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1 **Environmental assessment of multi-functional building elements** 2 **constructed with digital fabrication techniques**

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7

8 **Abstract**

9 *Purpose*

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

18 *Methods*

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

27 *Results and discussion*

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

34 *Conclusions*

35 The results from the case studies allow the identification of key environmental criteria to consider during the design

36 of digitally fabricated building elements. Multi-functionality provides material efficiency during production, but
37 design adaptability must be a priority to avoid a decrease in their environmental performance. Moreover, the high
38 environmental impacts caused by end-of-life processing should be compensated during design.

39 *Keywords*

40 Digital fabrication, LCA, service life, multi-functionality, hybrid materials, end of life.

41

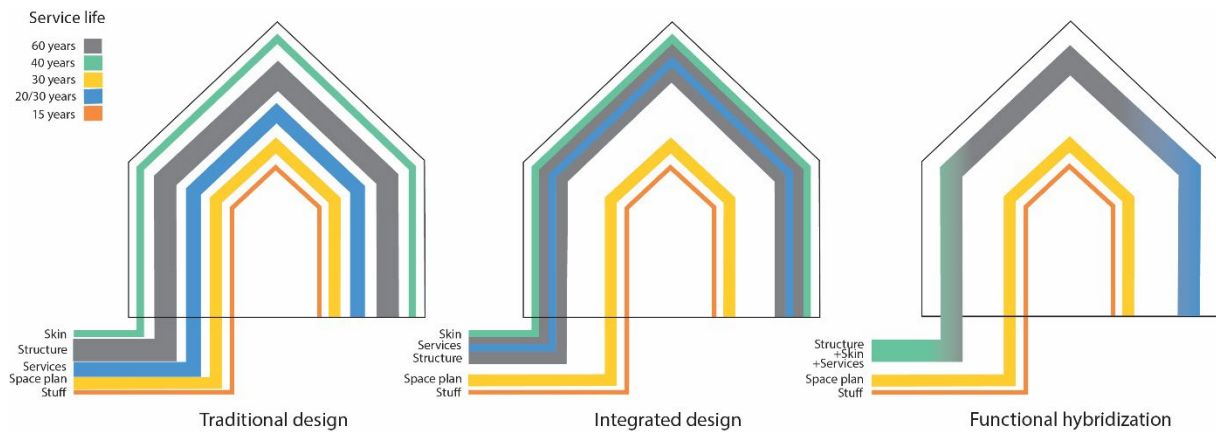
42 **1 Introduction**

43 Traditionally, buildings are conceived as a sequential and layered process with independent architectural elements
44 (e.g. slabs or exterior wall). As showed in Brand (1995), building elements can be organized in functions with
45 different service lives, from the longest (structure) to the shortest (space plan). As a consequence, classic
46 sustainable design strategies have promoted the separation of functions through layered building construction,
47 which enables flexibility in use and reduction of material waste when retrofitting buildings (Brancart et al. 2017).
48 In contrast, novel computational methods promote customization and material reduction through formal, structural
49 and material integration (Oxman and Rosenberg 2007). Computational design strategies together with additive
50 fabrication are proliferating in construction and demonstrate strong potential to construct complex structures
51 (Labonnote et al. 2016). Moreover, Agustí-Juan et al. (2017a) demonstrated that the production of large-scale
52 complex structures through digital fabrication techniques has a high environmental potential, without carrying
53 additional environmental costs associated with complex formworks, etc. However, this does not mean that
54 complexity in architecture has always an environmental advantage. It is decisive to evaluate whether this
55 complexity is needed to reduce material content in the structure or whether it has only aesthetic purposes. For the
56 reduction of environmental impacts, the structural complexity must be the result of material reduction strategies
57 such as structural optimization or multi-functionality.

58 Published literature on additive manufacturing applied to construction agrees on the potential of digital
59 technologies to facilitate the production of multi-functional building elements (Labonnote et al. 2016). Multi-
60 functional architecture can be the result of different design strategies: integrated design, functional hybridization
61 and material hybridization (De Schutter et al. 2018). On the one hand, buildings are nowadays highly complex
62 systems with multiple services, such as heating, lighting, acoustics, etc. The traditional linear design process, where
63 the different building systems are built sequentially, is not suitable to create high-performance buildings. The
64 design needs of the different systems must be considered from the beginning of the architectural design (Lechner
65 2015). As a result, complex geometries offer the possibility to integrate services such as piping or insulation in the
66 structure of building elements. For instance, Block et al. (2017) presented a complex shell roof that integrates
67 cooling, heating, photovoltaics and thermal insulation in its lightweight structure. The integrated design process
68 makes possible synergies between building systems that further improve the performance of a project. Moreover,
69 integrated building elements are associated with the reduction of building materials during production.

70 On the other hand, current research on digital fabrication methods have showed the potential of hybridizing
71 functions in complex building elements. The structure can provide additional performance (e.g. acoustics) through
72 its complex geometry, which saves an additional building component to provide this function. As a result,
73 architectural components, such as structure and insulation, are no longer separated in functions, but rather

74 integrated through the informed distribution of material (Oxman and Rosenberg 2007). Two examples of digitally
 75 fabricated building elements with functional hybridization are the 3D printed concrete walls presented in Gosselin
 76 et al. (2016). The study describes two structural elements designed and fabricated targeting multi-functionality
 77 through geometrical complexity. Specifically, the first wall example demonstrates that the thermal insulation
 78 efficiency can be improved 56% in comparison to a classic wall through geometric optimization. The second
 79 example describes a wall element, whose holes geometry provides enhanced soundproofing properties. Fig. 1
 80 shows a schematic explanation of the difference between integrated design and functional hybridization.



