Environmental assessment of Digital Fabrication: contribution of IT design to the overall life cycle impacts

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Abstract
Digital fabrication represents an innovative technology with the potential of expanding the boundaries of architectural design and construction. The control of the manufacturing process through computational design is transforming design disciplines. Initial studies based on 3D printing have associated digital technologies to a significant reduction of resources, energy and emissions. However, there have been no quantitative comparison between digital fabrication and traditional construction processes at architectural scale. This study researches the environmental implications of the development of digital fabrication on the improvement of sustainability in construction.
Questions related to digital fabrication are identified with the Life Cycle Assessment (LCA) framework present in ISO 14040-44 standards. The environmental approach undertakes the classification of architecture in four categories where digital fabrication enables improvements over traditional construction. In each category, life cycle assessments are applied with the aim of studying which processes produce larger impacts on the environmental profile of digital fabrication.
Finally, the impact assessment approach is applied to a case study of architecture digitally fabricated with additional functions. The life cycle of a self-shading brick façade is compared to conventional construction with specific focus on embodied energy of materials and technologies, processing, and operational energy. The results of the assessment will be used as environmental guidelines providing support to designers in the process of optimization of digital fabrication in architecture and construction.

Keywords: Digital Fabrication, Life Cycle Assessment, Environmental impact, Construction, Sustainability

1 Introduction

Since the invention of the computer, the influence of the digital culture in architecture has grown during the years. The term "Digital Architecture" can be defined as the production of architecture using the computer in an experimental perspective. However, since the second half of the 20th century, the increasing use of computer-aided design (CAD) software in architecture have created confusion in what digital architecture is about (Picon 2010). Nowadays, digital tools go further than the generation of 2D or 3D drawings. New integrated models such as Building Information Modelling (BIM) are based on virtual 3D models that contain all the relevant information of the project, allowing the assessment of the building during design and supporting the construction process (Czmoch and Pękala 2014). Digital fabrication goes one step further, combining design and production through the use of 3D modelling software and construction processes. The potential to make things directly from design information is transforming the design disciplines, as it allows the designer to control the entire manufacturing process from concept to the final product (Dunn 2012).

Gershenfeld (2012) defines "Digital Fabrication" as the processes that use the computer-controlled tools that are descendants of MIT's first numerically controlled mill. However, digital fabrication is more than additive manufacturing or 3D printing. The use of computer numerically controlled (CNC) machines in architecture allows mass-production of customized elements and often complex prefabricated pieces, which can be developed on-site. It becomes an innovative tool to assess and modify the architecture since the design phase and it influences completely the final construction. Digitally fabricated architecture incorporates the knowledge of its production already from his moment of conception, understanding construction as an integral part of architectural design (Gramazio and Kohler 2008). The evolution of digital technologies is inseparable from the transformation of the conventional building techniques, digital fabrication has the potential to expand the boundaries of design and construction and become relevant at a full architectural scale.

A revision of literature related to the field has revealed that in the few publications to date, the research is mainly focused on formal, structural and advances in digital technologies. For example, in Lloret et al. (2014) a new digital construction method is presented for the development of complex concrete structures. Only a few studies such as Gebler et al. (2014) or Faludi et al. (2015) focus on the assessment of digital technologies like 3D printing from a sustainable perspective. Therefore, research into sustainability of digital fabrication at architectural scale needs to be performed now that it is still an experimental technology, so adjustments can be made at an early stage.

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 impact of material processes and the embodied energy associated to this innovative construction, for a full life-cycle assessment. Therefore, a comparative of digital fabrication with conventional construction is performed to globally assess the environmental impacts of digital technologies and processes. The results of the assessment will be employed in a potential optimization and sustainable development of digital fabrication architecture from the design phase.

2 Methodology for Environmental Assessment

The evaluation of the environmental profile of digital fabrication requires a comprehensive understanding of the technologies and process involved for the elaboration of consistent methodology for assessment. The inexistence of such framework that could be specifically applied to digital fabrication, makes necessary the development of a new approach. The assessment method developed in this research is built upon the Life Cycle Assessment (LCA) framework for environmental and cost assessment established in the standards ISO 14040-44: 2006 (ISO 2006), published literature in related fields (Faludi et al. 2015) and through interdisciplinary collaboration with the NCCR Digital Fabrication (ETH Zürich).

