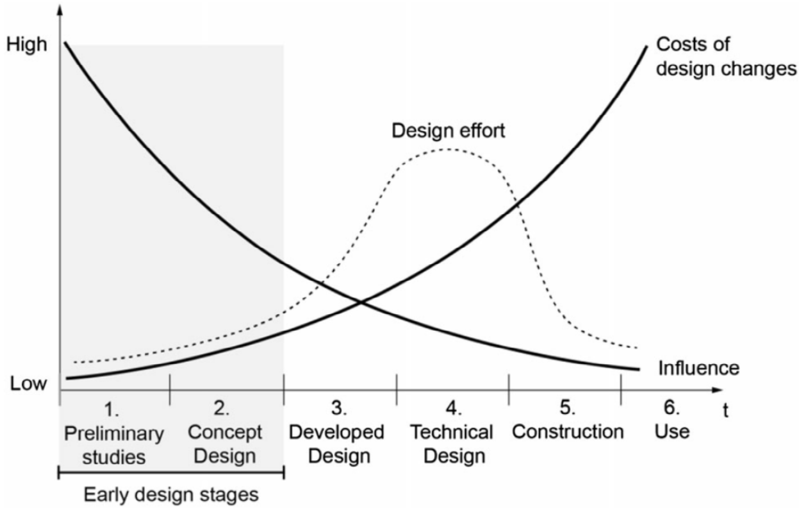


Figure 2. Stages in the architectural design process (Paulson Jr, 1976).

Several recent studies focus 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, a recent BIM-integrated method proposes a visual feedback of the environmental performance directly on the building model (Röck et al., 2016). 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. Due to the complexity of the models, application of BIM is limited for quick comparison of design variants in very early design phases. Furthermore, the evolution of modern architecture towards complex forms and shapes 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; consequently, they require alternative LCA approaches. First design-integrated LCA parametric tools, have been developed by Hollberg and Ruth (2016) or Tortuga, which aims to improve the visualization of results through a simple Global Warming Potential (GWP) overview of the building model.

The combination of parametric design and robotic construction processes in digital fabrication provides potential to create innovative architecture. In digital fabrication, architecture is planned, assessed, and optimized during the design phase, and understanding construction as an integral part of design (Gramazio and Kohler, 2008). Consequently, environmental criteria must be integrated during early design stages. However, there is a lack of tools to quantify the environmental performance of digitally fabricated architecture. The goal of this paper is to present a simplified method integrated in a parametric design tool (Grasshopper) for environmental assessment of digital fabrication in early stages of design. Finally, the method is applied to a case study of a digitally fabricated project to evaluate it.

2. Digital fabrication in architecture

Digital fabrication processes at the architectural scale are generally based on computational design methods and robotic construction processes, which are typically categorized as subtractive or additive fabrication. 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 digital fabrication in architecture demonstrate strong potential to construct customized complex structures (Gramazio et al., 2014). But most importantly, recent studies such as Agustí-Juan and Habert (2017) and Agustí-Juan et al. (2017) demonstrate the potential of digital technologies and processes to improve the sustainability of the construction sector. Projects such as Smart Dynamic Casting (Wangler et al., 2016), Mesh Mould (Hack et al., 2017) or The Sequential Roof (Willmann et al., 2016) save material compared to conventional construction through the use of innovative construction processes. One of the main conclusions drawn from the analysis of digitally fabricated architecture was that the impact of digital processes is negligible compared to the material manufacturing process. This means that any project saving material compared to a conventional construction will allow for reduction of environmental impacts. Furthermore, the study of different case studies highlighted the following environmental opportunities allowed by digital fabrication techniques:

- **Functional hybridization:** integration of additional functions in the main structural element, which potentially reduces the overall environmental impact. For example, the integration of acoustic or thermal performance.
- **Material hybridization:** production of structures with material efficiency and improved performance through using composite and hybrid materials (e.g. binder-jet 3D printing).
- **Structural optimization:** reduction of highly industrialized materials (high environmental impact) through computational structural optimization to only use material where it is structurally needed.
- **Complexity:** environmental benefits increase proportionally to the level of complexity of the structure due to the avoidance of additional environmental costs attributed to conventional construction techniques (e.g. formworks).

