Environmental Benefits when Reusing Load-Bearing Components in Office Buildings: A case study.

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ABSTRACT: This case study applies life-cycle assessment methods to the preliminary design of an office building in order to quantify the benefits achieved when reusing its load-bearing components. Results show that the production of the load-bearing system would account for 40% of the global warming potential indicator. The slabs are responsible for 65% of the environmental impacts among all structural elements and should be considered for reuse first. Compared to traditional constructions built from first-use material, a fictitious reuse of undamaged load-bearing components over three consecutive use cycles would reduce the global warming potential indicator by 25%. The global warming potential of reuse is eventually computed according to three repartition methods, highlighting the need to separate the life-cycle footprints related to production, use, and end-of-life more systematically.

KEYWORDS: Building life cycle assessment, Net zero energy building, Reuse.

1. INTRODUCTION

The reduction of the environmental footprint of buildings is of great importance because they are responsible for 42% of final energy demand and 35% of greenhouses gases emissions [1].

The prevalent strategy consists in minimizing the environmental impact of the operational phase of the building. Design parameters and active or passive solutions are optimized to reduce the scale and the impacts of the energy demand for heating, cooling, ventilation, domestic hot water, lighting, and appliances [2-4]. Another strategy consists in minimizing the impacts of the construction and the end-of-life of the building by replacing detrimental components [5-6] with components of lower impacts [7]. This second strategy not only reduces greenhouse gases emissions. It also responds to the exhaustion of raw materials and to waste management issues, which includes land use and pollution considerations. The building industry is the heaviest and most voluminous waste streams in the European Union [8].

Counteracting the systematic landfilling of construction components, end-of-life solutions have been developed to recover the embodied energy in those components, to recycle them in new ones, or to reuse them as they are. Energy recovery and recycling are two largely implemented approaches [9-10] with a real potential to reduce the environmental impact and the quantity of waste produced by building industry [11-12]. Still, recycling requires additional energy for transforming the components even though recycled components are usually of lower value than their sourced components. More importantly, energy recovery and recycling are in most cases applied before the actual obsolescence of the building component, which forces its premature replacement. Reuse is regarded as a more efficient solution [13].

The reuse of building components has been the object of numerous applications in practice [14-16]. Authors have also assessed the environmental benefits of reusing building components. Most of them consider that reused components have zero impact. Converging in quasi-similar results, they conclude that reuse reduces embodied energy and resources by 30% compared to traditional scenarios [17-19].

Other authors have assessed the environmental benefits of building projects whose components are designed to be reused in consecutive life cycle stages. According to Aye et al. [20], such option reduces embodied energy by 81%, 32% and 70% respectively for constructions in steel, concrete and timber. Akbarnezhad, et al. [21] show that designing to reuse structural elements in future building lifecycles reduce the embodied energy and carbon emissions respectively by 35% and 38%.

We believe that not only literature contains a limited number of studies but also that their results

are not uniform even though such cases are of crucial importance in both scientific and practical terms. Non-uniformity is due to various reasons, mainly related to the choice of functional unit, boundary of the study, hypothesis and assumptions, environmental product declaration's database or building project considered in the evaluations.

Looking forward to more rigorous evaluations, this paper discusses the assessment of the environmental impacts of a building designed to be reused, through a complete cradle-to-cradle cycle. We produce a time-dependent comparison of scenarios reusing and not reusing load bearing systems. Discrepancies of three methods to allocate the benefits of reuse are eventually introduced.

2. METHOD

Environmental impacts are here assessed according to the European standard [22], which breaks down the building in its life stages: production (A1-A3), construction (A4 & A5), use (B1-B7), end-of-life (C1-C4) and benefits (D). Based on this standard, the production phase (A1-A3) considers the environmental impacts associated to the production of building material and components. The impacts related to the transport of components from their production factory to the building site and all the impacts and processes for the construction of building are considered in the construction phase (A4-A5). The impacts related to maintenance, repair, replacement, the refurbishment of components and energy and water use during the operation phase are included in the use phase (B1-B7). The impacts related to the demolition or deconstruction of the building, to the transport of its components to the waste site, and to their elimination are taken into account in the end-of-life phase (C1-C4). Module D considers all probable benefits resulting from the recovery, recycling or reuse of building components.