The results of a preliminary assessment have been used to identify and classify four main categories of intervention that can significantly facilitate the environmental assessment. In each case computational design and robotic fabrication enable improvements over traditional construction by facilitating:

- Additional functions
- Efficiencies in construction processes
- Reduction of material
- Alternative materials

In the first category, digital fabrication makes possible additional functions such as thermal or energy performance that confer an added value to architecture. However, exists an evident arduousness on the environmental evaluation due to the difficulty on the performance of a LCA comparative with conventional construction. As a result, this paper describes the application of the methodology for environmental assessment to an example of digital architecture with additional functions. The life cycle of the project is compared with conventional construction with similar structural performance in order to evaluate the impacts during operation. And subsequently, the digitally fabricated element is compared with a second conventional construction with similar structural and thermal performance with the aim of studying which processes produce larger impacts during production.

3 Case Study

The digital fabrication case study selected for the environmental assessment is a self-shading brick wall modelled by computational design and constructed by an in-situ robotic arm. The research in geometry and performance innovation in ceramic building systems through design robotics performed by S. Andreani and M. Bechthold from the Design Robotics Group from Harvard University has been taken as a reference. The study researches mass-customization of brick forms, digitally designed ruled-surface brick units are robotically cut and positioned. In order to improve the energy efficiency and design of conventional brick façade systems, custom brick shapes optimize bricks configuration, creating shadows on the wall surface that contribute to an additional thermal function and development of new sustainable design opportunities (Gramazio et al. 2014).

3.1 System boundaries

The system boundaries cover the life cycle of the case study in accordance to a cradle-to-grave analysis, including raw material extraction; digital tools and construction materials production; cutting of the bricks; construction and operation of the brick façade. Transport of materials and machines to the construction site, tool replacement parts and maintenance are not considered, as well as, the end of life stage. The goal of the present LCA is the characterization of the flow of materials, embodied energy of digital tools, energy consumption during construction and operation of digital fabrication processes. Evaluating the potential environmental impacts associated with those inputs and outputs and compile them with the intention of building a knowledge base of digital fabrication.

3.2 Functional unit

The functional unit of the case study is 1 m^2 brick façade. Three systems have been compared: 1 m^2 of self-shading brick wall constructed with digital fabrication techniques with two conventional systems with a similar brick masonry aesthetic, one of them with the same structural performance and the other with the same structural and thermal functions achieved with the addition of insulation. The main objective of the functional unit is to provide a reference to relate the inputs and outputs considered during the life cycle inventory and be able to compare different LCA results (ISO 2006).

For the functional unit definition, physical properties as well as the aesthetics of the wall systems have been taken in consideration. It has been discussed in other publications how the integration of traditional values such as aesthetics together with environmental properties can lead to significant environmental improvements (Nielsen and Wenzel 2002). The self-shading novel brick façade shows the advantages of combining aesthetics to improve the energy efficiency. Computationally designed brick shapes create dynamic façades, whose geometric and material characteristics are strategically calibrated to maximize the energy benefits of solar radiation (Gramazio et al. 2014).

3.3 Data selection

A detailed literature review and collaboration in the NCCR Digital Fabrication (ETH Zürich) has been performed to study the processes involved in digital fabrication and to select the relevant data for the elaboration of the Life Cycle Inventory (LCI) of the present case study. The inputs and outputs of the three systems have been extracted mainly from digital fabrication case studies and environmental data related to digital fabrication (Faludi et al. 2015).

Primary data concerning to the amount of construction materials, digital fabrication technologies manufacturing and energy consumption related to the construction of the walls has been identified. Where the data was not complete, more generic information obtained from the Ecoinvent v2.2 database (Hischier et al. 2010) has been included. The three brick wall systems have been modelled in SimaPro 7.3.3 software package, taking the Ecoinvent database as a reference to configure the data inventory of materials and energy.

3.3.1 Construction materials

Data from the material composition of the three systems has been collected in the life cycle inventory. The basic composition of the conventional wall are plain clay bricks with 5x11x14 cm dimensions assembled leaving 1 cm of cement mortar joints. In total, 111 bricks with a density of 2300 kg/m^3 have been included in the functional unit, obtaining a total mass of 197 kg of brick per m^2 of wall. The remaining volume is assigned to the cement mortar, obtaining the corresponding mass of 53 kg with a density of 2162 kg/m^3.

In the functional unit of digitally fabricated wall, the amount of brick is 10% superior for the creation of the self-shading effect and to conserve the same structural performance as the first conventional brick wall. The second conventional brick wall system requires additional insulation to archive the same structural and thermal performance as the digital fabrication façade (see Figure 1). The calculation of the insulation thickness shows that approximately 1.5 cm of EPS is required to achieve the same thermal performance during the use phase.

