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Journal Article

Author(s):
Agustí-Juan, Isolda; Jipa, Andrei; Habert, Guillaume

Publication date:
2018-11

Permanent link:
https://doi.org/10.3929/ethz-b-000306286

Originally published in:
The International Journal of Life Cycle Assessment 24(6), https://doi.org/10.1007/s11367-018-1563-4

The International Journal of Life Cycle Assessment (2019) 24:1027–1039
https://doi.org/10.1007/s11367-018-1563-4

BUILDING COMPONENTS AND BUILDINGS

Environmental assessment of multi-functional building elements constructed with digital fabrication techniques

Isolda Agustí-Juan[1] · **Andrei Jipa**[2] · **Guillaume Habert**[1]

Received: 4 February 2018 / Accepted: 16 November 2018 / Published online: 23 November 2018

Abstract

Purpose Digital fabrication is revolutionizing architecture, enabling the construction of complex and multi-functional building elements. Multi-functionality is often achieved through material reduction strategies such as functional or material hybridization. However, these design strategies may increase environmental impacts over the life cycle. The integration of functions may hinder the maintenance and shorten the service life. Moreover, once a building element has reached the end of life, hybrid materials may influence negatively its recycling capacity. Consequently, the aim of this paper is to analyze the influence of multi-functionality in the environmental performance of two digitally fabricated architectural elements: The Sequential Roof and Concrete-Sandstone Composite Slab and to compare them with existing standard elements.

Methods A method based on the life-cycle assessment (LCA) framework is applied for the evaluation of the environmental implications of multi-functionality in digital fabrication. The evaluation consists of the comparison of embodied impacts between a multi-functional building element constructed with digital fabrication techniques and a conventional one, both with the same building functions. Specifically, the method considers the lifetime uncertainty caused by multi-functionality by considering two alternative service life scenarios during the evaluation of the digitally fabricated building element. The study is extended with a sensitivity analysis to evaluate the additional environmental implications during end-of-life processing derived from the use of hybrid materials to achieve multi-functionality in architecture.

Results and discussion The evaluation of two case studies of digitally fabricated architecture indicates that their environmental impacts are very sensitive to the duration of their service life. Considering production and life span phases, multi-functional building elements should have a minimum service life of 30 years to bring environmental benefits over conventional construction. Furthermore, the case study of Concrete-Sandstone Composite Slab shows that using hybrid materials to achieve multi-functionality carries important environmental consequences at the end of life, such as the emission of air pollutants during recycling.

Conclusions The results from the case studies allow the identification of key environmental criteria to consider during the design of digitally fabricated building elements. Multi-functionality provides material efficiency during production, but design adaptability must be a priority to avoid a decrease in their environmental performance. Moreover, the high environmental impacts caused by end-of-life processing should be compensated during design.

Keywords Digital fabrication · End of life · Hybrid materials · LCA · Multi-functionality · Service life

1 Introduction

Traditionally, buildings are conceived as a sequential and layered process with independent architectural elements (e.g., slabs or exterior wall). As showed in Brand (1995), building elements can be organized in functions with different service lives, from the longest (structure) to the shortest (space plan). As a consequence, classic sustainable design strategies have promoted the separation of functions through layered building construction, which enables flexibility in use and reduction of material waste when retrofitting buildings (Brancart et al. 2017). In contrast,

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Responsible editor: Holger Wallbaum

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11367-018-1563-4) contains supplementary material, which is available to authorized users.

✉ Isolda Agustí-Juan
agusti@ibi.baug.ethz.ch

[1] Chair of Sustainable Construction, IBI, ETH Zürich, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland

[2] Digital Building Technologies, ITA, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland

novel computational methods promote customization and material reduction through formal, structural, and material integration (Oxman and Rosenberg 2007). Computational design strategies together with additive fabrication are proliferating in construction and demonstrate strong potential to construct complex structures (Labonnote et al. 2016). Moreover, Agustí-Juan et al. (2017a) demonstrated that the production of large-scale complex structures through digital fabrication techniques has a high environmental potential, without carrying additional environmental costs associated with complex formworks, etc. However, this does not mean that complexity in architecture has always an environmental advantage. It is decisive to evaluate whether this complexity is needed to reduce material content in the structure or whether it has only esthetic purposes. For the reduction of environmental impacts, the structural complexity must be the result of material reduction strategies such as structural optimization or multi-functionality.

Published literature on additive manufacturing applied to construction agrees on the potential of digital technologies to facilitate the production of multi-functional building elements (Labonnote et al. 2016). Multi-functional architecture can be the result of different design strategies: integrated design, functional hybridization, and material hybridization (De Schutter et al. 2018). On the one hand, buildings are nowadays highly complex systems with multiple services, such as heating, lighting, and acoustics. The traditional linear design process, where the different building systems are built sequentially, is not suitable to create high-performance buildings. The design needs of the different systems must be considered from the beginning of the architectural design (Lechner 2015). As a result, complex geometries offer the possibility to integrate services such as piping or insulation in the structure of building elements. For instance, Block et al. (2017) presented a complex shell roof that integrates cooling, heating, photovoltaics, and thermal insulation in its lightweight structure. The integrated design process makes possible synergies between building systems that further improve the performance of a project. Moreover, integrated building elements are associated with the reduction of building materials during production.

On the other hand, current research on digital fabrication methods have showed the potential of hybridizing functions in complex building elements. The structure can provide additional performance (e.g., acoustics) through its complex geometry, which saves an additional building component to provide this function. As a result, architectural components, such as structure and insulation, are no longer separated in functions, but rather integrated through the informed distribution of material (Oxman and Rosenberg 2007). Two examples of digitally fabricated building elements with functional hybridization are the 3D-printed concrete walls presented in Gosselin et al. (2016). The study describes two structural elements designed and fabricated targeting multi-functionality through geometrical complexity. Specifically, the first wall example demonstrates that the thermal insulation efficiency can be improved 56% in comparison to a classic wall through geometric optimization. The second example describes a wall element, whose hole geometry provides enhanced soundproofing properties. Figure 1 shows a schematic explanation of the difference between integrated design and functional hybridization.

Finally, multi-functionality can also be achieved through material hybridization, such as cementitious materials with very low thermal conductivity achieved through the addition of wood or thermally activated concrete enriched with phase-change materials. The combination of materials, each responsible for a specific function such as compression load-bearing, tensile load-bearing, insulation, etc., offers many opportunities for digitally fabricated smart structures such as weight reduction or increased durability (De Schutter et al. 2018).