As the main objective of this work is the evaluation of the reuse of building components, energy and water use during the operational phase is not considered into the boundary of the study. The impacts of these stages are anyway minor in low or net zero energy buildings [23].

The reference study period of the building is assumed as equal to 60 years and the chosen functional unit is a square meter of floor area per year. Regarding the transport of components from factory to the building site and the processes linked with the construction phase, assumptions are similar to those considered in [24]. For simplification reasons, it is assumed that the renovation of the building happens after 30 years of its use and only comprises the replacement of the technical installations, windows, and doors. The KBOB database is used for the evaluation of impacts as it is found as the most pertinent for the Swiss context. This database relies largely on Ecoinvent [25] and contains information about the environmental impacts of building materials and components, which are evaluated in accordance with the CEN standard [26].

The cumulative energy demand, non-renewable energy and global warming potential indicators are assessed as they are considered as the most important according "2000-watt society vision" [27].

Finally, the problematic of the allocation of the benefits of reused is tackled while reviewing the various methods proposed in [28].

3. CASE STUDY

The office building that is used as case study is described in [29] and illustrated on Figure 1. It is a preliminary design that has been specifically developed to estimate the future performance values of a yet-to-be-designed building in Fribourg, Switzerland. This upcoming building is meant to be representative of the future buildings' trends, according to the directives of the Council of the European Parliament, which requires all new buildings to be NZEBs by the end of 2020 [1]. Responding to this requirement the building has a very low environmental impact during its operational phase due to a well-insulated envelope (0.1 W/m2·K) and the implementation of a district heating system, solar panels, and photovoltaics panels, for covering heating, cooling and electricity demands. With an energy reference area of 6035 m² mostly for office purposes, the load-bearing structure is supposed to be reversible and without any strong link with other non-structural components and systems.

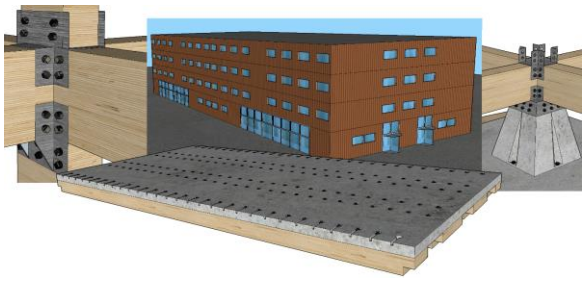
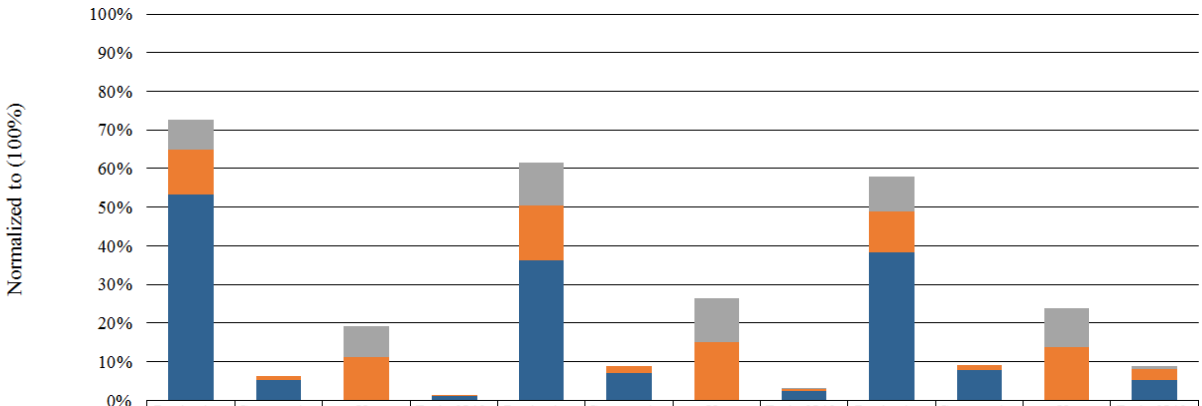


Figure 1: Conceptual design and some connectors.