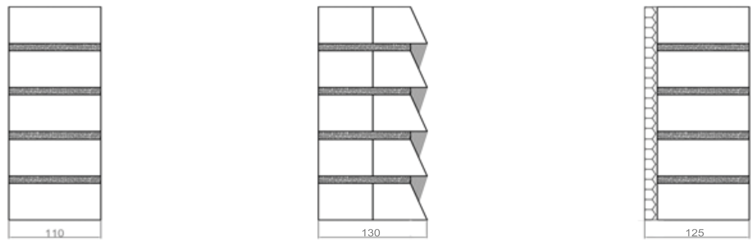

Figure 1 Conventional brick, self-shading brick and conventional brick with insulation wall sections.

3.3.2 Digital fabrication technologies

The life cycle inventory of the self-shading system includes the embodied energy of the digital fabrication tools production. The production data of the construction robot has been obtained from the prototype "In-Situ Fabricator" in collaboration with the NCCR- Digital Fabrication research group from the ETH Zürich. The impacts of the robot production process are studied via the mass of the composition materials. The resources presented in Table 1 are expressed in kg per unit of robot. Due to the uncertainty about the service life of the construction robot, the data of 10 years is based on the service life of a mini-excavator used for construction.

Table 1 Material composition of the construction robot (kg)

Flow	Category	Unit	Amount
Steel, low-alloyed, at plant	material	kg	570.621
Steel, electric, un- and low-alloyed, at plant	material	kg	120.607
Cast iron, at plant	material	kg	119.576
Copper, primary, at refinery	material	kg	35.55
Aluminum, production mix, at plant	material	kg	37.707
Alkyd paint, white, 60% in H_2O, at plant	material	kg	1.65
Epoxy resin, liquid, at plant	material	kg	4.357
Polyvinylchloride, suspension polymerized, at plant	material	kg	16.418
Polyurethane, flexible foam, at plant	material	kg	0.309
Tin, at regional storage	material	kg	0.141
Lead, primary, at plant	material	kg	0.081
Nickel, 99,5%, at plant	material	kg	0.056
Silver, at regional storage	material	kg	0.004
Gold, primary, at refinery	material	kg	0.001
Synthetic rubber, at plant	material	kg	40
Lubricating oil	material	kg	40
Battery, LiIo, rechargeable, prismatic, at plant	material	kg	50

For the data inventory of the laptop computer required for sending instructions to the robot, the process of a laptop computer production from the Ecoinvent database (Weidema B. P. 2013) has been included. Additionally, the production of mass-customized bricks requires a saw tool that attached to the robot cuts the bricks in the desired shape. For the production process of the diamond wire cutting tool, data from the composition of a 500 mm saw collected in literature has been taken as a reference (Ioannidou et al. 2014).

3.3.3 Construction energy

The self-shading system construction process includes electricity consumption during the operation of digital fabrication technologies. Data of US electricity from Ecoinvent database has been included in the LCI. The power supply of the robot are two Li-on rechargeable batteries with a capacity of 5.12 kWh. The operation energy of the robot and the energy consumption of a laptop computer (Deng et al. 2011) during the construction of the functional unit produces the total electricity consumption. The construction time is the sum of the cutting and the assembling time and it has been calculated in base of 2 seconds of cutting and 30 seconds of assembling per brick. Additionally, a time of 2 minutes is added every 50 bricks for the robot positioning.

The construction of the conventional wall systems involves manual labor. However, energy requirements and emissions related to human life typically are not included in environmental analysis (Zhang and Dornfeld 2007). In Table 2 the processes included in the Life Cycle Inventory (LCI) of the digitally fabricated system production are presented:

Table 2 Life Cycle Inventory of self-shading wall construction process (1 m^2)

Flow	Unit	Amount
Construction robot	p	2.26E-5
Laptop computer, at plant	p	7.54E-5
Diamond cutting tool	p	1.40E-6
Brick, at plant	kg	216.456
Cement mortar, at plant	kg	52.849
Electricity, medium voltage, at grid,	MJ	36.639

3.3.4 Operation energy

Secondary data concerning to the energy consumption during the operation phase of the systems has been calculated based on a residential cooling consumption system present in the "Life cycle assessment of residential heating and cooling systems in four regions in the United States"(Shah et al. 2008). The house model taken as a reference is located in Texas (US) due to the high effectiveness of self-shading systems in hot climates. The total habitable area of the house are 181 m^2 in L-shape and it has 2 stories above the ground. The house construction is made of 18% of glazing area and opaque walls made of wood framed brick finish. The building is surrounded by trees and other houses.