3. Method

Tools for environmental assessment of digital fabrication must be parametric and present results in a visual and simple way to support designers during real-time project optimization. Specifically, the evaluation method must consider characteristic aspects of digitally fabricated architecture, such as an increased structural complexity, the integration of additional functions in the structure and the optimization of material use, facilitated by digital fabrication techniques (Agustí-Juan and Habert, 2017). The complexity of the design and fabrication process usually implies that digitally fabricated elements are planned individually. Therefore, the method focuses on the environmental evaluation of a single building element, considering the geometry and parameters attributed to digital fabrication, such as complexity and functional hybridization.

In a conventional design process, the architect begins with the creation of geometric variants of a building model. In contrast, in digital fabrication the geometry is a 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. Consequently, the first step for the elaboration of the methodology is the definition of four design stages following the digital fabrication design process. The levels of development (LOD) for conventional building elements from BIM Forum (2016) are considered as a reference. Each design stage is formed by four categories of information about the model:

- **Geometry:** refers to the building element that is designed. The geometry evolves from a generic surface in level 1 to a detailed geometry in level 4.

- **Element function:** 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.
- **Additional function:** refers to the information related to additional functions integrated in the element, such as acoustic or thermal insulation.
- **Complexity:** refers to the information related to the shape of the element and conventional construction elements such as formworks.

Table 1 shows the design levels established for digital fabrication and the geometry and parameters defined in each level:

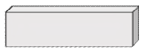
Level definitions			Grasshopper inputs				
Level	**Design stage**	**Specification**	**Data source**	**Geometry**	**Element function**	**Complexity**	**Functional hybridization**
1	Conceptual design	The model is presented with a generic surface. The information related to the model are generic type of building function and additional function. Data from conventional construction are used for the definition of parameters that allow to obtain a benchmark of the environmental impact of digital fabrication.	Conventional construction	 Surface (m2)	Type of building element	Defined by geometry	Type of additional function
2	Schematic design	The model is represented with a generic volume with approximate size. The information related to the model are generic type of material and additional function. Data from conventional construction are used for the definition of parameters that allow to obtain a benchmark of the environmental impact of digital fabrication.	Conventional construction	 Approximate volume (m3)	Type of material from building element	Defined by geometry	Type of building element with additional function
3	Developed design	The model presents a defined geometry with known thickness. The information of type of material and functions is defined. The complexity is defined by the geometry and formwork. In this level, the impact of digital fabrication and conventional construction are compared for a possible optimization of the model.	Digital fabrication	 Defined volume (m3)	Type of material	Defined by geometry	Defined by geometry
			Conventional construction	Standard building element (m2)	Generic thickness of building element according to structural capacity	Generic complexity of formwork solution	Type of material from additional function
4	Detailed design	The model presents a detailed geometry with detailed final dimensions. The information related to materials and functions are detailed. The complexity is defined accurately by the geometry and formwork. In this level, the impact of digital fabrication and conventional construction are compared for a possible optimization of the model.	Digital fabrication	 Detailed volume (m3)	Specific material	Defined by geometry	Defined by geometry
			Conventional construction	Standard building element (m2)	Specific building element with defined material and thickness	Specific formwork solution with defined complexity and material	Specific additional function with defined material and thickness

Table 1. Definition of design stages in digital fabrication and parameters that define the evaluation method.

The environmental assessment of each design stage is performed through applying LCA. The evaluation provides an overview of embodied impacts expressed in Global Warming Potential (GWP) per 1 m^2 of building element (kg CO_2 eq/m^2). For the evaluation, environmental data from Swiss production of materials and building elements are collected from KBOB and Bauteilkatalog and organized in three different databases: building materials, building elements and additional functions/complexity. 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 and Habert (2017). Each database is divided in different levels of detail to evaluate the four successive design stages. This simplified LCA method differs from usual environmental analysis of traditional construction elements, which only use 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.