81
 82 *Fig. 1* Comparison of functions between traditional design, integrated design and functional hybridization. The
 83 color of the layers represent the service life (based on Brand (1995)).

84
 85 Finally, multi-functionality can also be achieved through material hybridization, such as cementitious materials
 86 with very low thermal conductivity achieved through the addition of wood or thermally activated concrete enriched
 87 with phase-change materials. The combination of materials, each responsible for a specific function such as
 88 compression load-bearing, tensile load-bearing, insulation, etc. offers many opportunities for digitally fabricated
 89 smart structures such as weight reduction or increased durability (De Schutter et al. 2018).

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

101 The aim of this paper is to quantitatively study the environmental risks and opportunities of multi-functionality in
 102 digitally fabricated building elements. Firstly, a method based on the Life Cycle Assessment (LCA) framework is
 103 applied to evaluate the influence of functional integration and hybridization on the environmental performance of

104 digitally fabricated architecture, considering service life uncertainty. The evaluation consists of a cradle-to-gate
 105 comparison of impacts between a multi-functional digitally fabricated building element and a conventional one.
 106 The method is applied to evaluate two case studies of digitally fabricated structures: The Sequential Roof and
 107 Concrete-Sandstone Composite (CSC) Slab. Secondly, the evaluation of the second case study is extended to a
 108 cradle-to-grave analysis to tackle additional environmental implications associated with material hybridization.
 109 Specifically, a LCA focused on end-of-life phase is applied to evaluate the potential environmental impacts on
 110 recycling loops. The results of both analyses enable to define general guidelines for the design of multi-functional
 111 building elements constructed with digital fabrication techniques.

112

113 2 Methods

114 2.1 Evaluation of multi-functional building elements

115 In this section, we present the method selected for the environmental evaluation of multi-functional building
 116 elements. The EN 15978 European Standard (CEN EN 2011) specifies a calculation method of the environmental
 117 performance of buildings based on the Life Cycle Assessment (LCA) framework (ISO 2006). Specifically, the
 118 standard defines the environmental performance of buildings as the sum of the embodied energy of building
 119 materials plus the energy and water consumed during the use phase. The scope of this evaluation focuses on a
 120 cradle-to-gate analysis at the building element scale. Therefore, only the environmental impact of building
 121 materials production is considered in the method. Further research should be conducted to understand how water
 122 and energy consumption during operation can be integrated. Similar to the approach presented in Hoxha et al.
 123 (2014) to calculate the environmental performance of buildings, the environmental impact of conventional
 124 building elements can be calculated as a decomposition in c building components:

$$125 \quad I_{elem}^{conv} = \sum_{i=1}^c I_{comp_i}^{conv} * n_i \quad (1)$$

126 Where I_{elem}^{conv} is the environmental impact of the conventional building element and $I_{comp_i}^{conv}$ is the environmental
 127 impact of each conventional building component and n_i is the number of times that each component has to be
 128 replaced during the service life of the building. $I_{comp_i}^{conv}$ and n_i are calculated following equations 2 and 3:

$$129 \quad I_{comp_i}^{conv} = m_i * k_i \quad (2)$$

$$130 \quad n_i = \frac{SL_{build}}{ESL_{comp_i}^{conv}} \quad (3)$$

131 Where m_i is the mass of each building component, k_i is the environmental impact of one unit mass of each building
 132 component, SL_{build} is the service life of the building and $ESL_{comp_i}^{conv}$ is the estimated service life of each component.
 133 In contrast, multi-functional digitally fabricated structures combine the different building components in a single
 134 element. Therefore, we assume a single service life for the whole building element, which is usually defined by
 135 the component with a shortest lifetime. Consequently, the environmental performance of a multi-functional
 136 digitally fabricated building element is calculated according to equation 4:

$$137 \quad I_{elem}^{dfab} = n * \sum_{i=1}^c I_{comp_i}^{dfab} \quad (4)$$

138 Where I_{elem}^{dfab} is the environmental impact of the digitally fabricated building element, n is the number of times that
 139 the building element has to be replaced during the service life of the building and $I_{comp_i}^{dfab}$ is the environmental
 140 impact of each building component. $I_{comp_i}^{dfab}$ is calculated following the equation for the calculation of $I_{comp_i}^{conv}$ (see
 141 equation 2) and n according to equation 5, where ESL_{elem}^{dfab} is the estimated service life of the digitally fabricated
 142 building element:

$$143 \quad n = \frac{SL_{build}}{ESL_{elem}^{dfab}} \quad (5)$$

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

$$148 \quad I_{elem}^{dfab} < I_{elem}^{conv} \quad (6)$$

149 The complete equation developed to evaluate multi-functional digitally building elements is shown in equation 7.
 150 Specifically, the impact of the digitally fabricated element is compared with the impacts of the components that
 151 constitute the conventional element. These additional components needed in conventional construction are avoided
 152 in digital fabrication due to multi-functionality. Finally, equation 8 represents the two alternative service life
 153 scenarios considered for the digitally fabricated element (ESL_{elem}^{dfab}). Due to service life uncertainty derived from
 154 multi-functionality, the ESL of the hybridized component with the longest service life ($ESL_{comp_{max}}^{dfab}$) and the ESL
 155 of shortest one ($ESL_{comp_{min}}^{dfab}$) are considered.