The reinforced concrete foundation is connected to wooden beams and columns through steel connectors. Reversibility of the connections is everywhere ensured thanks to the use of bolts. The 3×6m-slab consists in a 0.1m-reinforced concrete layer bolted to 6×0.6×0.18m wooden beams. Following an approach similar to [30], we have assumed that a 40t crane would lift the components during construction process and that a 1000-watt drill would tighten the bolts. The duration for lifting a slab or a wall is assumed equal to 30 minute. The duration for drilling each bolt is assumed equal to 30 seconds.

4. RESULTS

The results obtained for the cumulative energy demand (CED), non-renewable energy (CEDnr) and global warming potential (GWP) indicators are presented on Figure 2.



	Cumulative energy demand				Nonrenewable				Global warming potential			
	Production	Construction	Use	End-of Life	Production	Construction	Use	End-of Life	Production	Construction	Use	End-of Life
Total	48.8 kWh/m² ERA yr				24.4 kWh/m² ERA yr				6.0 kg CO_2-eq/m² ERA yr			
Installations	3.8	0.0	3.9	0.0	2.7	0.0	2.8	0.0	0.6	0.0	0.6	0.0
Nonstructural elements	5.7	0.5	5.4	0.1	3.5	0.4	3.7	0.1	0.6	0.1	0.8	0.2
Structural elements	26.0	2.6	0.0	0.6	8.9	1.8	0.0	0.6	2.3	0.5	0.0	0.3

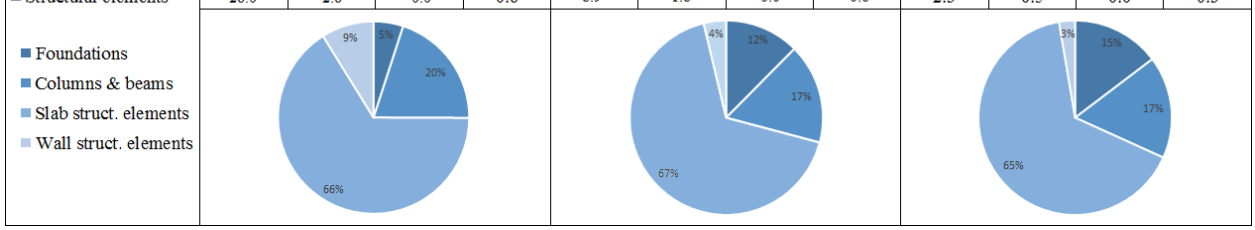


Figure 2: Environmental impacts.

A comparison of these impacts with the 2050 intermediate targets of the "2000-watt society vision" [27] – i.e. respectively 42 kWh/m² ERA yr, 36.1 kWh/m²ERA yr and 10 kg CO2-eq/m²ERA yr [30-32] shows that only the non-renewable energy and global warming potential criteria are fulfilled. A more-detailed analysis is required to understand what changes are needed in order to satisfy the CED criteria. To that purpose, the bottom of figure 2 details the relative contribution of each construction elements to the overall environmental impacts of the building.

For all indicators the production phase is the biggest responsible with 72%, 60% and 58% respectively regarding the CED, CEDnr and GWP indicators. Moreover, the production of the structural elements and in particular the production of the slabs accounts for the highest impacts. Their reuse is therefore greatly encouraged. Figure 3 presents the distribution of impacts over time when columns, beams, slabs, and walls are reused over three consecutive use phases. This scenario is ideal since each transition to a new use phase assumes no damage due to deconstruction, transport, storage or reconstruction. Moreover, this scenario implicitly assumes that all elements are reused, meaning that the new versions of the building are exactly similar and that all reused components have a longer lifespan than at least three times that of the building.

The results for the cumulative energy demand (black), non-renewable (red) and global warming potential (blue) indicators are compared for both the reuse scenario (solid line) and the traditional scenario (dashed line). The study shows that reuse can be a pertinent solution for significantly reducing the environmental impacts of buildings. For instance, the global warming potential indicator is 43% lower when the chosen structural components are used over three phases. The reduction of impacts is approximately 48% for renewable energy and 43% for non-renewable energy. These large numbers are not representative of conventional constructions since they are mainly due to the comparably very low operational energy demands.

Under reuse assumptions, the global impacts of the building eventually reach the 2150' future targets [31].