For the operation energy calculation, it has been considered that each house has 230 m^2 of opaque façade. In the life cycle inventory of the conventional brick façade, 4240 kWh of cooling electricity consumption per year and house are considered during a service life of 50 years. From this total energy demand, just a 20% is equivalent to the heat gain through the house walls (Department of State Development 2015). The electricity consumption differs between to the three façades due to the savings that the self-shading system produces on the cooling energy demand during the service life of the house. In the study performed by the Design Robotics Group from Harvard University, the comparative physical test performed to a self-shading brick façade and a traditional flat brick façade shows reductions of the 16% simulating the thermal effects of shading on a hot sunny day (Gramazio et al. 2014). Therefore, a 16% less of consumption per year is considered for the two façade systems with improved thermal performance. Table 3 presents the cooling electricity demand during operation of 1 m^2 for the three façade systems:

Table 3 Façade systems operation energy (1 m^2)

Flow	Unit	Brick	Self-shading brick	Brick + EPS
Electricity, low voltage, at grid	MJ	665,40	558,94	558,94

3.4 Impact assessment

The processes have been modelled and analyzed using the SimaPro 7.3.3 and the method Recipe Midpoint (H) V1.06 (Goedkoop et al. 2009). The method is used to evaluate and compare the environmental impacts during the life cycle of the three systems. Generically, the Recipe method relates the results of the inventory to three endpoint indicators, human health, ecosystem diversity and resource availability via 18 impact categories. However, in the present Life Cycle Impact Assessment (LCIA), the calculation has been made using the Recipe Midpoint method, which allows to obtain directly the environmental impacts expressed in the different midpoint impact categories.

The focus impact categories quantified are climate change, human toxicity and metal depletion due to carbon dioxide emissions, resources and human health are the main impacts of the implementation of digital construction processes and technologies.

4 Results of the analysis

4.1 Environmental impact of digital fabrication production

Figure 2 shows the relative contribution of each process involved in the construction of 1 m^2 of self-shading wall to the overall environmental impacts. In each midpoint category the total environmental impact is divided into four processes: brick production, cement mortar production, digital technology production and electricity production.

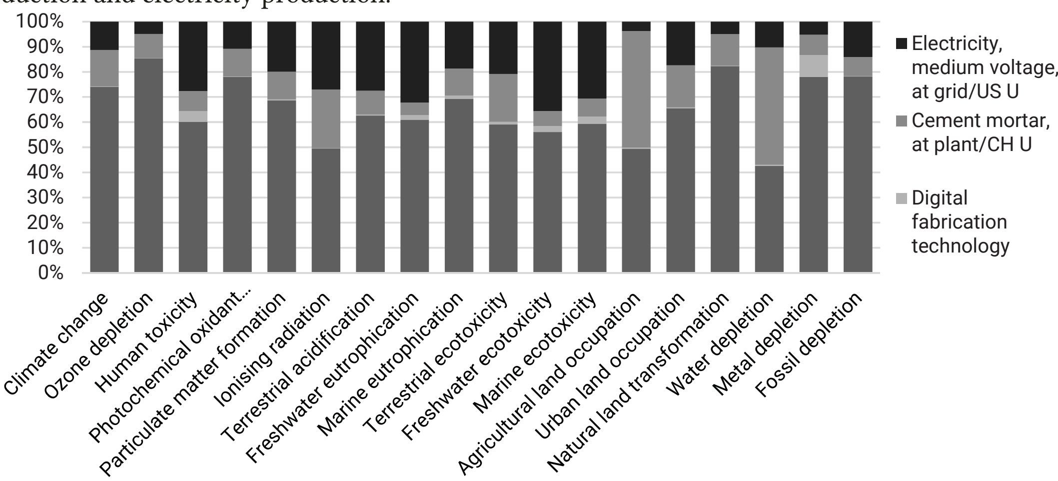

Figure 2 Relative contribution of each process to the total environmental impact of the production of 1 m^2 of self-shading wall.

The graph reveals that the highest environmental impact of the digital fabrication façade in all the midpoint categories is attributed to the brick production. This process is very energy intensive and most of the emissions to the environment are generated by the use of large amounts of electricity (Koroneos and Dompros 2007). A difference is observed among the impact of the cement mortar in the different indicators. Their production impacts contribute in more than 45% to the categories of agricultural land occupation and water depletion due to its material composition. The impact of the electricity used during construction derived from the US generation mix produces relative high contributions in many categories, for example, around 35% in freshwater ecotoxicity and freshwater eutrophification due to the use of hydroelectric power plants in the electricity generation (El-Shamy 1977). Finally, the relative contribution of the production of digital fabrication technology is very low or almost insignificant in all the midpoint indicators. The impact is slightly higher in human toxicity due to the use of lithium batteries in the robot and the laptop and it represents almost 20% in metal depletion due to high percentage of steel in the construction robot composition (see Table 1). It is therefore the production of the brick and not the digital fabrication process what produces the largest impacts on the environmental profile of the self-shading brick façade.