$$156 \quad \frac{SL_{build}}{ESL_{elem}^{dfab}} * \sum_{i=1}^c I_{comp_i}^{dfab} < \sum_{i=1}^c I_{comp_i}^{conv} * \frac{SL_{build}}{ESL_{comp_i}^{conv}} \quad (7)$$

$$157 \quad ESL_{elem}^{dfab} = [ESL_{comp_{max}}^{dfab}, ESL_{comp_{min}}^{dfab}] \quad (8)$$

158

159 2.1.1 Service life of building elements

160 The main difficulty of applying the evaluation method is the estimation of the service life of the conventional
 161 building components (ESL_{comp_i}) and the digitally fabricated element (ESL_{elem}). The International Standard ISO
 162 15686 (ISO 2000) defines service life as the period of time after installation in which the buildings or their elements
 163 meet or exceed the minimum performance requirements. These requirements may be intrinsic to the physical
 164 performance or be imposed by economic or subjective factors (Rincón et al. 2013). Multiple factors influence the
 165 service life of buildings and building elements, leading to a high uncertainty in the estimation of their service life
 166 (Hoxha et al. 2014). The ISO 15686 standard tackles the problems of service life prediction and provides a
 167 methodology for estimating the service life. This methodology is based on two different service life concepts: the
 168 Reference Service Life (RSL) and the Estimated Service Life (ESL). Emídio et al. (2014) define the RSL as the
 169 expected service life under normal use and maintenance conditions, which is identified with the physical or
 170 technical service life. The RSL is related with the deterioration of the materials and building elements over time
 171 mainly due to the action of degradation agents and natural ageing processes (humidity, UV, temperature, etc....).
 172 But, as shown by Aktas and Bilec (2012), the RSL should be corrected with modifying factors related to quality,

173 design, environment, use and maintenance to predict the ESL or real service life of a building or building element.
174 Multi-functionality may reduce the design adaptability of a building element and its ability to accommodate
175 functional changes over time. Therefore, the ESL of a multi-functional digitally fabricated structure is mainly
176 driven by functional factors. The functional service life or functional obsolescence described by Silva et al. (2016)
177 is considered as ESL for the evaluation presented in this paper. Due to the high variability of functional service
178 life data present in the literature (Hoxha et al. 2014), average service life values per building component were
179 extracted from the Swiss standard SIA 2032 (SIA 2010) for the present evaluation.

180

181 **2.1.2 Environmental impact assessment**

182 For the evaluation of each case study with the method proposed, a functional unit of one m² of digitally fabricated
183 building element was compared with one m² of a conventional structure with equal functional and structural
184 performance. The system boundaries of the assessment included the environmental impacts from raw material
185 extraction and transport, building materials production, robotic fabrication and replacement of building
186 components during service life (EN 15978 modules: A1-A3, A5 and B4). For the digitally fabricated building
187 element, two alternative ESL scenarios were defined due to the uncertainty on the service life associated with the
188 multi-functionality. A complete replacement of the building element was considered when it reached the end of
189 life. In contrast, an ESL was defined for each component of the conventional building element and they were
190 replaced independently when each one reached the end of its service life. The evaluation was implemented in the
191 software SimaPro 8 and because of the Swiss context of the projects, Ecoinvent v3.3 (Weidema B. P. 2013)
192 database was used to calculate the environmental impacts of the building elements. Additionally, environmental
193 information regarding certain standard components (e.g. installations) was extracted from the Bauteilkatalog
194 (Holliger Consult GmbH 2017) database due to the lack of precise data. The Intergovernmental Panel on Climate
195 Change (IPCC) 2013 GWP 100a V1.03 was chosen as impact assessment method (IPCC 2013), which is based on
196 a single impact category (kg CO₂ eq.). This method was chosen because the evaluation focused on analyzing the
197 effect of service life uncertainty on the environmental impact and the question of pollution was not discussed.

198

199 **2.2 Evaluation of hybrid building elements**

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

211 On the one hand, two modelling approaches were considered: recycled content approach or Cut-off and End-of-

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

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

225 For modelling the different scenarios, we used data from Swiss production processes and the Swiss energy mix.
226 The impact assessment methods selected were the IPCC 2013 GWP 100a for the calculation of the Global
227 Warming Potential (GWP) in kg CO₂ eq., and the Ecological Scarcity Method 2013 (UBP) in eco-points. The
228 ecological scarcity method focuses on the evaluation of pollutant emissions, which are commonly released during
229 end-of-life processing. These two impact methods were chosen because they are the main environmental impacts
230 assessed in Swiss standards (in addition with energy) (CRB 2011).