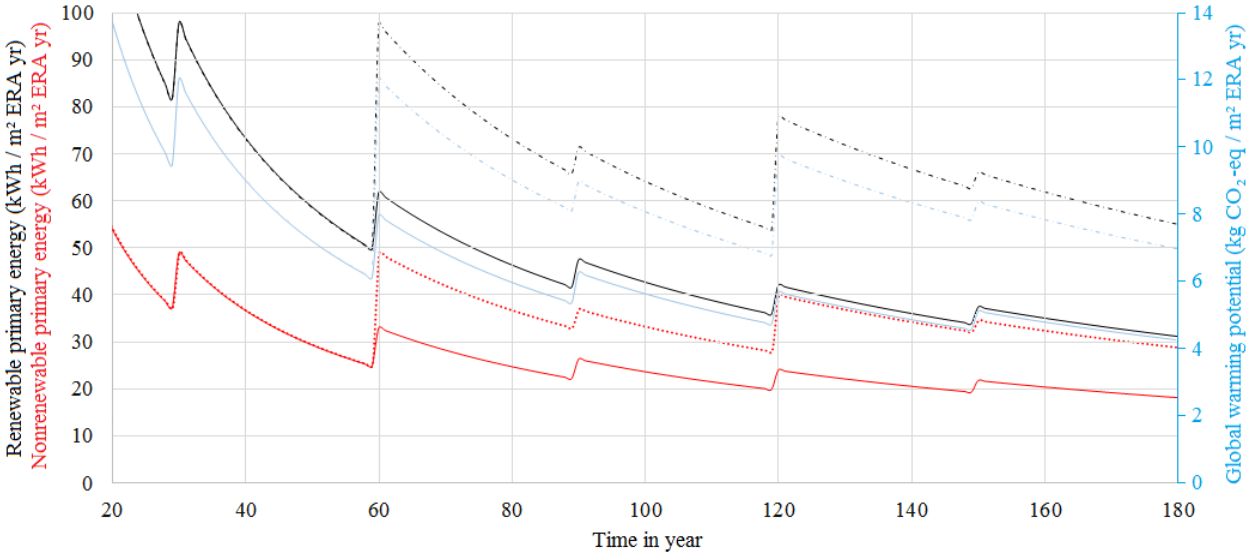


Figure 3: Dynamic analysis of the environmental impacts of the building with and without reuse of its load-bearing components.