4.2 Comparative LCA of production processes

The second life cycle assessment pretends to compare the environmental impact of digital fabrication with conventional construction. Figure 3 presents the environmental impacts of the production process of 1 m^2 of self-shading brick façade compared with two conventional systems: 1 m^2 of brick façade with the same structural performance and 1 m^2 of insulated brick façade with equal structural and thermal performance.

The self-shading wall produces the highest impacts in all the midpoint categories and both conventional system have similar results, being the insulated wall the one with slightly superior impacts. The logical reason for the small difference between the two conventional façades is the addition of EPS in one of them to achieve the same thermal performance as the digitally fabricated. On the other hand, following the conclusions of Figure 3, the production process of the 10% of extra brick necessary for the self-shading function is potentially the biggest contribution to the higher impacts of the digitally designed façade.

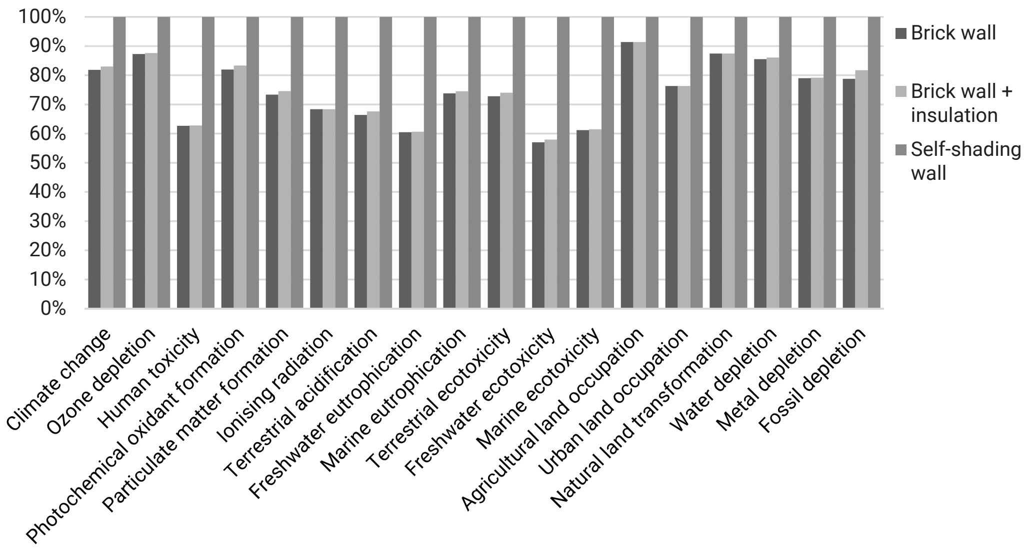

Figure 3 Relative contribution of the three façade construction processes to the different environmental impact categories.

4.3 Comparative LCA of production and operation stages

Figure 4 graphically depicts the contribution of production and 50 years of operation of the 3 systems of façade previously analyzed, applied to a familiar house situated in Texas (US). The operation phase has been calculated in function of a total 230 m^2 of exterior façade, which heat gains are responsible of the 20% of the total cooling energy used during the lifespan of the building. Additionally, a 16% of operation energy is reduced in both walls with equal thermal performance due to the thermal effect of the self-shading function and the EPS insulation in the conventional structure.