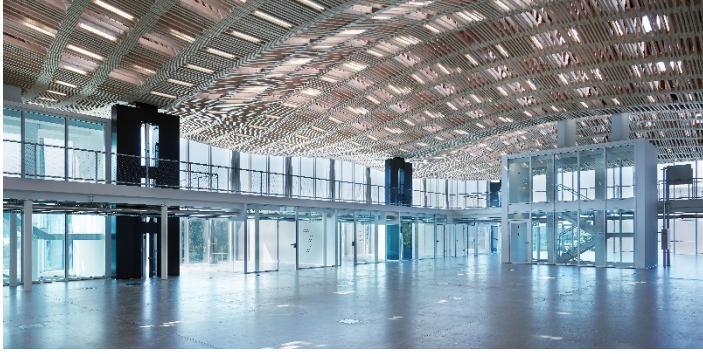
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232 **3 Case studies**

233 **3.1 The Sequential Roof**

234 **3.1.1 Description**

235 The first multi-functional case study selected was “The Sequential Roof” (Gramazio Kohler Research, ETH
236 Zurich), the wooden roof of the Arch_Tec_Lab at ETH Zurich. “The Sequential Roof” consists of 168 single
237 trusses of C24 fir/spruce wood, which are woven into a 2,308 m² freeform roof design (see *Fig. 2*). The structure
238 has a total wood volume of 384 m³, including 48624 timber slats of approximately 100-150 cm in length that were
239 robotically assembled using 815,984 steel nails. The automated assembly of the large-scale load bearing structures
240 was performed by a custom six-axis overhead gantry robot in the manufacturer’s factory. The off-site digital
241 fabrication process enabled a reduction in construction time to 12 hours per truss, which is considerably lower than
242 manual assembly (Willmann et al. 2016). The project demonstrates the potential of combining digital fabrication
243 methods with timber for the creation of complex structural elements at architectural scale. The architectural
244 complexity enables the structure to provide finishing and acoustic functions, avoiding additional elements such as
245 suspended ceilings. The hybridization of functions with high environmental impact in the structure reduces
246 approximately 40% of CO₂ emissions compared with a conventional structure with similar performance (Agustí-
247 Juan and Habert 2017).



248

249 *Fig. 2* “The Sequential Roof” (Gramazio Kohler Research, ETH Zurich).

250

251 3.1.2 Definition of product systems

252 One reference flow was chosen for evaluating the case study: one m² of The Sequential Roof and one m² of
 253 conventional wooden roof structure with suspended ceiling. Both building elements have the same structural and
 254 functional factors as well as materiality in order to be comparable. Specifically, the acoustic and finishing functions
 255 hybridized in the digitally fabricated roof are performed by the suspended ceiling with rockwool insulation in the
 256 conventional roof. For the definition of each product system, we collected the material composition and fabrication
 257 information of both roofs from Agustí-Juan and Habert (2017). For the Sequential Roof, the energy consumption
 258 of the robot and a desktop computer (Williams and Sasaki 2003) during prefabrication were included in the
 259 assessment. Moreover, service life data was collected for each building component. The complete data of both
 260 product systems can be found in the supplementary information.

261 *Production*

262 Based on the product system data of The Sequential Roof, *Table 1* shows the Life Cycle Inventory (LCI) built with
 263 Ecoinvent 3.3 processes for the impact assessment.

264 *Table 1* LCI of The Sequential Roof production (1 m²).

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

265

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

268 *Table 2* LCI of the conventional roof production (1 m²).

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

269 **Service life**

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

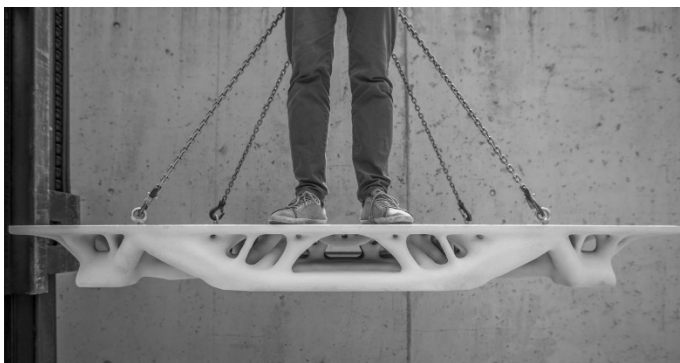
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279 **3.2 Concrete-Sandstone Composite Slab**

280 **3.2.1 Description**

281 The second case study selected for analysis was the “CSC Slab” prototype (Digital Building Technologies, ETH
282 Zurich), a floor slab prefabricated through additive digital fabrication techniques. The “CSC Slab” is a 1.8 x 1 x
283 0.15 m³ hybrid structure which relies on ultra-high performance, fiber-reinforced concrete (UHPFRC) for its
284 structural capacity. The complex shape is inherited from a 6-to-10-mm-thick 3D-printed shell which acts as
285 permanent formwork for the concrete (see Fig. 3). The slab was designed using topology optimization algorithms
286 to reduce material, minimize the strain in the slab under uniform load and meet fabrication constraints. The design
287 was 3D printed in silica sand using a binder jetting Ex-One S-MAX 3D printer (Meibodi et al. 2017). After post-
288 processing, UHPFRC with 2.75% vol. steel fibers was cast in the formwork. The average concrete thickness
289 achieved is 30 mm, enough to provide the structural strength when tested with a 2,500 KN/m² distributed load.
290 The use of digital fabrication methods enables the optimization of the structure for material reduction and the
291 production of detailed and complex geometries (Jipa et al. 2016). The structural complexity of the slab enables the
292 hybridization of the exposed structure with an acoustic function or with an ornamental, three-dimensional finish.
293 Moreover, building services and installations can be integrated in the structure, avoiding the need for a suspended
294 ceiling.

