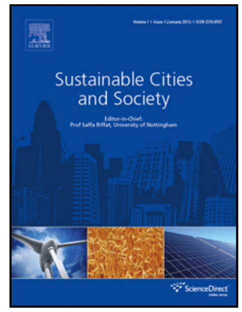

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Comparison of environmental assessment methods when reusing building components: a case study

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Highlights

- Challenges when allocating environmental impacts of reused building components
- Case study of a commercial building with reused components
- Comparison of design with upstream reuse and design for downstream reuse
- Comparison of six impact allocation methods over three typical life cycles
- Environmental assessment issues when applying circular economy principles in construction

Abstract

The building industry is responsible for 35% of all solid waste in Europe and more than a third of greenhouse gas (GHG) emissions. To address this, applying circular economy principles to the building sector is crucial, for example by reusing building elements from demolition sites rather than extracting and producing new materials. However, most current life-cycle assessment (LCA) tools are not appropriate to evaluate the environmental impact of a building when its components originate from prior buildings and/or will be used in future unknown ones. Still, robust measurement is needed to demonstrate the benefits of reuse towards environmentally sustainable cities. This paper compares existing methodologies to quantify the global warming potential (GWP, expressed in kg_{CO2e}/unit) of recycled/recyclable and reused/reusable products, selected within widely recognised standards, rating schemes, and academic studies, such as the cut-off method, the end-of-life method, the distributed allocation (PAS-2050) method, the Environmental Footprint method, the Degressive method and the SIA 2032 method. Based on these recognised approaches for assessing the GWP of products, new equations are written and applied to buildings with reused/reusable materials for each of the methods. The Kopfbau Halle 118 building (Winterthur, CH, 2021), which is designed with reclaimed elements from local demolition sites, is chosen as a case study. Discrepancies in LCA methods are highlighted by applying them to three different life cycles corresponding to the first, intermediate, or final use of building components. This paper shows that current quantification methods to assess reuse give wide-ranging results and do not address the full spectrum of the reuse practice, that their boundaries are too limited, and that a number of critical features are currently hardly quantifiable, such as embedded use value, versatility, storage and transformation impacts, user-owner separation, dis/re-mountability, or design complexity.

Keywords: embodied carbon; reuse; life cycle assessment; circular economy; buildings

1. Introduction

The building industry, which is responsible for 40% of primary energy demand, is the most resource-intensive sector in all industrialised countries, producing a third of all generated waste in Europe and emitting more than a third of global anthropogenic greenhouse gases (European Commission, 2019). It is therefore critical to identify an effective means of remediating this detrimental condition worldwide. Benchmarking the embodied carbon in buildings is an important first step towards reducing their environmental impacts (Simonen *et al.*, 2017). This effort can only move forward if time is considered when designing buildings, i.e. if materials are thought of in larger industrial and social systems that span multiple use cycles, hence creating a circular economy.

In a circular economy (Kirchherr *et al.*, 2017; EllenMcArthur Foundation, 2019), design, use, maintenance, repair, refurbishment, reuse and remanufacturing are leveraged to close energy and material loops while minimising resource use, waste generation, and greenhouse gas emissions. This concept contrasts with the predominant linear extract-produce-dispose model. When building components are used over multiple life cycles in multiple buildings, allocation of environmental impacts is debated. Paiho *et al.* (2020) describe the challenges and enablers of a circular economy in cities (food, buildings, mobility, nature) and concludes that indicators are needed to show the progress of a transition towards 'circular' cities. Such indicators inherently contribute to defining what makes a city sustainable (Petit-Boix *et al.*, 2017) and should integrate existing sustainability rating systems (Huang *et al.*, 2015) or goal-oriented assessment frameworks (Cohen, 2017).