The evaluation is performed according to the information available in each design stage. In level 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 environmental impact of conventional construction. In the second design level, when a basic geometry is available, the user defines further parameters such as type of material to estimate the GWP impact of the digital fabrication element based on the GWP that a conventional element would have. In levels 3 and 4, when a more accurate geometry is available, the quantities are taken-off automatically to calculate the GWP impacts with the specific material selection. The impact of digital fabrication is compared to the environmental impact of conventional construction with the same functionality. This impact is simultaneously calculated through the definition of parameters: element function, structural capacity, type of material, hybridized functions and complexity.

4. Case study

One case study of a building element is evaluated to prove the effectiveness of the method and the usability of the tool.

4.1. Mesh Mould

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 concrete structures require 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 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., 2015). 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 3 shows one of the recent prototypes of the Mesh Mould project.

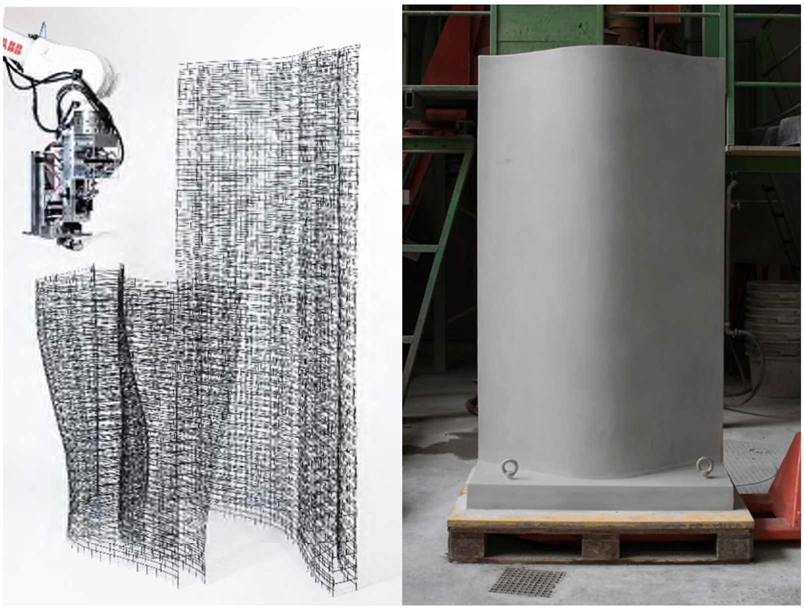


Figure 3. Prototypes of the Mesh Mould structure (Gramazio Kohler Research, ETH Zurich).

4.2. Evaluation tool

To apply the developed method it is integrated in the design process using 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 level one, the user selects the element function and the additional function, if available. Here, this is an exterior wall with no additional function, see Table 2. Based on the median of typical conventional exterior wall solutions, the GWP is output as result. In level two, the main material of the element is defined, which is concrete in this case. The median of the conventional concrete wall solutions is calculated from the database providing a more accurate result than in level 2.

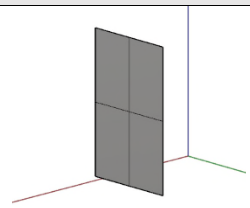
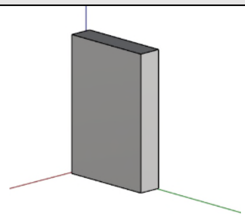
Data	Parameters	Level 1	Level 2
Conventional construction	**Geometry**		
	Element function	exterior wall	exterior wall: concrete
	Functional hybridization	no additional function	no additional function

Table 2. Definition of parameters defined for the evaluation of design levels 1 and 2 from the case study.

In levels 3 and 4, when a more accurate geometry is available, the tool automatically extracts the geometrical information from Rhinoceros to calculate the GWP impacts with the specific material selection. The impact of digital fabrication is compared to the environmental impact of conventional construction with the same functionality. This impact is simultaneously calculated through the definition of parameters: element function, structural capacity, type of material, hybridized functions and complexity. Furthermore, the tool displays a real-time visualization of the environmental comparison directly on the 3D model using a color scale from green to red depending on positive or negative performance of digital fabrication, see Table 3. 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.