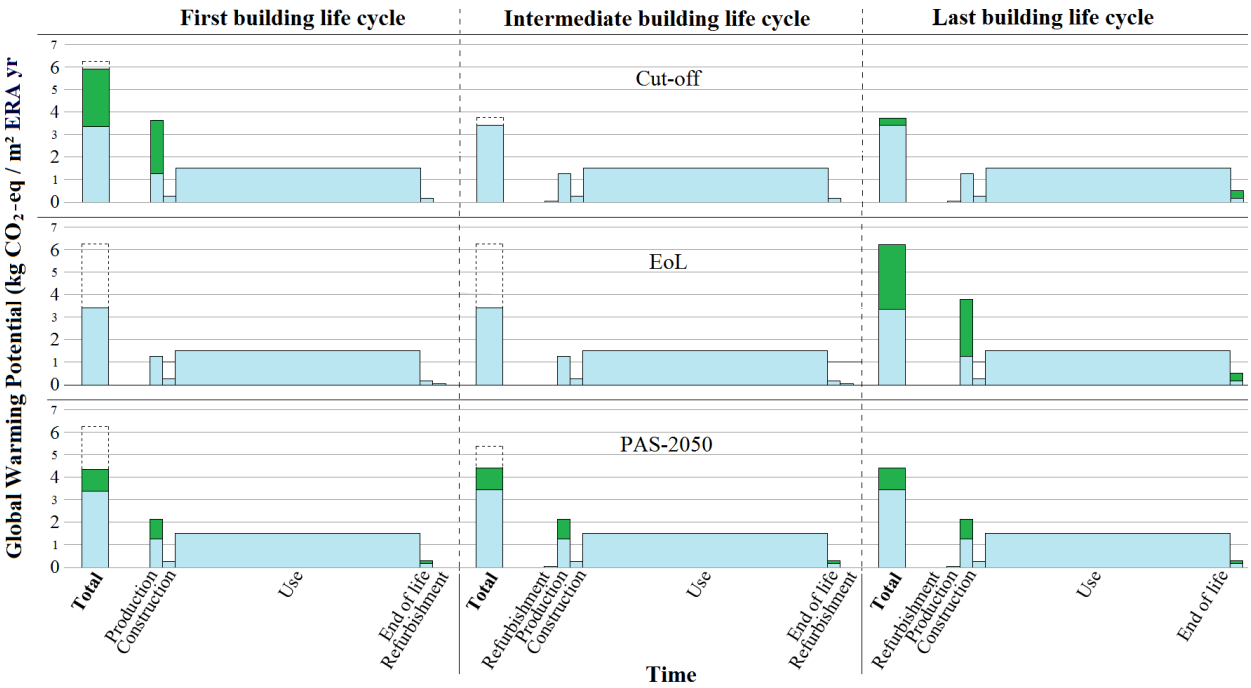


Figure 4: Allocation of impacts for three different methods of distributions, and according to the three representative types of life cycles.

Although this case study emphasizes the need for reusing load-bearing components, its practical implementation is undermined by the lack of consistent LCA indicators to encourage both the construction of reusable components and their reuse. Indeed, the way the LCA benefits are allocated to the various building actors highly influences their motivation to implement reuse. Figure 4 presents three possible distributions of the environmental impacts generated after reuse, as introduced in [28]. We here present them according to three representative types of life cycle: the first cycle, which includes the manufacture of the component; all intermediary cycles, and the last cycle, which includes the end-of-life treatment of the component. This subdivision displays the discrepancy between the three aforementioned distribution methods.

According to the first method, i.e. the Cut-off method, the impacts of the production of the reused components are attributed to the first life cycle. According to the second method, i.e. the End-of-life (EoL) method, the impacts are attributed to the last life cycle. According to the third method, i.e. the PAS-

2050, impacts are distributed proportionally over all use cycles.

Let us first consider the impact of those distribution methods over their incentives to reuse. If one applies the cut-off method, the producer is not rewarded for producing components that can be reused. However, contractors who reuse the same components do not account for any impact related to those components.

The exact opposite behaviour stems from the EoL method. While producers are encouraged to build reusable components, building contractors take a high risk when reusing them. They are responsible for all environmental impacts if the components can no longer be reused.

The PAS-2050 rewards everyone in the same way and may therefore appear as ideal to promote reuse.

However, the above conclusion is different if the distribution methods are compared according to the degree of reliability of their calculated results. Indeed, the PAS-2050 method presents the largest uncertainties because the number of use cycles of a component is unknown before the component reaches its end of life. The EoL method also calculates unreliable results since the probability of reusing the building components elements after the current cycle is never 100%. Only the cut-off method provides results that can be considered as reliable because the method does not depend on future uses. From this point of view, we identified the Cut-off method as most reliable.

In conclusion, there is an impossibility to allocate the benefits of reuse in such a way that all actors are rewarded with reliable values. A direction of future research therefore consists in assigning reuse probabilities to every type of components, according to their potential uses, to the way they can be assembled and disassembled, and to the probable market demands. The resulting life-cycle assessment would then include an analysis of uncertainties.

5. CONCLUSION

This paper addressed the environmental benefits of reusing load-bearing components over multiple use cycles. The evaluation of the benefits is applied to a case study that considers the preliminary design of a state-of-the-art building to be constructed in the upcoming years.

Results show that the impacts of the production of the load-bearing system would account for 38% of the global warming potential (GWP) indicator, and for 53% and 37% of the cumulative demand of renewable (CED) and non-renewable (CEDnr) energy respectively. Within the structural system, the slabs account for the largest impacts (66%) and would therefore be considered for reuse firstly.

Compared to traditional constructions built from raw material, a fictitious reuse of undamaged load-bearing components over three consecutive use cycles would reduce the GWP indicator by 39% and the CED and CEDnr indicators by 43% and 36% respectively. These high numbers, although pumped up by very low operational energy demands, call for reversible structural systems and for the assessment of further case studies.

The paper concludes with a comparison of three methods to distribute the impacts of reuse between the various life cycles: the cut-off method, the end-of-life method, and the PAS-2050 method. This comparison highlights the impossibility to reward every reuse actor in a reliable way. Future research in the field shall focus on defining probabilities of reuse within uncertainty analyses.

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