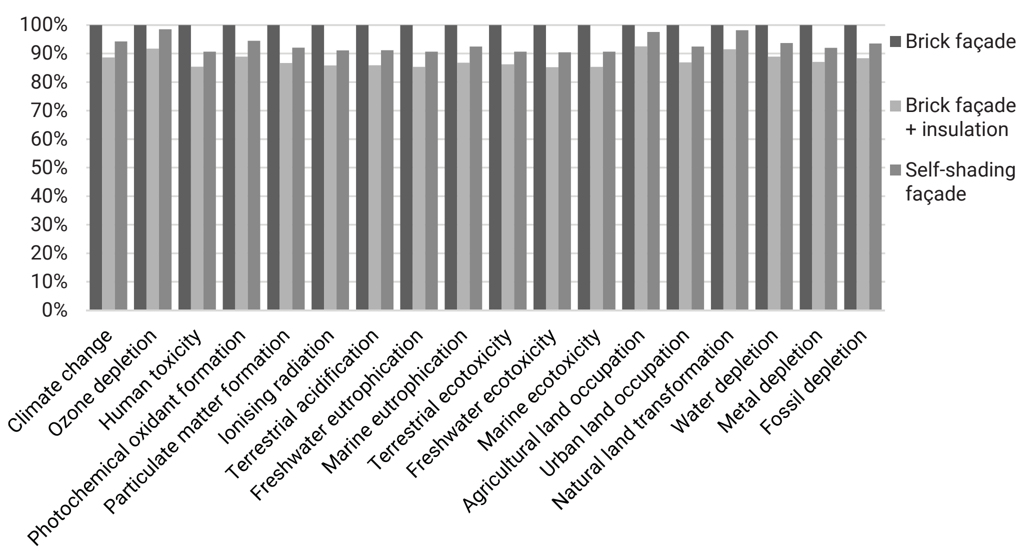

Figure 4 Relative contribution of the three façade production and operation phases to the different environmental impact categories.

The graph shows the relative importance of the operation phase in the overall environmental impacts. The comparative results show that the conventional brick façade with worse thermal performance and therefore, with more cooling consumption, is the system with the biggest contribution to all the environmental impacts. However, the self-shading façade has superior impacts than the conventional façade with equal structural and thermal performance in all the midpoint categories. Therefore, Figure 4 accentuates the importance of the production process in the total life cycle impacts of a construction element.

5 Discussion

The environmental assessment performed indicate that the relative sustainability of a self-shading façade depends primarily on the materials production process. However, a potential optimization of the present case study and further digital architecture with additional functions requires a revision and deeper study of the results for the elaboration of guidelines to help designers in the improvement of architecture from the design phase.

5.1 Cleaner electricity generation energy mix

In the electricity generation mix of the US, only 12% are renewable sources and the highest energy contribution is coming from the coal and natural gas (Energy Information Administration 2015). Therefore, it is logical to think that the impacts derived to the electricity use during the production could decrease with the use of a cleaner energy mix.

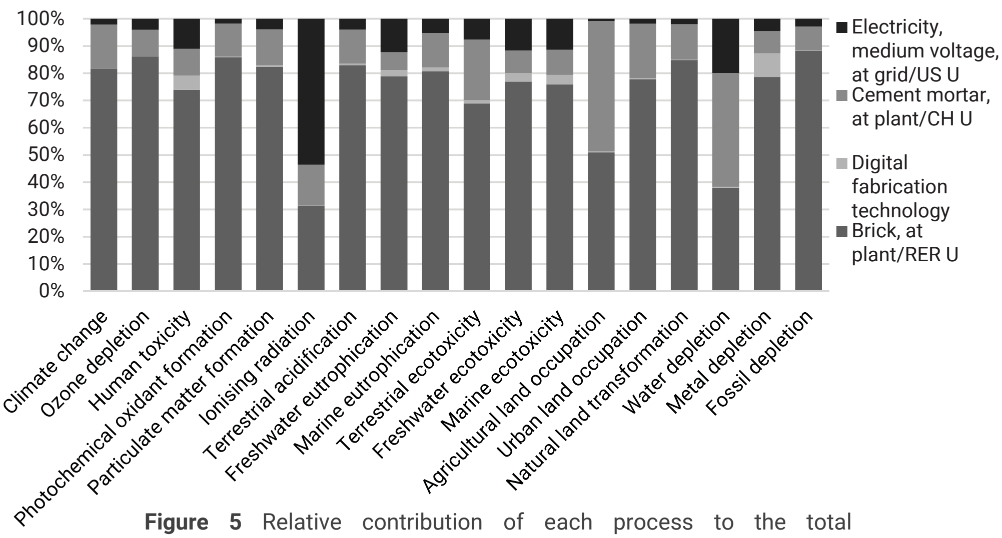

Figure 5 Relative contribution of each process to the total environmental impact of the production of 1 m2 of self-shading wall with the CH electricity generation mix.

Figure 5 shows a decrease in the relative contribution of the electricity to the overall impacts of the self-shading façade production including data from the Switzerland generation mix. Switzerland has a cleaner primary energy supply, with very low shares of natural gas (12%), less than 1% in coal and a 22% of renewable sources (International Energy Agency 2012).