Recent European Union (EU) efforts largely praise the reuse of building components as an attractive path towards sustainability (EU, 2016). Still, the reliability of such a conclusion remains hard to judge and current assessment methods are not robust enough to allow their day-to-day application by designers. For a series of reasons (Ritzén and Sandström, 2017; Bullen and Love, 2011; Tingley and Davison, 2011), industrial reuse is a strategy that is explored sporadically in Western countries today, although it has been shown that it can provide valuable economic and social benefits (Wijkman and Skånberg, 2015). Reuse, unlike repair and recycling, extends the service life of components by limiting their transformation and hence the manufacturing of new components and the generation of additional waste (Baker-Brown, 2017; Ghyoot *et al.*, 2018). The use value of a component is usually redefined. Additional costs related to the refurbishment, transport, and storage of the components in between two use cycles arise. Reuse may or may not involve a change of location or be reused for the same purpose. In addition, the potential to be reused in future cycles does not only depend on the material types and quantities but also on the geometry and topology of the components and on the assembly process of the system. From a design perspective (Fivet and Brütting, 2020), reuse happens in two ways:

1. *Design with upstream reuse* – the design of new products from existing, reclaimed components: achieved environmental benefits are evaluated once former building components are reused in newly built projects (Thormark, 2000; USEPA, 2011, Paduart *et al*, 2011, Aye *et al.*, 2012; Akbarnezhad *et al.*, 2014; Diyamandoglu and Fortuna, 2015; Assefa and Ambler, 2017);
2. *Design for downstream reuse* – the design of new products whose components are meant to be reused in future systems that are sometimes unpredictable: environmental benefits are predicted to compare reuse with other end-of-life options like recycling, energy recovery, or landfill (Gao *et al.*, 2001; Boyd *et al.*, 2012; Vefago and Avallenada, 2013; Chau *et al.*, 2017).

Figure *1* illustrates how design *from* and *for* reuse relate to the stages of conventional life-cycle assessment (LCA), as described in the European Standard (EN 15978, 2011).