Multi-functionality in building elements is often explored in digital fabrication targeting material efficiency (Meibodi et al. 2017). Agustí-Juan and Habert (2017) demonstrated that functional hybridization in digitally fabricated structures can save materials during production, associated with reductions in environmental impacts. The life-cycle assessment (LCA) applied to the case study of a digitally fabricated roof showed that the hybridization of acoustics in the roof structure avoided the construction of a suspended ceiling, which is responsible for high environmental impacts. However, multi-functionality achieved either through a hybridization at the material level or at structural level can influence the environmental performance of building elements. For instance, an integrated design may rise the difficulty of retrofitting individual building components during a building's service life and increase replacement rates. This reduction in the lifetime of digitally fabricated building elements would influence negatively their environmental performance. Moreover, the intermixing of different materials raises the question of recyclability at the end of life (Agustí-Juan et al. 2017b).

The aim of this paper is to quantitatively study the environmental risks and opportunities of multi-functionality in digitally fabricated building elements. Firstly, a method based on the life-cycle assessment (LCA) framework is applied to evaluate the influence of functional integration and hybridization on the environmental performance of digitally fabricated architecture, considering service life uncertainty. The evaluation consists of a cradle-to-gate comparison of impacts between a multi-functional digitally fabricated building element and a conventional one. The method is applied to evaluate two case studies of digitally fabricated structures: The Sequential Roof and Concrete-Sandstone Composite (CSC) Slab. Secondly, the evaluation of the second case study is extended to a cradle-to-grave analysis to tackle additional environmental implications associated with material hybridization. Specifically, a LCA focused on end-of-life phase is applied to evaluate the potential environmental impacts on recycling loops. The results of both analyses enable to define general guidelines for the design of multi-functional building elements constructed with digital fabrication techniques.

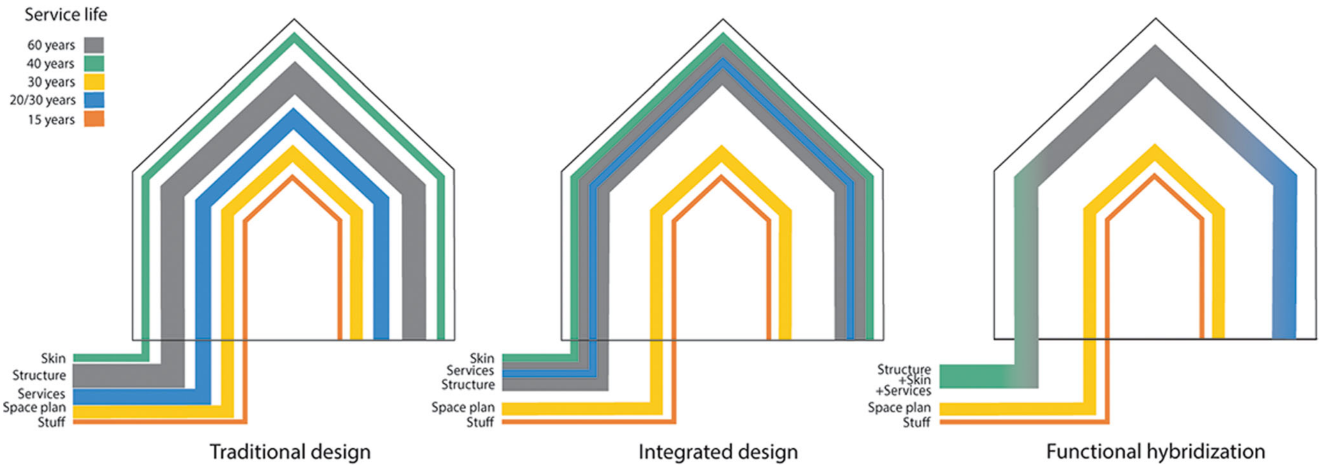


Fig. 1 Comparison of functions between traditional design, integrated design, and functional hybridization. The color of the layers represents the service life (based on Brand (1995))

2 Methods

2.1 Evaluation of multi-functional building elements

In this section, we present the method selected for the environmental evaluation of multi-functional building elements. The EN 15978 European Standard (CEN EN 2011) specifies a calculation method of the environmental performance of buildings based on the life-cycle assessment (LCA) framework (ISO 2006). Specifically, the standard defines the environmental performance of buildings as the sum of the embodied energy of building materials plus the energy and water consumed during the use phase. The scope of this evaluation focuses on a cradle-to-gate analysis at the building element scale. Therefore, only the environmental impact of building materials production is considered in the method. Further research should be conducted to understand how water and energy consumption during operation can be integrated. Similar to the approach presented in Hoxha et al. (2014) to calculate the environmental performance of buildings, the environmental impact of conventional building elements can be calculated as a decomposition in c building components:

$$I^{\mathrm{conv}}_{\mathrm{elem}} = \sum_{i=1}^{c} I^{\mathrm{conv}}_{\mathrm{comp_i}} * n_{\mathrm{i}} \tag{1}$$

where $I^{\mathrm{conv}}_{\mathrm{elem}}$ is the environmental impact of the conventional building element and $I^{\mathrm{conv}}_{\mathrm{comp_i}}$ is the environmental impact of each conventional building component, and n_{i} is the number of times that each component has to be replaced during the service life of the building. $I^{\mathrm{conv}}_{\mathrm{comp_i}}$ and n_{i} are calculated following Eqs. (2) and (3):

$$I^{\mathrm{conv}}_{\mathrm{comp_i}} = m_{\mathrm{i}} * k_{\mathrm{i}} \tag{2}$$

$$n_{\mathrm{i}} = \frac{\mathrm{SL_{build}}}{\mathrm{ESL}^{\mathrm{conv}}_{\mathrm{comp_i}}} \tag{3}$$

where m_{i} is the mass of each building component, k_{i} is the environmental impact of one unit mass of each building component, $\mathrm{SL_{build}}$ is the service life of the building, and $\mathrm{ESL}^{\mathrm{conv}}_{\mathrm{comp_i}}$ is the estimated service life of each component. In contrast, multi-functional digitally fabricated structures combine the different building components in a single element. Therefore, we assume a single service life for the whole building element, which is usually defined by the component with a shortest lifetime. Consequently, the environmental performance of a multi-functional digitally fabricated building element is calculated according to Eq. (4):

$$I^{\mathrm{dfab}}_{\mathrm{elem}} = n * \sum_{i=1}^{c} I^{\mathrm{dfab}}_{\mathrm{comp_i}} \tag{4}$$

where $I^{\mathrm{dfab}}_{\mathrm{elem}}$ is the environmental impact of the digitally fabricated building element, n is the number of times that the building element has to be replaced during the service life of the building, and $I^{\mathrm{dfab}}_{\mathrm{comp_i}}$ is the environmental impact of each building component. $I^{\mathrm{dfab}}_{\mathrm{comp_i}}$ is calculated following the equation for the calculation of $I^{\mathrm{conv}}_{\mathrm{comp_i}}$ (see Eq. (2)) and $n$according to Eq. (5), where ESL^{dfab}_{elem} is the estimated service life of the digitally fabricated building element:

$$n = \frac{\mathrm{SL_{build}}}{\mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{elem}}} \tag{5}$$

Based on the previous equations, the evaluation method developed consists of the comparison between the life-cycle impact of digital fabrication and conventional construction with the same functionality. Digitally fabricated building elements will be more environmentally performant than conventional construction if Eq. (6) is true:

$$I^{\mathrm{dfab}}_{\mathrm{elem}} < I^{\mathrm{conv}}_{\mathrm{elem}} \tag{6}$$

The complete equation developed to evaluate multi-functional digitally building elements is shown in Eq. (7).