295



296

297 *Fig. 3* Prototype of “CSC Slab” (Digital Building Technologies, ETH Zurich).

298

299 **3.2.2 Definition of product systems**

300 One reference flow was chosen for evaluating this case study: one m² of CSC Slab and one m² of conventional
 301 reinforced concrete slab with suspended ceiling. Both building elements have the same structural, material and
 302 functional factors to be comparable. Specifically, the acoustic and finishing functions which can be hybridized in
 303 the digitally fabricated slab are performed by the suspended ceiling from the conventional slab. Moreover, both
 304 building elements include the same standard installations required by normative. For the definition of the product
 305 systems, the material composition and fabrication information of the CSC Slab was collected on-site and from the
 306 literature. Moreover, service life data for each building component and data related to the three end-of-life
 307 scenarios detailed in the section 2.2 were collected. The complete data of the product systems can be found in the
 308 supplementary information.

309 **Production**

310 The CSC Slab is a hybrid structure composed of a 3D-printed permanent formwork filled with ultra-high
 311 performance, fiber-reinforced concrete (UHPC). Based on the product system data of the CSC Slab, *Table 3*
 312 shows the Life Cycle Inventory (LCI) built with Ecoinvent 3.3 for the impact assessment. Moreover, the impact
 313 of the integrated installations was included in the assessment. This impact was obtained from the sum of the
 314 emissions from electrical installations, heat distribution, ventilation system and sanitary facilities in the
 315 Bauteilkatalog.

316 *Table 3* LCI of the CSC Slab production and end of life (1 m²).

Process	Unit	Amount
UHPC	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

317

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

321 *Table 4* Life cycle inventory of conventional slab production (1 m²).

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

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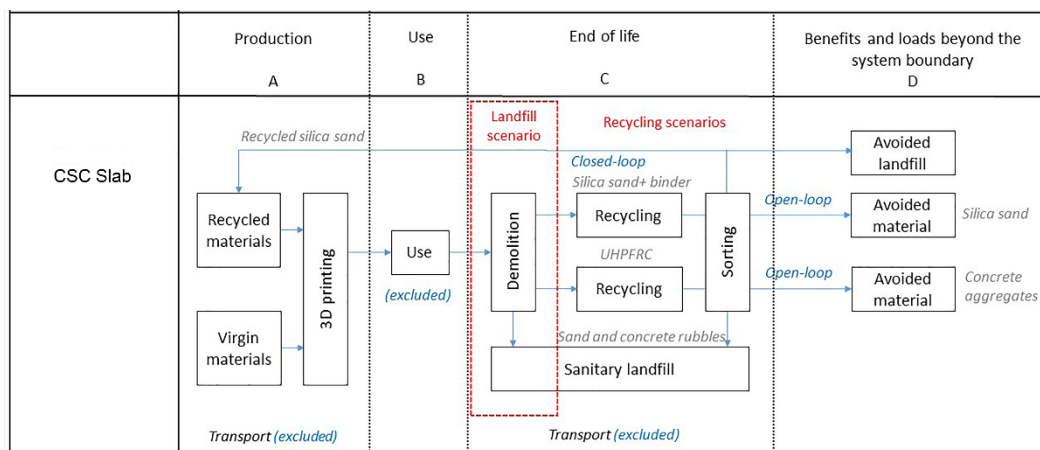
323 **Service life**

324 We evaluated the CSC Slab and conventional slab along 60 years of service life, corresponding to the lifetime of
 325 a building. The analysis of each building element was performed by component, which needed replacement if their

326 service life was inferior to the lifetime of the building. For the CSC Slab, we studied two alternative scenarios due
 327 to the uncertainly derived from the hybridization of acoustic and finishing functions and the integration of
 328 installations in the structure. Scenario 1 assumed that the service life of the CSC Slab could be as long as a
 329 conventional structure (60 years). Scenario 2 considered that the integration of installations could lead to the
 330 complete replacement of the structure when installations need to be replaced after 20 years. For the conventional
 331 slab, a service life of 60 years was considered for the structure, 30 years for the suspended ceiling and 20 years for
 332 the installations. A complete replacement was assumed when a component reached the end of its functional service
 333 life.