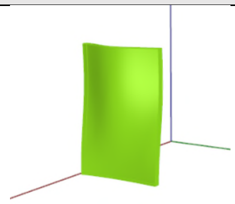
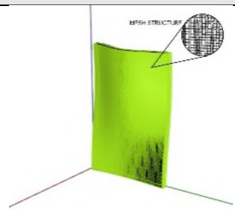
Data	Parameters	Level 3	Level 4
Digital Fabrication	**Geometry**		
	Material type	reinforced concrete	high performance fibre reinforced concrete
Conventional construction	**Element function**	structural concrete wall (0.20 m)	concrete wall (0.20 m), reinforcement content: 105 kg/m^3
	Functional hybridization	no additional function	no additional function
	Complexity	double-curved formwork	double-curved EPS formwork

Table 3. Definition of parameters defined for the evaluation of design levels 3 and 4 from the case study.

5. Results

The results for the individual design levels are shown in figure 4. Since the geometry is not yet defined in level 1 and 2, only the results for the conventional construction are displayed. These serve as benchmarks or target values for the digitally fabricated element. The range of the possible results is visualized through the whiskers in the graph. The variability is greatest in level 1 because all database solutions for exterior wall are considered. The uncertainty decreases in successive levels due to the definition of parameters, such as type of material, until a single conventional construction is chosen as reference in level 4. We observe that the reference value from conventional construction increases from level 1 to level 4 due to choice of a reinforced concrete wall, which CO2 emissions are higher than other exterior wall solutions. Finally, the results clearly indicate the environmental benefits of the digitally fabricated element compared to the conventional one. In level 4, the digital fabrication performs better and causes 46% less GWP. In level 3, the uncertainty for both elements is still high, which results in the assumption that 65% of GWP can be saved through digital fabrication.

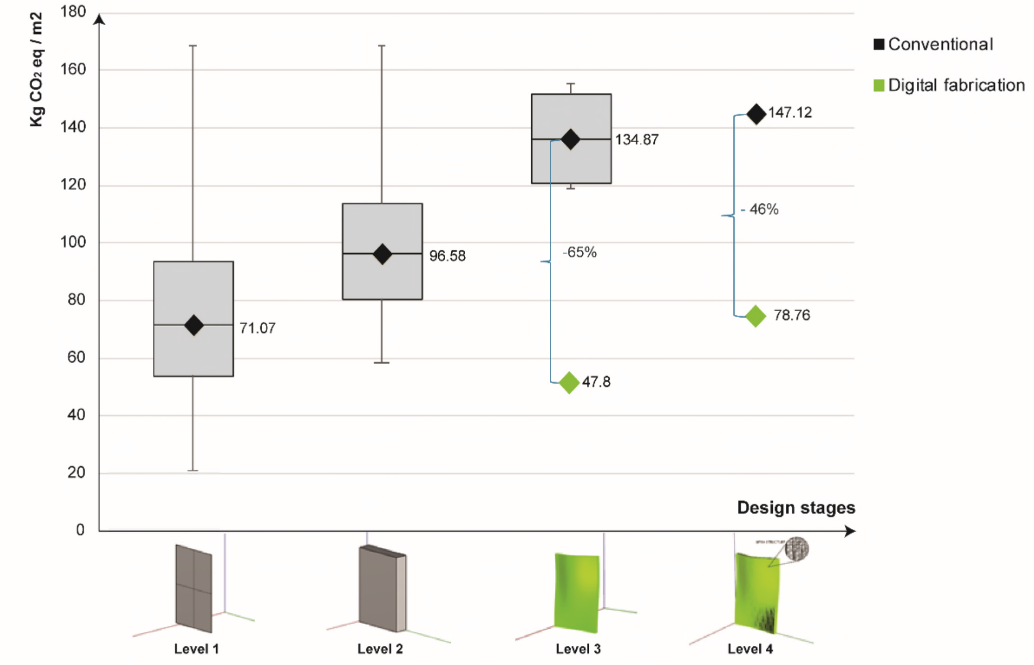


Figure 4. GWP results of each design stage of digital fabrication.