Specifically, the impact of the digitally fabricated element is compared with the impacts of the components that constitute the conventional element. These additional components needed in conventional construction are avoided in digital fabrication due to multi-functionality. Finally, Eq. (8) represents the two alternative service life scenarios considered for the digitally fabricated element $\left(\mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{elem}}\right)$. Due to service life uncertainty derived from multi-functionality, the ESL of the hybridized component with the longest service life ($\mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{comp}_{\max}}$) and the ESL of shortest one $\left(\mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{comp}_{\min}}\right)$ are considered.

$$\frac{\mathrm{SL}_{\mathrm{build}}}{\mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{elem}}} * \sum_{i=1}^{c} I^{\mathrm{dfab}}_{\mathrm{comp}_{\mathrm{i}}} < \sum_{i=1}^{c} I^{\mathrm{conv}}_{\mathrm{comp}_{\mathrm{i}}} * \frac{\mathrm{SL}_{\mathrm{build}}}{\mathrm{ESL}^{\mathrm{conv}}_{\mathrm{comp}_{\mathrm{i}}}} \tag{7}$$

$$\mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{elem}} = \left[\mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{comp}_{\max}}, \mathrm{ESL}^{\mathrm{dfab}}_{\mathrm{comp}_{\min}}\right] \tag{8}$$

2.1.1 Service life of building elements

The main difficulty of applying the evaluation method is the estimation of the service life of the conventional building components $\left(\mathrm{ESL}_{\mathrm{comp}_{\mathrm{i}}}\right)$ and the digitally fabricated element ($\mathrm{ESL}_{\mathrm{elem}}$). The International Standard ISO 15686 (ISO 2000) defines service life as the period of time after installation in which the buildings or their elements meet or exceed the minimum performance requirements. These requirements may be intrinsic to the physical performance or be imposed by economic or subjective factors (Rincón et al. 2013). Multiple factors influence the service life of buildings and building elements, leading to a high uncertainty in the estimation of their service life (Hoxha et al. 2014). The ISO 15686 standard tackles the problems of service life prediction and provides a methodology for estimating the service life. This methodology is based on two different service life concepts: the Reference Service Life (RSL) and the Estimated Service Life (ESL). Emídio et al. (2014) define the RSL as the expected service life under normal use and maintenance conditions, which is identified with the physical or technical service life. The RSL is related with the deterioration of the materials and building elements over time mainly due to the action of degradation agents and natural aging processes (humidity, UV, temperature, etc.…). But, as shown by Aktas and Bilec (2012), the RSL should be corrected with modifying factors related to quality, design, environment, use, and maintenance to predict the ESL or real service life of a building or building element. Multi-functionality may reduce the design adaptability of a building element and its ability to accommodate functional changes over time. Therefore, the ESL of a multi-functional digitally fabricated structure is mainly driven by functional factors. The functional service life or functional obsolescence described by Silva et al. (2016) is considered as ESL for the evaluation presented in this paper. Due to the high variability of functional service life data present in the literature (Hoxha et al. 2014), average service life values per building component were extracted from the Swiss standard SIA 2032 (SIA 2010) for the present evaluation.

2.1.2 Environmental impact assessment

For the evaluation of each case study with the method proposed, a functional unit of 1 m^2 of digitally fabricated building element was compared with 1 m^2 of a conventional structure with equal functional and structural performance. The system boundaries of the assessment included the environmental impacts from raw material extraction and transport, building materials production, robotic fabrication, and replacement of building components during service life (EN 15978 modules: A1–A3, A5, and B4). For the digitally fabricated building element, two alternative ESL scenarios were defined due to the uncertainty on the service life associated with the multi-functionality. A complete replacement of the building element was considered when it reached the end of life. In contrast, an ESL was defined for each component of the conventional building element and they were replaced independently when each one reached the end of its service life. The evaluation was implemented in the software SimaPro 8 and because of the Swiss context of the projects, Ecoinvent v3.3 (Weidema et al. 2013) database was used to calculate the environmental impacts of the building elements. Additionally, environmental information regarding certain standard components (e.g., installations) was extracted from the Bauteilkatalog (Holliger Consult GmbH 2017) database due to the lack of precise data. The Intergovernmental Panel on Climate Change (IPCC) 2013 GWP 100a V1.03 was chosen as impact assessment method (IPCC 2013), which is based on a single impact category (kg CO$_2$ eq.). This method was chosen because the evaluation focused on analyzing the effect of service life uncertainty on the environmental impact and the question of pollution was not discussed.

2.2 Evaluation of hybrid building elements

Multi-functional building elements are often composed of hybrid materials that efficiently reduce weight and material usage, associated with energy savings (Hong et al. 2012). However, mixing materials of different nature (e.g., organic and inorganic) may increase the difficulty of recycling hybrid structures at the end of their service life. Their heterogeneous composition may increase the difficulty and energy demand to separate and recycle the mixed fractions of material (Yang et al. 2012). Consequently, a second analysis was performed to analyze additional environmental implications associated with digitally fabricated building elements with material hybridization. Specifically, a LCA focused on end-of-life phase was applied to evaluate the potential environmental impacts on recycling loops. The system boundaries of the evaluation extended from cradle to grave to study in depth the environmental impacts caused by the end-of-life processing of hybrid materials. The evaluation was conducted according to three factors: (a) choice of modeling approach, (b) end-of-life scenarios depending on the possibility of separation, and (c) use of recycled materials during production.

On the one hand, two modeling approaches were considered: recycled content approach or cut-off and end-of-life (EoL) recycling approach or avoided impact (Frischknecht 2010). The cut-off approach (100:0) included the burdens from materials production (A1-A3), construction (A5), demolition (C1), and disposal (C4) of the life-cycle stages described in EN 15804 (CEN EN 2012) in the total impact of the building element. In the EoL recycling approach (0:100), the total impact included also the benefits and loads beyond the system boundary. Therefore, the impacts and benefits caused by material recycling were included in this approach (EN 15804 modules: C3, D). Additionally, the system boundaries were adapted to the end-of-life management scenarios evaluated. Specifically, the following three scenarios were considered in the LCA evaluation:

- Landfill scenario: hybrid materials are not separated at the end of life and the structure is directly deposited in landfill.
- Recycling in open-loop: the building element is composed of hybrid materials with 0% recycled material content, which are separated for recycling at the end of life.
- Recycling in closed-loop: the building element is composed of hybrid materials with 100% recycled material content, which are separated for recycling at the end of life.