334 **End of life**

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



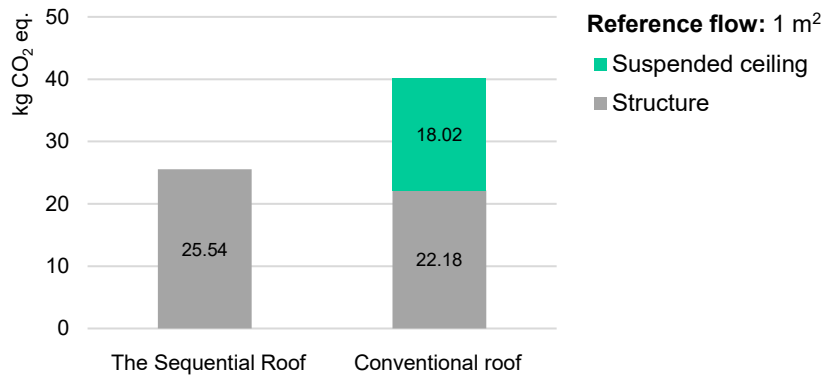
346
 347 Fig. 4 System boundaries considered for the life cycle assessment of the CSC Slab.

348
 349 **4 Results**

350 **4.1 Environmental impacts of production.**

351 Based on the material and fabrication information collected from Agustí-Juan and Habert (2017), we performed
 352 an environmental evaluation of the impacts associated with the production of the building elements to be compared.
 353 The LCA results were broken down into building components: structure and suspended ceiling. Fig. 5 graphically
 354 depicts the Global Warming Potential (GWP) impacts caused by the production process of both building elements.

355 We observe that the hybridization of acoustic and finishing functions in the structure of The Sequential Roof avoids
 356 a suspended ceiling, which decreases the impact of this element to a total of 25.54 kg CO₂ eq. In contrast, the
 357 conventional roof is responsible for 40.20 kg CO₂ eq. due to the need for a suspended ceiling (18.02 kg CO₂ eq.)
 358 to hide installations and finish the structure (22.18 kg CO₂ eq.). These environmental data demonstrate that the
 359 multi-functionality achieved through digital fabrication techniques enables a material-efficient construction
 360 process.

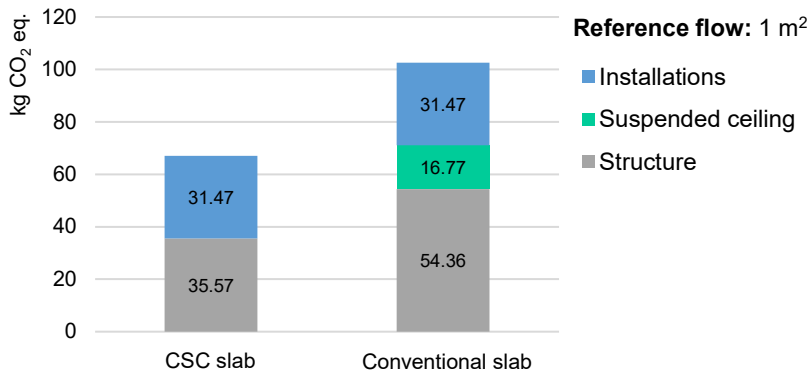


361

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

363

364 Based on the material and fabrication data collected, we evaluated the production impacts of the CSC Slab and the
 365 conventional slab. The LCA results were broken down into three building components: structure, suspended
 366 ceiling and installations. *Fig. 6* graphically depicts the Global Warming Potential (GWP) impacts of both building
 367 elements. We observe that the Smart Slab is responsible for a total of 67.04 kg CO₂ eq. divided between structure
 368 and integrated installations. The lower impact of the CSC Slab compared to a conventional slab (102.60 kg CO₂
 369 eq.) is mainly attributed to the structural optimization, which reduces considerably the environmental impact of
 370 the structure compared to a conventional one (54.36 kg CO₂ eq.). Furthermore, the hybridization of finishing and
 371 acoustic functions in the structure avoids the need for an additional suspended ceiling to provide these functions,
 372 which is responsible for 16.77 kg CO₂ eq. in a conventional slab. Similarly to the previous case study, the present
 373 comparison demonstrates that through multi-functionality, significant environmental benefits are gained during
 374 production.



375

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

377

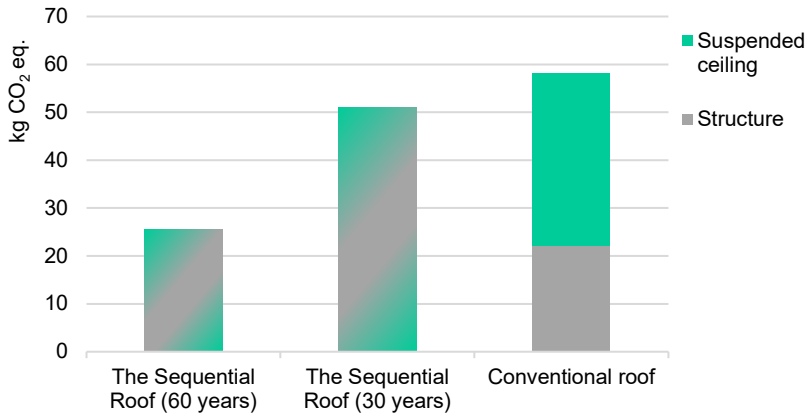
378 4.2 Environmental impacts including service life.