5.2 Reduction of the amount of brick

The high impact of the brick production process on the life cycle impacts of the self-shading façade makes necessary a reduction of the amount of brick. The production process of the self-shading system presented by S. Andreani and M. Bechthold shows that the minimum cutting angle to create shading effect on the bricks is 8° (Gramazio et al. 2014). According to this angle, it is possible to consider only a 3% extra brick respect the conventional systems for the digital fabrication façade. Figure 6 graphically depicts how in the climate change category, the CO_2 emissions during production and operation of the self-shading façade decrease proportionally to the reduction of amount of extra brick considered. However, it would be necessary a reduction of the structural capacity of the façade to conserve the self-shading effect and be able to have the same amount of brick as the conventional systems compared.

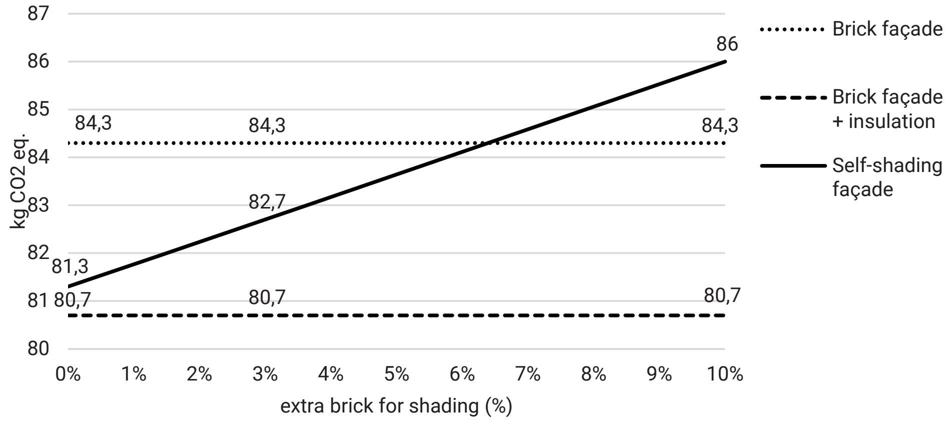

Figure 6 Climate change impacts of the three façade systems during production and operation, in function of the extra brick considered for the self-shading façade.

The graph shows how the CO_2 emissions of the self-shading façade decrease until 81.3 kg of CO_2 eq. with 0% of extra brick. And consequently, only 0.6 kg CO_2 eq. higher than the brick façade with the same thermal performance.

5.3 Study of the digital fabrication process

Further optimization requires the study of the digital fabrication process. Figure 7 graphically depicts the relative contribution of the four main processes involved in the self-shading façade production to the overall CO_2 emissions obtained in the climate change midpoint category. The 98% of the emissions are product of the materials and technology production and the remaining 1.33 kg of CO_2 eq. are the emissions result of the construction process. Therefore, with a reduction of the 45% of these emissions, it would be possible for the self-shading façade to achieve the same climate change impacts as the conventional brick façade with insulation.

Overall, it can be concluded that it is possible an optimization of the present digital fabrication case study and a reduction of their impacts below conventional construction with a cleaner energy generation mix, a reduction of 10% of the structural performance and 50% of the construction energy. For the achievement of this objectives, it will be necessary a future improvement of digital technology prototypes to be able to reduce construction times and increase the efficiency of the process. These conclusions will be compared with future digital fabrication environmental assessments for the elaboration of a methodology for the optimization of digitally fabricated architecture.

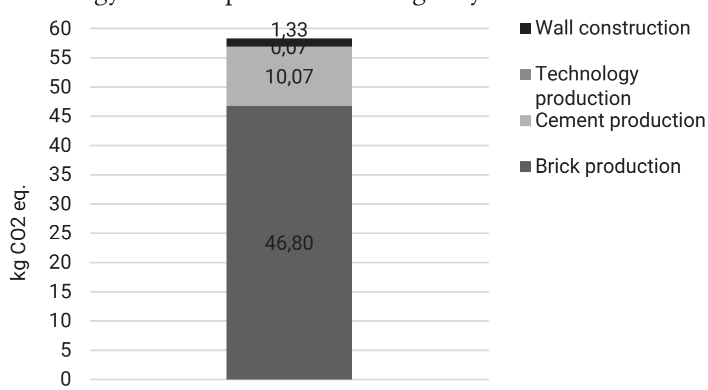

Figure 7 Relative contribution of each process of self-shading system production to climate change impacts, considering 0% extra brick and CH electricity generation mix.