For modeling the different scenarios, we used data from Swiss production processes and the Swiss energy mix. The impact assessment methods selected were the IPCC 2013 GWP 100a for the calculation of the global warming potential (GWP) in kg CO_2 eq. and the Ecological Scarcity Method 2013 (UBP) in eco-points. The ecological scarcity method focuses on the evaluation of pollutant emissions, which are commonly released during end-of-life processing. These two impact methods were chosen because they are the main environmental impacts assessed in Swiss standards (in addition with energy).

3 Case studies

3.1 The "Sequential Roof"

3.1.1 Description

The first multi-functional case study selected was "The Sequential Roof" (Gramazio Kohler Research, ETH Zurich), the wooden roof of the Arch_Tec_Lab at ETH Zurich. The Sequential Roof consists of 168 single trusses of C24 fir/spruce wood, which are woven into a 2308-m^2 freeform roof design (see Fig. 2). The structure has a total wood volume of 384 m^3, including 48,624 timber slats of approximately 100–150 cm in length that were robotically assembled using 815,984 steel nails. The automated assembly of the large-scale load bearing structures was performed by a custom six-axis overhead gantry robot in the manufacturer's factory. The off-site digital fabrication process enabled a reduction in construction time to 12 h per truss, which is considerably lower than manual assembly (Willmann et al. 2016). The project demonstrates the potential of combining digital fabrication methods with timber for the creation of complex structural elements at architectural scale. The architectural complexity enables the structure to provide finishing and acoustic functions, avoiding additional elements such as suspended ceilings. The hybridization of functions with high environmental impact in the structure reduces approximately 40% of CO_2 emissions compared with a conventional structure with similar performance (Agustí-Juan and Habert 2017).

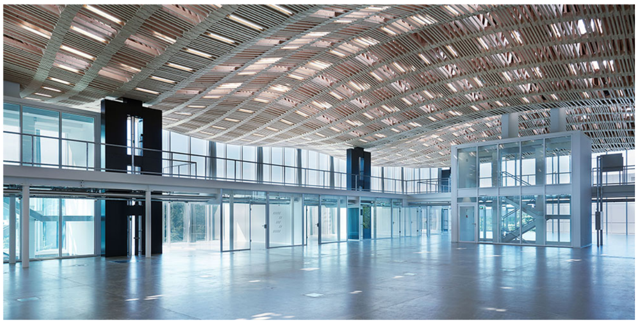


Fig. 2 "The Sequential Roof" (Gramazio Kohler Research, ETH Zurich)

3.1.2 Definition of product systems

One reference flow was chosen for evaluating the case study: 1 m^2 of The Sequential Roof and 1 m^2 of conventional wooden roof structure with suspended ceiling. Both building elements have the same structural and functional factors as well as materiality to be comparable. Specifically, the acoustic and finishing functions hybridized in the digitally fabricated roof are performed by the suspended ceiling with rockwool insulation in the conventional roof. For the definition of each product system, we collected the material composition and fabrication information of both roofs from Agustí-Juan and Habert (2017). For the Sequential Roof, the energy consumption of the robot and a desktop computer (Williams and Sasaki 2003) during prefabrication were included in the assessment. Moreover, service life data was collected for each building component. The complete data of both product systems can be found in the Electronic Supplementary Material.

Production Based on the product system data of The Sequential Roof, Table 1 shows the life-cycle inventory (LCI) built with Ecoinvent 3.3 processes for the impact assessment.

Table 1 LCI of The Sequential Roof production (1 m^2)

Process	Unit	Amount
Sawnwood, softwood, dried (*u* = 10%), planed (RER) | production | Alloc Def,U	kg	0.17
Steel, low-alloyed (RER) | steel production, converter, low-alloyed | Alloc Def,U	kg	2.27
Electricity, medium voltage (CH) | market for | Alloc Def,U	kWh	4.38

The basic composition of the conventional roof is a glulam structure and an acoustic suspended ceiling. Table 2 shows the LCI built with Ecoinvent 3.3 processes for the LCIA.

Service life For the evaluation of the present case study, we assumed that both digitally fabricated and conventional building elements were part of a building with a service life of 60 years. For The Sequential Roof, two alternative scenarios were evaluated due to the uncertainty on the service life derived from the functional hybridization. Scenario 1 considered an ESL of 60 years, as the building element could last as long as a conventional structure. Scenario 2 considered an ESL of 30 years because the hybridization of acoustic and finishing functions could lead complete replacement each time that the services need to be refurbished. For the conventional roof, a service life of 60 years was considered for the structure and 30 years for the suspended ceiling, considering a complete replacement when each component reached the end of life.

3.2 Concrete-Sandstone Composite Slab

3.2.1 Description

The second case study selected for analysis was the "CSC Slab" prototype (Digital Building Technologies, ETH Zurich), a floor slab prefabricated through additive digital fabrication techniques. The "CSC Slab" is a 1.8 × 1 × 0.15 m^3 hybrid structure which relies on ultra-high performance, fiber-reinforced concrete (UHPFRC) for its structural capacity. The complex shape is inherited from a 6-to-10-mm-thick 3D-printed shell which acts as permanent formwork for the concrete (see Fig. 3). The slab was designed using topology optimization algorithms to reduce material, minimize the strain in the slab under uniform load, and meet fabrication constraints. The design was 3D printed in silica sand using a binder jetting Ex-One S-MAX 3D printer (Meibodi et al. 2017). After post-processing, UHPFRC with 2.75% vol. steel fibers was cast in the formwork. The average concrete thickness achieved is 30 mm, enough to provide the structural strength when tested with a 2500 KN/m^2 distributed load. The use of digital fabrication methods enables the optimization of the structure for material reduction and the production of detailed and complex geometries (Jipa et al. 2016). The structural complexity of the slab enables the hybridization of the exposed structure with an acoustic function or with an ornamental, three-dimensional finish. Moreover, building services and installations can be integrated in the structure, avoiding the need for a suspended ceiling.

3.2.2 Definition of product systems

One reference flow was chosen for evaluating this case study: 1 m^2 of CSC Slab and 1 m^2 of conventional reinforced concrete slab with suspended ceiling. Both building elements have the same structural, material, and functional factors to be comparable. Specifically, the acoustic and finishing functions which can be hybridized in the digitally fabricated slab are performed by the suspended ceiling from the conventional slab. Moreover, both building elements include the same standard installations required by normative. For the definition of the product systems, the material composition and fabrication information of the CSC Slab was collected on-site and from the literature. Moreover, service life data for each building component and data related to the three end-of-life scenarios detailed in Sect. 2.2 were collected. The complete data of the product systems can be found in the Electronic Supplementary Material.