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

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

$$386 \frac{SL_{build}}{[ESL_{str}^{dfab}, ESL_{ceil}^{dfab}]} * I_{str}^{dfab} < I_{str}^{conv} * \frac{SL_{build}}{ESL_{str}^{conv}} + I_{ceil}^{conv} * \frac{SL_{build}}{ESL_{ceil}^{conv}} \quad (9)$$

387 Where I_{str}^{dfab} is the production impact of the digitally fabricated structure and $[ESL_{str}^{dfab}, ESL_{ceil}^{dfab}]$ represent the
 388 two service life scenarios for The Sequential roof: the estimated service life of a structure and a suspended ceiling.
 389 On the other side, I_{str}^{conv} is the production impact of the conventional structure, ESL_{str}^{conv} is the service life of this
 390 structure, I_{ceil}^{conv} is the production impact of the conventional ceiling and ESL_{ceil}^{conv} is the service life of this
 391 suspended ceiling. The results of the evaluation are graphically depicted in Fig. 7:



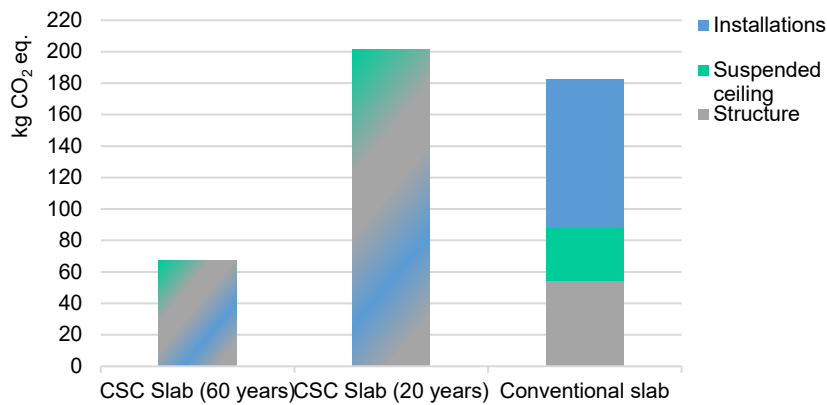
392 Fig. 7 Results of the application of the evaluation method to the first case study: The Sequential Roof.
 393 Environmental impacts expressed in GWP (kg CO₂ eq.).

394

395 For the evaluation of the environmental implications of multi-functionality on the CSC Slab, we applied the
 396 method described in section 2.1 for its comparison with the conventional slab. Equation 10 shows the method
 397 application to this case study:

$$398 \frac{SL_{build}}{[ESL_{str}^{dfab}, ESL_{inst}^{dfab}]} * (I_{str}^{dfab} + I_{inst}^{dfab}) < I_{str}^{conv} * \frac{SL_{build}}{ESL_{str}^{conv}} + I_{ceil}^{conv} * \frac{SL_{build}}{ESL_{ceil}^{conv}} + I_{inst}^{conv} * \frac{SL_{build}}{ESL_{inst}^{conv}} \quad (10)$$

399 Where $(I_{str}^{dfab} + I_{inst}^{dfab})$ is the impact of the digitally fabricated structure with integrated installations and
 400 $[ESL_{str}^{dfab}, ESL_{inst}^{dfab}]$ represent the estimated service life of a structure and installations, considered as possible
 401 service life scenarios for the CSC Slab. On the other side, I_{inst}^{conv} is the impact of conventional installations and
 402 ESL_{inst}^{conv} is the service life of these installations. The results of the evaluation are graphically depicted in Fig. 8:



403 *Fig. 8* Results of the application of the evaluation method to the second case study: CSC Slab. Environmental
 404 impacts expressed in GWP (kg CO₂ eq.).

405

406 The results of the evaluation show that the GWP impact of The Sequential Roof are lower than the conventional
 407 roof in both scenarios compared. Considering an ESL of 60 years (scenario 1), this digitally fabricated roof is
 408 responsible for approximately half of the GWP impact (25.54 kg CO₂ eq.) from the conventional roof. However,
 409 considering a reduction of the ESL to 30 years (scenario 2), the GWP impact of The Sequential Roof reaches 51.08
 410 kg CO₂ eq. Therefore, even with a higher replacement rate caused by the multi-functionality of the structure, the
 411 environmental impact of The Sequential Roof would be lower than the conventional roof. In contrast, the
 412 comparison of GWP impacts between the CSC Slab and the conventional slab vary depending on the service life
 413 scenario. If we assume that the CSC Slab is replaced after 60 years (scenario 1), this structure is responsible for
 414 67.04 kg CO₂ eq., which value is considerably lower than the embodied impact of the conventional slab (182.31
 415 kg CO₂ eq.). However, the integration of installations in the structure may reduce the ESL of the CSC Slab to 20
 416 years (scenario 2). As a result, this building element is responsible for 18.82 kg CO₂ eq. more than the conventional
 417 slab.