6. Conclusion & outlook

Digital fabrication will gain more and more importance for the manufacturing of building elements. In contrast to the conventional design process, digital fabrication begins with the definition of functional and structural parameters, without a clear geometry. The geometry is a consequence of the interaction with digital technologies. Therefore, design-integrated analysis methods have to be adapted. This paper presents a method to assess the environmental impact through simplified LCA at different levels throughout the design process. The method adapts to the level of information available and the detail of the geometry. By defining element function and additional functions, the digitally fabricated project can be compared to a conventional one. In level 1 and 2, the method provides a target value for the designer, while in level 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. The case study proved the applicability. 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 that are typically not assessed because the final geometry is not available or the project data is uncertain.

The case study presented here focuses on the aspect of complexity. The results indicate the environmental benefits that digital fabrication can provide. However, the method could provide more benefits when assessing functional hybridization such as an acoustic performance through the complex surface of a digitally fabricated element. Therefore, further case studies should be carried out in the future to further validate the proposed method. In addition, the method could be extended through integrating further performance analysis, such as the analysis of operational energy or the possibility to choose the environmental indicator to be displayed.

7. Acknowledgements

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8. References

Agustí-Juan, I., Habert, G., 2017. Environmental design guidelines for digital fabrication. Journal of Cleaner Production 142, 2780-2791.
Agustí-Juan, I., Müller, F., Hack, N., Wangler, T., Habert, G., 2017. Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall. Journal of Cleaner Production 154, 330-340.
Bates, R., Carlisle, S., Faircloth, B., Welch, R., 2013. Quantifying the Embodied Environmental Impact of Building Materials During Design: A Building Information Modeling Based Methodology. PLEA. Munich, 1-6.
BIM Forum, 2016. Level of Development Specification.
Gramazio, F., Kohler, M., 2008. Digital materiality in architecture. Lars Müller Publishers, Baden, Switzerland.
Gramazio, F., Kohler, M., Langenberg, S., 2014. FABRICATE: Negotiating Design & Making. gta Verlag, Zurich, Switzerland.
Hack, N., Lauer, W., Gramazio, F., Kohler, M., 2015. Mesh Mould: robotically fabricated metal meshes as concrete formwork and reinforcement. Ferro 11, 347-359.
Hack, N., Wangler, T., Mata-Falcón, J., Dörfler, K., Kumard, N., Walzer, A.N., Grasere, K., Reiterb, L., Richnerb, H., Buchlid, J., Kaufmann, W., Flattb, R.J., Gramazio, F., Kohler, M., 2017. Mesh mould: An on site, robotically fabricated, functional formwork, Conference: High Performance concrete and Concrete Innovation Conference, At Tromsø, Norway.
Hollberg, A., Ruth, J., 2016. LCA in architectural design—a parametric approach. The International Journal of Life Cycle Assessment 21, 943-960.
Ingrao, C., Scrucca, F., Tricase, C., Asdrubali, F., 2016. A comparative Life Cycle Assessment of external wall-compositions for cleaner construction solutions in buildings. Journal of Cleaner Production 124, 283-298.
Passer, A., Kreiner, H., Maydl, P., 2012. Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings. The International Journal of Life Cycle Assessment 17, 1116-1130.
Paulson Jr, B.C., 1976. Designing to reduce construction costs. Journal of the construction division 102, 587 - 592.
Rippmann, M., Lachauer, L., Block, P., 2012. Interactive vault design. International Journal of Space Structures 27, 219-230.
Röck, M., Habert, G., Passer, A., 2016. Quantification and visualisation of embodied impacts using Building Information Modelling (BIM), World Sustainable Built Environment Conference 2017, Hong Kong.
Soust-Verdaguer, B., Llatas, C., García-Martínez, A., 2017. Critical review of bim-based LCA method to buildings. Energy and Buildings 136, 110-120.
UNEP, 2012. Building Design and Construction: Forging Resource Efficiency and Sustainable Development, Geneva, Switzerland.
Wangler, T., Lloret, E., Reiter, L., Hack, N., Gramazio, F., Kohler, M., Bernhard, M., Dillenburger, B., Buchli, J., Roussel, N., 2016. Digital Concrete: Opportunities and Challenges. RILEM Technical Letters 1, 67-75.
Willmann, J., Knauss, M., Bonwetsch, T., Apolinarska, A.A., Gramazio, F., Kohler, M., 2016. Robotic timber construction—Expanding additive fabrication to new dimensions. Automation in Construction 61, 16-23.