Production The CSC Slab is a hybrid structure composed of a 3D-printed permanent formwork filled with ultra-high performance, fiber-reinforced concrete (UHPFRC). Based on the product system data of the CSC Slab, Table 3 shows the life-cycle inventory (LCI) built with Ecoinvent 3.3 for the impact assessment. Moreover, the impact of the integrated installations was included in the assessment. This impact was

Table 2 LCI of the conventional roof production (1 m^2)

Process	Unit	Amount
Glue laminated timber, for indoor use (RER) | production | Alloc Def,U	m^3	0.079
Steel, low-alloyed (RER) | steel production, converter, low-alloyed | Alloc Def,U	kg	0.11
Rock wool (CH) | production | Alloc Def,U	kg	5
Three layered laminated board (RER) | production | Alloc Def,U	m^3	0.016
Particle board, for indoor use (RER) | production | Alloc Def,U	m^3	0.019
Steel, low-alloyed (RER) | steel production, converter, low-alloyed | Alloc Def,U	kg	3.323

Fig. 3 Prototype of "CSC Slab" (Digital Building Technologies, ETH Zurich)

obtained from the sum of the emissions from electrical installations, heat distribution, ventilation system, and sanitary facilities in the Bauteilkatalog.

The basic composition of this slab is a reinforced concrete structure and an acoustic suspended ceiling. Table 4 shows the LCI built with Ecoinvent 3.3 processes for the impact assessment. Moreover, the impact of the installations hidden in the void above the suspended ceiling was included in the assessment.

Service life We evaluated the CSC Slab and conventional slab along 60 years of service life, corresponding to the lifetime of a building. The analysis of each building element was performed by component, which needed replacement if their service life was inferior to the lifetime of the building. For the CSC Slab, we studied two alternative scenarios due to the uncertainty derived from the hybridization of acoustic and finishing functions and the integration of installations in the structure. Scenario 1 assumed that the service life of the CSC Slab could be as long as a conventional structure (60 years). Scenario 2 considered that the integration of installations could lead to the complete replacement of the structure when installations need to be replaced after 20 years. For the conventional slab, a service life of 60 years was considered for the structure, 30 years for the suspended ceiling and 20 years for the installations. A complete replacement was assumed when a component reached the end of its functional service life.

End of life We collected data related to landfill, recycling in open-loop (0% recycled material content) and recycling in closed-loop (100% recycled material content) scenarios for the CSC Slab. Figure 4 shows the system boundaries of each scenario evaluated. In the first scenario, we assumed that the CSC Slab was deposited directly in sanitary landfill after demolition. The choice of landfill type was made according to the list of main hazardous components in C&D waste from European Commission (2011), where the phenol-based binder from the structure is considered hazardous. In both recycling scenarios, the sand-binder and the UHPFRC waste fractions are recycled individually after demolition and mechanical separation. The concrete is crushed for reuse as low-quality concrete aggregate, and the sand-binder structure is thermally recycled. This process consists of crushing the material and processes it during 20 min at 980 °C in an industrial furnace to burn off the binder content (AMCOL Metalcasting 2013). After the processing, the material is sorted and up to 95% of silica sand can be reused due to the high quality after treatment (Lahl 1992). The 5% left, containing possible binder residues, is deposited in sanitary landfill.

4 Results

4.1 Environmental impacts of production

Based on the material and fabrication information collected from Agustí-Juan and Habert (2017), we performed an environmental evaluation of the impacts associated with the production of the building elements to be compared. The LCA results were broken down into building components: structure and suspended ceiling. Figure 5 graphically depicts the global warming potential (GWP) impacts caused by the production process of both building elements. We observe that the hybridization of acoustic and finishing functions in the structure of The Sequential Roof avoids a suspended ceiling, which decreases the impact of this element to a total of 25.54 kg CO_2 eq. In contrast, the conventional roof is responsible for 40.20 kg CO_2 eq. due to the need for a suspended ceiling (18.02 kg CO_2 eq.) to hide installations and finish the structure (22.18 kg CO_2 eq.). These environmental data demonstrate that the multi-functionality achieved through digital fabrication techniques enables a material-efficient construction process.

Table 3 LCI of the CSC Slab production and end of life (1 m^2)

Process	Unit	Amount
UHPFRC	m^3	0.033
Silica sand (DE) | production | Alloc Def,U	kg	22.633
Phenolic resin (RER) | production | Alloc Def,U	kg	0.307
Phenyl isocyanate (RER) | production | Alloc Def, U	kg	0.252
Electricity, medium voltage (CH) | market for | Alloc Def, U	kWh	1.46
Inert waste (CH) | treatment of, sanitary landfill | Alloc Def,U	kg	105.692

Table 4 Life-cycle inventory of conventional slab production (1 m^2)

Process	Unit	Amount
Concrete, normal (CH) | unreinforced concrete production, with cement CEM II/A | Alloc Def,U	m^3	0.148
Steel, low-alloyed (RER) | steel production, converter, low-alloyed | Alloc Def,U	kg	12.613
Gypsum plasterboard (CH) | production | Alloc Def,U	kg	9
Steel, low-alloyed (RER) | steel production, converter, low-alloyed | Alloc Def,U	kg	6.38
Three layered laminated board (RER) | production | Alloc Def,U	m^3	0.006

Based on the material and fabrication data collected, we evaluated the production impacts of the CSC Slab and the conventional slab. The LCA results were broken down into three building components: structure, suspended ceiling, and installations. Figure 6 graphically depicts the global warming potential (GWP) impacts of both building elements. We observe that the Smart Slab is responsible for a total of 67.04 kg CO_2 eq. divided between structure and integrated installations. The lower impact of the CSC Slab compared to a conventional slab (102.60 kg CO_2 eq.) is mainly attributed to the structural optimization, which reduces considerably the environmental impact of the structure compared to a conventional one (54.36 kg CO_2 eq.). Furthermore, the hybridization of finishing and acoustic functions in the structure avoids the need for an additional suspended ceiling to provide these functions, which is responsible for 16.77 kg CO_2 eq. in a conventional slab. Like the previous case study, the present comparison demonstrates that through multi-functionality, significant environmental benefits are gained during production.

4.2 Environmental impacts including service life

The case studies were evaluated with the method selected for environmental assessment of multi-functional digitally fabricated building elements. The evaluation of the case studies was performed using the GWP impacts during production and service life information presented in Sect. 3.1.2 for The Sequential Roof and Sect. 3.2.2 for the CSC Slab.