6 Conclusion

Digital fabrication can be the motor of social and economic changes and a potential tool to achieve environmental benefits through the construction life cycle. However, data necessary for the life cycle assessment and optimization of digital fabrication projects are not existing yet in the literature and environmental databases. In the current research, a life cycle assessment has been applied to compare a digitally fabricated brick façade with an additional self-shading function with conventional brick constructions with similar aesthetic. The first conventional wall system has been designed with the same structural capacity and the second one with both, structural and thermal performance.

The results of the evaluation indicate that the largest impacts on the environmental profile of digitally fabricated architecture depend primarily on the materials production. Nevertheless, digital fabrication processes, including embodied energy of the technologies and energy consumption, contribute minimally in terms of energy and environmental impacts. Therefore, we conclude that regardless of whether a building is constructed traditionally or by digital fabrication, a reduction in the amount of materials used leads to an important decrease in embodied energy and contributions to environmental emissions. As a result, any improvement on the efficiency of material usage is more significant than the energy required to use or implement robots.

The aim of this paper, is not to establish the categorical statement that robotic fabrication is more environmentally friendly compared to conventional construction or vice-versa. The goal of this research is clearly targeted at supporting sustainable construction processes by providing designers with environmental guidelines to be able to make better informed, and more sustainable choices about implementing digital fabrication in architecture and construction.

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References

Czmoch, I. and Pękala, A. (2014) Traditional Design versus BIM Based Design. *Procedia Engineering, 91*, pp. 210-215.

Deng, L., Babbitt, C. W. and Williams, E. D. (2011) Economic-balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer. *Journal of Cleaner Production, 19*(11), pp. 1198-1206.

Department of State Development, G. o. S. A. (2015) Insulation, ventilation and draught proofing your home.

Dunn, N. (2012) *Digital fabrication in architecture,* Laurence King.

El-Shamy, F. M. (1977) Environmental impacts of hydroelectric power plants. *J. Hydraul. Div., Am. Soc. Civ. Eng.; (United States), 103*.

Energy Information Administration, U. S. (2015) Electric Power Monthly.

Faludi, J., Bayley, C., Bhogal, S. and Iribarne, M. (2015) Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal, 21*(1), pp. 14-33.

Gebler, M., Uiterkamp, A. J. S. and Visser, C. (2014) A global sustainability perspective on 3D printing technologies. *Energy Policy, 74*, pp. 158-167.

Gershenfeld, N. (2012) How to make almost anything: The digital fabrication revolution. *Foreign Aff., 91*, pp. 43.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. and van Zelm, R. (2009) ReCiPe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1*.

Gramazio, F. and Kohler, M. (2008) *Digital materiality in architecture,* Lars Müller Publishers Baden.

Gramazio, F., Kohler, M. and Langenberg, S. (2014) *FABRICATE: Negotiating Design & Making*.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M. and Nemecek, T. (2010) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent v2.2 No. 3. *Swiss Centre for Life Cycle Inventories, Dübendorf, CH*.

International Energy Agency, i. (2012) Energy Policies of IEA Countries, Switzerland.

Ioannidou, D., Zerbi, S. and Habert, G. (2014) When more is better – Comparative LCA of wall systems with stone. *Building and Environment, 82*, pp. 628-639.

ISO (2006) 14040: Environmental management–life cycle assessment–principles and framework. *London: British Standards Institution*.

Koroneos, C. and Dompros, A. (2007) Environmental assessment of brick production in Greece. *Building and Environment, 42*(5), pp. 2114-2123.

Lloret, E., Shahab, A. R., Linus, M., Flatt, R. J., Gramazio, F., Kohler, M. and Langenberg, S. (2014) Complex concrete structures: Merging existing casting techniques with digital fabrication. *Computer-Aided Design.*

Nielsen, P. H. and Wenzel, H. (2002) Integration of environmental aspects in product development: a stepwise procedure based on quantitative life cycle assessment. *Journal of Cleaner Production, 10*(3), pp. 247-257.

Picon, A. (2010) *Digital culture in architecture: an introduction for the design professions,* Birkhäuser Basel/Boston/Berlin.

Shah, V. P., Debella, D. C. and Ries, R. J. (2008) Life cycle assessment of residential heating and cooling systems in four regions in the United States. *Energy and Buildings, 40*(4), pp. 503-513.

Weidema B. P., B. C., Hischier R., Mutel C., Nemecek T., Reinhard J., Vadenbo C. O., Wernet G. (2013) Data quality guideline for the ecoinvent database version 3.

Zhang, T. W. and Dornfeld, D. A. (2007) Energy use per worker-hour: Evaluating the contribution of labor to manufacturing energy use. *Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses*: Springer. pp. 189-193.