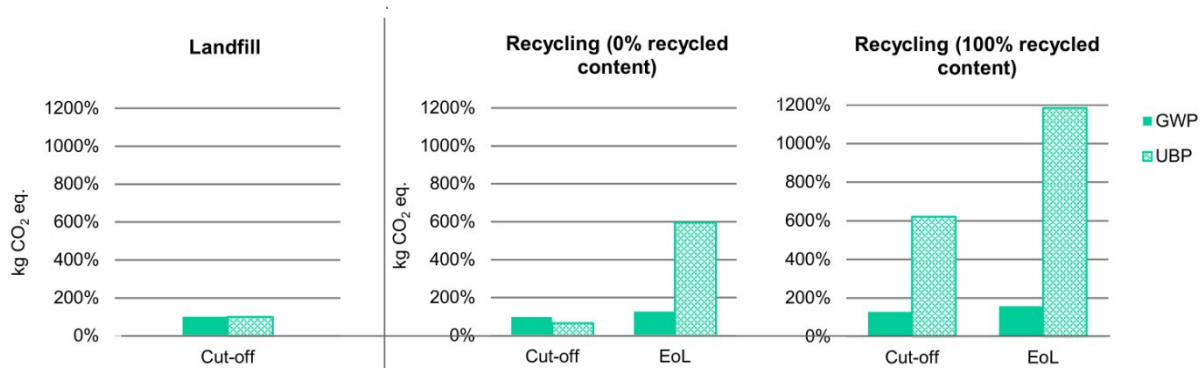
418 In the first case study, we observe that the environmental benefits of The Sequential Roof are mainly attributed to
 419 the hybridization of acoustic and finishing functions within the roof structure, which avoids an additional
 420 suspended ceiling. However, the structural optimization and the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

424

425 4.3 Environmental impacts including end of life.

426 Digitally fabricated building elements such as the CSC Slab, where not only functions but also materials are
 427 hybridized, require further study of potential environmental implications associated with end-of-life processing of
 428 hybrid materials material hybridization. The cradle-to-grave evaluation presented in *Fig. 9* focuses on the LCA
 429 comparison of the different modeling approaches and end-of-life scenarios for the digitally fabricated building
 430 element described in section 2.2. The analysis demonstrates that recycling the CSC Slab can increase considerably
 431 life-cycle impacts compared to the landfill scenario. The avoided production of sand in open-loop recycling and

432 the avoided disposal in closed-loop recycling does not compensate the high impact of the recycling process.
 433 Between recycling scenarios, we observe that the scenario with 100% of recycled silica sand content has the
 434 highest environmental impact in GWP and UBP. Therefore, recycled silica sand has larger environmental impacts
 435 than virgin silica sand. Simultaneously, the results show a big difference between modelling approaches. However,
 436 this difference is not relevant in this study because in both approaches (EoL and Cut-off) the impact is higher than
 437 landfilling.



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

440

441 5 Discussion

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

457 Finally, we performed a sensitivity analysis on the second case study to evaluate the potential additional
 458 environmental impacts associated with multi-functional structures with hybrid materials. The results showed that
 459 recycling hybrid structures such as the CSC Slab, considerably increases environmental emissions. Specifically,
 460 recycling structures composed of silica sand bound with organic binders demands a thermal processing for
 461 decomposition of the binder. However, the thermal activation of organic resins is energy intensive and source of
 462 air emissions, such as volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) (Wang et al. 2007).

463 The difficult separation and high environmental and economic impacts of recycling this type of structures usually
464 leads to down recycling and little materials recovery (Pickering 2006). Moreover, the lack of confidence in the
465 quality of recycled materials and the potential health risks reduce the demand for recycled materials, which inhibits
466 the development of waste management and recycling infrastructures in Europe (Yang et al. 2012). Consequently,
467 the most common disposal method for hybrid materials and structures is landfill (Conroy et al. 2006).
468 Environmental concerns regarding landfilling have led to a change in the European legislation. As part of the
469 Construction 2020 strategy (European Parliament and Council 2012), the European Commission has developed a
470 Construction & Demolition Waste Management Protocol (European Commission 2016) to address Construction
471 and Demolition (C&D) waste. The protocol promotes a waste management system that gives priority to re-use,
472 recycling, and material and energy recovery. Therefore, the proposed actions may limit the development of current
473 digital fabrication techniques if they are not improved.

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

492

493 **6 Conclusions**

494 The study presented in this paper aimed to evaluate the potential environmental consequences of multi-
495 functionality in digital fabrication. With this objective, we evaluated the environmental impacts of two multi-
496 functional building elements with a comparative method based on the Life Cycle Assessment (LCA), which
497 considered service life uncertainty. The evaluation of the case studies showed that multi-functionality brings high
498 environmental benefits during production, associated with the reduction of material and costs. However, this study
499 showed that the environmental impact of digitally fabricated building elements increases over conventional
500 construction if their service life is reduced due to functional integration. The study was extended to a cradle-to-
501 grave evaluation to analyze the additional environmental risks of multi-functional building elements with material

502 hybridization. Hybrid materials enable material efficiency during production, but raise the question of recyclability
503 at the end of life. The results of the environmental assessment of a case study showed that recycling structures
504 with hybrid materials can be energy intensive and source of air pollutants. The research conducted in this paper
505 allowed us to identify key design criteria to avoid a decrease in the environmental performance of multi-functional
506 building elements. On the one hand, the design adaptability must be a priority to enable maintenance and facilitate
507 material separation for recycling at the end of life. On the other hand, alternative materials and waste management
508 systems must be developed to reduce end-of-life impacts of structures with hybrid materials.

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

519

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522 was funded by the Swiss National Science Foundation (project number 51NF40_141853).

523

524 **Appendix. Supplementary information**

525 Supplementary information regarding background data and results from the LCAs can be found in appendix.

526

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