For the evaluation of the environmental implications of multi-functionality on The Sequential Roof, we applied the method described in Sect. 2.1 for its comparison with the conventional roof. Equation (9) shows the method application to this case study:

$$\frac{SL_{build}}{\left[ESL^{dfab}_{str}, ESL^{dfab}_{ceil}\right]} * I^{dfab}_{str} < I^{conv}_{str} * \frac{SL_{build}}{ESL^{conv}_{str}} + I^{conv}_{ceil} * \frac{SL_{build}}{ESL^{conv}_{ceil}} \qquad (9)$$

where I^{dfab}_{str} is the production impact of the digitally fabricated structure and $\left[ESL^{dfab}_{str}, ESL^{dfab}_{ceil}\right]$ represent the two service life scenarios for The Sequential Roof: the estimated service life of a structure and a suspended ceiling. On the other side, I^{conv}_{str} is the production impact of the conventional structure, ESL^{conv}_{str} is the service life of this structure, I^{conv}_{ceil} is the production impact of the conventional ceiling, and ESL^{conv}_{ceil} is the service life of this suspended ceiling. The results of the evaluation are graphically depicted in Fig. 7:

For the evaluation of the environmental implications of multi-functionality on the CSC Slab, we applied the method

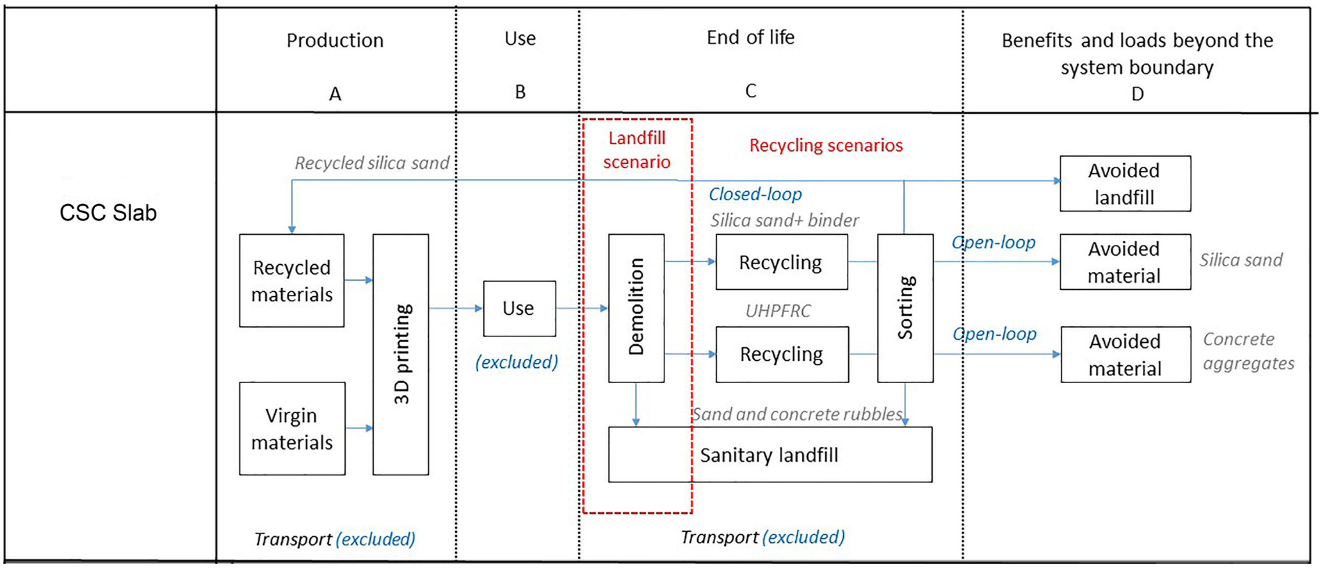
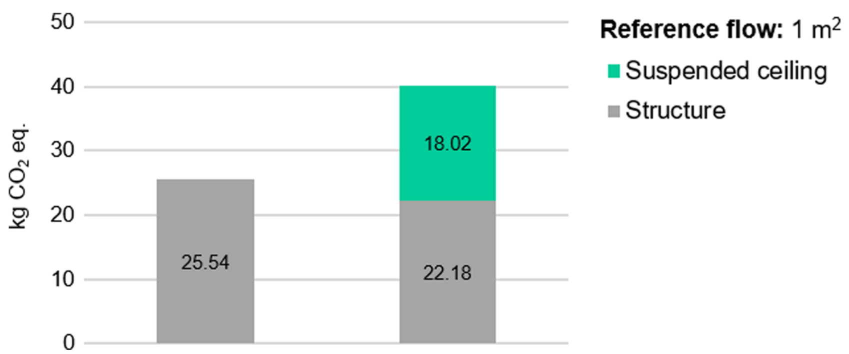


Fig. 4 System boundaries considered for the life-cycle assessment of the CSC Slab

Fig. 5 GWP emissions of the production of The Sequential Roof and conventional roof



described in Sect. 2.1 for its comparison with the conventional slab. Equation (10) shows the method application to this case study:

$$\frac{SL_{build}}{\left[ESL^{dfab}_{str}, ESL^{dfab}_{inst}\right]} * \left(I^{dfab}_{str} + I^{dfab}_{inst}\right) < I^{conv}_{str} * \frac{SL_{build}}{ESL^{conv}_{str}} + I^{conv}_{ceil} * \frac{SL_{build}}{ESL^{conv}_{ceil}} + I^{conv}_{inst} * \frac{SL_{build}}{ESL^{conv}_{inst}} \qquad (10)$$

where $(I^{dfab}_{str} + I^{dfab}_{inst})$ is the impact of the digitally fabricated structure with integrated installations and $\left[ESL^{dfab}_{str}, ESL^{dfab}_{inst}\right]$ represent the estimated service life of a structure and installations, considered as possible service life scenarios for the CSC Slab. On the other side, I^{conv}_{inst} is the impact of conventional installations and ESL^{conv}_{inst} is the service life of these installations. The results of the evaluation are graphically depicted in Fig. 8.

The results of the evaluation show that the GWP impacts of The Sequential Roof are lower than the conventional roof in both scenarios compared. Considering an ESL of 60 years (scenario 1), this digitally fabricated roof is responsible for approximately half of the GWP impact (25.54 kg CO_2 eq.) from the conventional roof. However, considering a reduction of the ESL to 30 years (scenario 2), the GWP impact of The Sequential Roof reaches 51.08 kg CO_2 eq. Therefore, even with a higher replacement rate caused by the multifunctionality of the structure, the environmental impact of The Sequential Roof would be lower than the conventional roof. In contrast, the comparison of GWP impacts between the CSC Slab and the conventional slab varies depending on the service life scenario. If we assume that the CSC Slab is replaced after 60 years (scenario 1), this structure is responsible for 67.04 kg CO_2 eq., which value is considerably lower than the embodied impact of the conventional slab (182.31 kg CO_2 eq.). However, the integration of installations in the structure may reduce the ESL of the CSC Slab to 20 years (scenario 2). As a result, this building element is responsible for 18.82 kg CO_2 eq. more than the conventional slab.

In the first case study, we observe that the environmental benefits of The Sequential Roof are mainly attributed to the hybridization of acoustic and finishing functions within the roof structure, which avoids an additional suspended ceiling. However, the structural optimization and the hybridization of functions in the CSC Slab are not sufficient to compensate the potential increase of environmental impacts derived from the integrated design. The evaluation shows that a potential reduction of the service life to 20 years due to the integration of installations has important environmental consequences for the CSC Slab.

4.3 Environmental impacts including end of life

Digitally fabricated building elements such as the CSC Slab, where not only functions but also materials are hybridized, require further study of potential environmental implications associated with end-of-life processing of hybrid materials. The cradle-to-grave evaluation presented in Fig. 9 focuses

Fig. 6 GWP emissions of the production of the CSC Slab and conventional slab

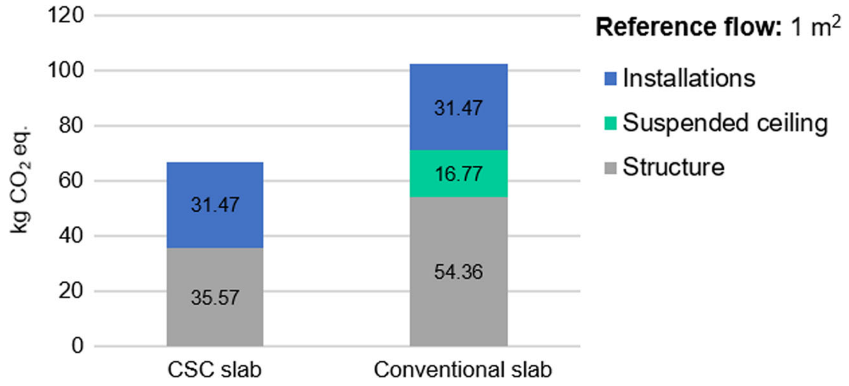
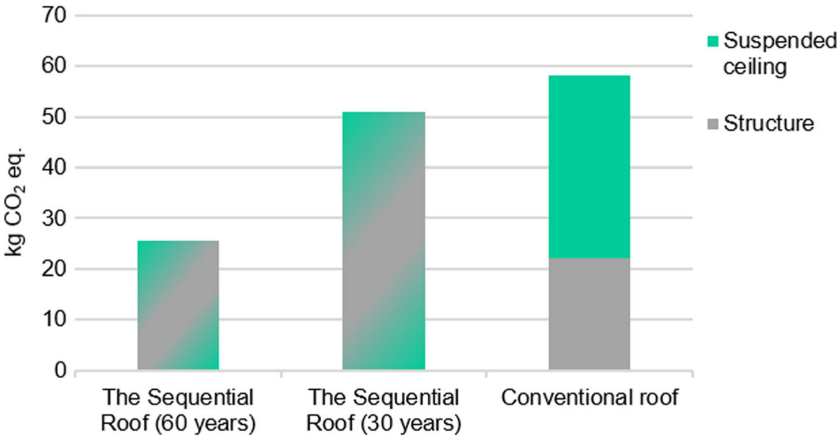


Fig. 7 Results of the application of the evaluation method to the first case study: The Sequential Roof. Environmental impacts expressed in GWP (kg CO_2 eq.)



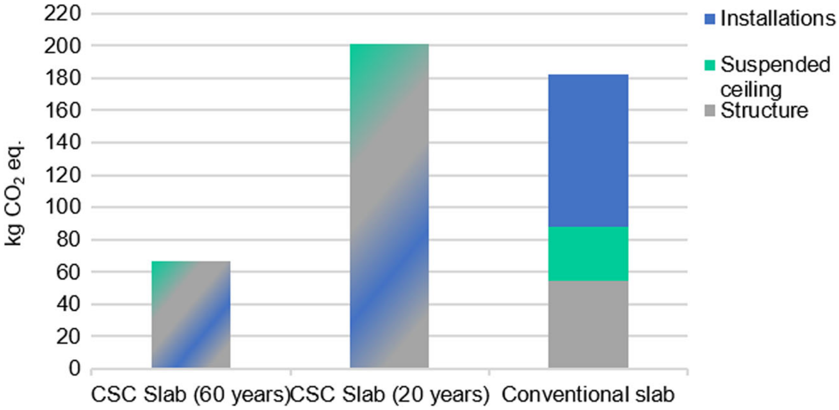
on the LCA comparison of the different modeling approaches and end-of-life scenarios for the digitally fabricated building element described in Sect. 2.2. The analysis demonstrates that recycling the CSC Slab can increase considerably life-cycle impacts compared to the landfill scenario. The avoided production of sand in open-loop recycling and the avoided disposal in closed-loop recycling does not compensate the high impact of the recycling process. Between recycling scenarios, we observe that the scenario with 100% of recycled silica sand content has the highest environmental impact in GWP and UBP. Therefore, recycled silica sand has larger environmental impacts than virgin silica sand. Simultaneously, the results show a big difference between modeling approaches. However, this difference is not relevant in this study because in both approaches (EoL and cut-off), the impact is higher than landfilling.

5 Discussion

The evaluation of two case studies enabled us to demonstrate that multi-functionality achieved through digital fabrication techniques results in a material-efficient construction process with important environmental benefits during production. However, we observed that the environmental impacts of multi-functional building elements considerably increase if their service life is reduced due to the need for refurbishing or replacing individual components integrated. The evaluation of The Sequential Roof showed that a decrease in the service life of the complete building element to 30 years causes an environmental impact that is still comparable with the impact of the conventional roof. However, the second case study showed that a possible reduction of the service life to 20 years caused by the integrated design of structures and installations was negative for the environmental performance of the CSC Slab. Therefore, multi-functional building elements should have an estimated service life (ESL) of a minimum of 30 years to bring environmental benefits compared to conventional construction. Nevertheless, the scenario where the service life of the entire structure is reduced to the service life of the functional layers is unlikely. If it is necessary to retrofit a hybrid building component with more performant functional layers, this could still be done in a conventional way. For example, suspended acoustic ceiling panels could be added to the CSC Slab if sufficient floor-to-ceiling height is accounted for. However, this conventional layered way of retrofitting would affect the esthetic aspect of digitally fabricated structures.

Finally, we performed a sensitivity analysis on the second case study to evaluate the potential additional environmental

Fig. 8 Results of the application of the evaluation method to the second case study: CSC Slab. Environmental impacts expressed in GWP (kg CO_2 eq.)



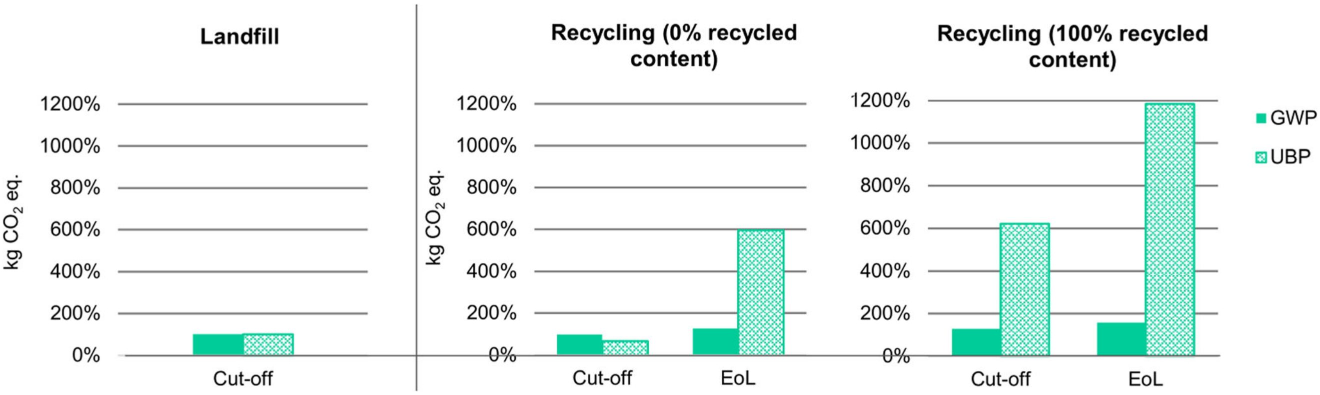


Fig. 9 LCA results for the CSC Slab relative to different end-of-life scenarios, use of recycled materials, and modeling approaches. Reference is the landfill scenario set at 100%

impacts associated with multi-functional structures with hybrid materials. The results showed that recycling hybrid structures such as the CSC Slab considerably increases environmental emissions. Specifically, recycling structures composed of silica sand bound with organic binders demand a thermal processing for decomposition of the binder. However, the thermal activation of organic resins is energy intensive and source of air emissions, such as volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) (Wang et al. 2007). The difficult separation and high environmental and economic impacts of recycling this type of structures usually lead to down recycling and little material recovery (Pickering 2006). Moreover, the lack of confidence in the quality of recycled materials and the potential health risks reduces the demand for recycled materials, which inhibits the development of waste management and recycling infrastructures in Europe (Yang et al. 2012). Consequently, the most common disposal method for hybrid materials and structures is landfill (Conroy et al. 2006). Environmental concerns regarding landfilling have led to a change in the European legislation. As part of the Construction 2020 strategy (European Parliament and Council 2012), the European Commission has developed a Construction & Demolition Waste Management Protocol (European Commission 2016) to address Construction and Demolition (C&D) waste. The protocol promotes a waste management system that gives priority to re-use, recycling, and material and energy recovery. Therefore, the proposed actions may limit the development of current digital fabrication techniques if they are not improved.

Design strategies such as material hybridization or an integrated design, which consist of mixing materials or building components, are common in digitally fabricated architecture. However, the technical, environmental, and economic constraints may limit their implementation in construction. To counteract it, designers should focus on design strategies such as functional hybridization, which provide multi-functionality without additional components. However, we recommend to study carefully the service life of building functions that intend to be hybridized to avoid a drastic reduction in the ESL of the complete structure. Further studies should analyze the service life of digitally fabricated building elements. Improved service life data would lead to a more consistent evaluation with the developed methodology. Nevertheless, the ideal scenario from a sustainable perspective would be to ensure enough design adaptability in multi-functional building elements through the integration of components that are easy to separate to enable maintenance during their service life and facilitate recycling at the end of life. Design decisions are of high importance to avoid low environmental performance of multi-functional building elements. Especially end-of-life impacts should be considered when designing the structure, for instance through material optimization strategies or a design for disassembly. Simultaneously, the use of hybrid materials in construction requires the development of alternative materials and constructive systems, such as inorganic binders (Odaglia et al. 2018). 3D printing with geopolymers avoids the thermal recycling to decompose furan/phenolic binders and the emissions caused by these components. This reduction of contaminants is especially relevant to comply with indoor air quality (IAQ) normative when using 3D-printed structures in the construction sector.

6 Conclusions

The study presented in this paper aimed to evaluate the potential environmental consequences of multi-functionality in digital fabrication. With this objective, we evaluated the global warming potential and ecological scarcity of two multi-functional building elements with a comparative method based on the life-cycle assessment (LCA), which considered service life uncertainty. The evaluation of the case studies showed that multi-functionality brings high environmental benefits during production, associated with the reduction of material and costs. However, this study showed that the considered environmental impact of digitally fabricated building elements increases over conventional construction if their service life is reduced due to functional integration. Our results are limited to a craddle-to-gate system, not considering service life impacts generated by different thermal functional properties of compared elements. Indeed, a difference in thermal resistance between compared solutions would result in a difference of energy consumption of the building. This aspect should be considered in the building design. The system was completed to the assessment of end-of-life scenarios to analyze the additional environmental risks of multi-functional building elements with material hybridization. Hybrid materials enable material efficiency during production but raise the question of recyclability at the end of life. The results of the environmental assessment of a case study showed that recycling structures with hybrid materials can be energy intensive and source of air pollutants. The research conducted in this paper allowed us to identify key design criteria to avoid a decrease in the environmental performance of multi-functional building elements. On the one hand, the design adaptability must be a priority to enable maintenance and facilitate material separation for recycling at the end of life. On the other hand, alternative materials and waste management systems must be developed to reduce end-of-life impacts of structures with hybrid materials.

Another important finding emerging from the study is the need to adapt standard environmental assessment methods for digital fabrication processes. This study could not consider potential benefits of digital fabrication which are difficult to quantify. The geometric freedom and potential for optimization and mass customization of building elements associated with digital fabrication can enable the construction of better architectural spaces which can in turn have a longer service life due to the economic factors associated with higher design quality standards. Optimized structural design which uses less material can have a knock-on benefit for sub-structures and in turn extend the physical service life of structures. Therefore, given the ability of digital fabrication to produce custom solutions for particular contexts, the environmental benefit of multi-functionality in buildings could be even higher than what is already identified in this study based on statistical data associated with conventional construction methods.

Funding information This research was supported by the National Competence Centre for Research, NCCR Digital Fabrication, which was funded by the Swiss National Science Foundation (project number 51NF40_141853).

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