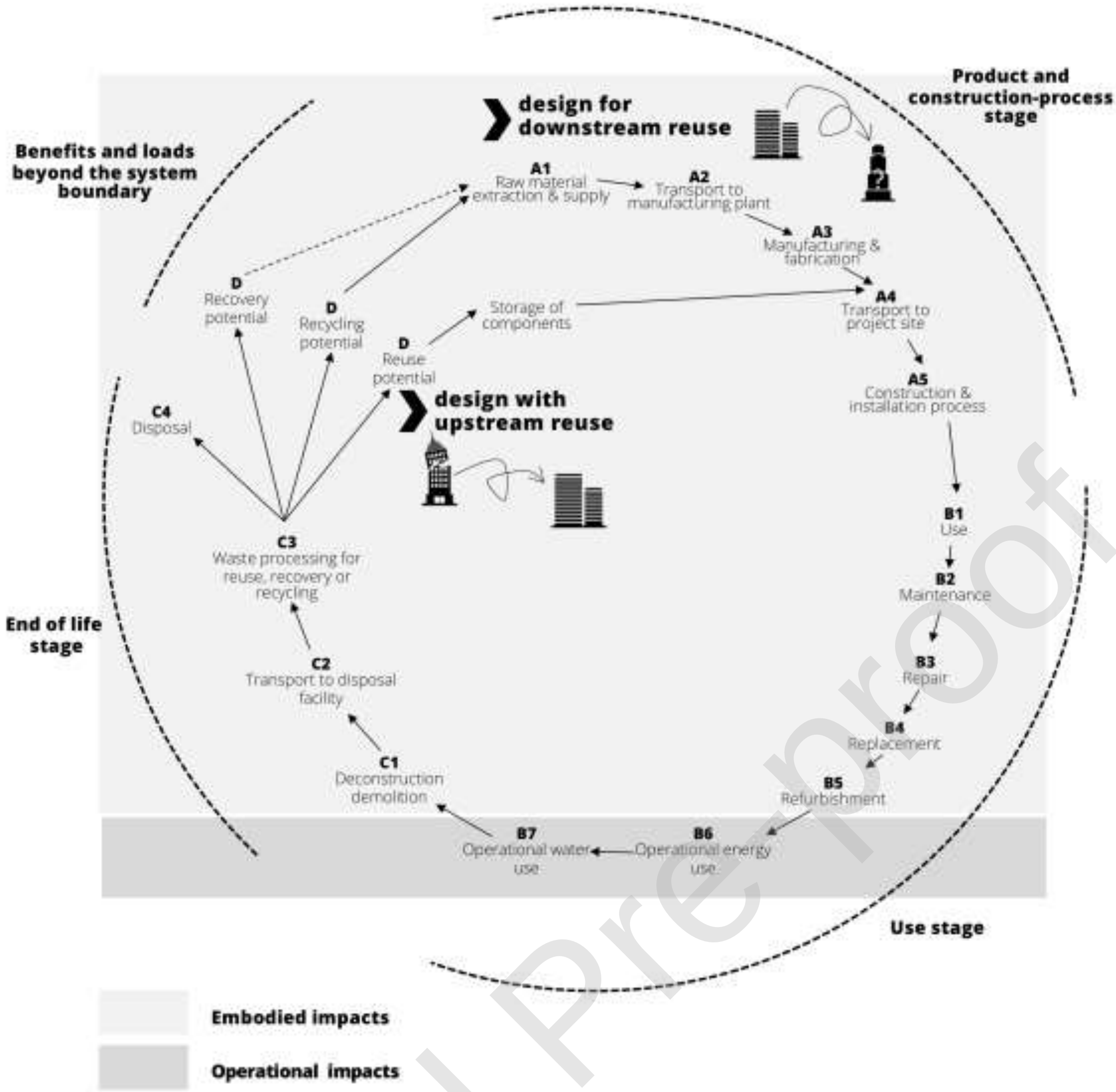

Figure 1: Circular concept of design from and for reuse at the building or component scale, based on life cycle stages from EN 15978 (2011) and SIA 2032 (2018)

2. Problem statement and methodology

This paper compares various current LCA methodologies in Europe, applying them to a case study of a recent building in Winterthur, Switzerland, that is primarily made with reused components. The aim is to highlight how currently used methodologies for assessing the environmental impacts of buildings are not adapted to assess the impact savings/burdens related to reuse in buildings in a quantitative and accurate way, as the allocations of the benefits and loads of reuse are addressed in different life-cycle stages and in different building life-cycles. The case study shows that the interpretation of LCA results differ for the same building component or building according to different assessment methodologies. Moreover, the lack of quantification of embedded use value, versatility, storage and transformation impacts, user-owner separation, dis/re-mountability, and design complexity is illustrated. Figure *1* illustrates the life cycle stages for the LCA of buildings according to the European Norms EN 15804 and the Swiss Norms SIA 2032. Stages A1-3 are known as the production stage, A4-5 as the construction process stage, B1-B5 the embodied use stage, and C1-4 the end-of-life stage. An extra module D is defined in the European Norms to account for the loads and benefits beyond the system boundary of potential reuse, recycling, and recovery. Operational stages B6 and B7 are excluded in this paper, which focuses only on the embodied stages.

To perform the LCA of the case study, data from ecoinvent (2019) and from the Co-ordination Conference of the Construction Sector and the Buildings of Public Owner database (KBOB, 2019) are used. Ecoinvent is a globally recognized life cycle inventory data source initiated in Switzerland and therefore has data specific to the Swiss construction industry. KBOB publishes a regularly updated list of embodied carbon coefficients of the most common construction materials used in Switzerland. The calculation methodologies to account for the environmental impacts of reused building components are discussed extensively in section 3. The different methodologies are applied and compared in section 4.

3. Literature review of existing assessment methods

While literature about LCA of reuse is recent, researchers and institutions have looked at the assessment of environmental benefits of recycling for the past decades. Recycling induces a complete remanufacturing of the material and therefore often uses energy (e.g. steel melting) or downgrades materials (e.g. concrete crushing). On the contrary, reuse entails a minimum amount of transformation by using the component again with its original features (e.g. reuse of timber beam on another site). Frischknecht (2010) distinguishes two strategies for assessing the recycling of materials in LCA: one credits the recycled content and the other the recycling rate. The first strategy is incentivising recycling at the production stage, while the second is incentivising recycling at the end-of-life stage. Allacker *et al.* (2017) have reviewed end-of-life formulas from existing methodologies for the European Commission Environmental Footprint initiative. Although the environmental impact assessment of material recycling has been discussed for a long time (Ekvall and Tillman, 1997), how to assess the reuse of building components is still debated because existing methods differ from each other on how the impacts are allocated in the various cycles of a component's life. Carpenter *et al.* (2012) discuss LCA of end-of-life management of construction and demolition debris. Scheepens *et al.* (2016) also try to assess the impacts of complex circular economy systems. Elia *et al.* (2017) measure circular economy strategies through index methods. Assefa and Ambler (2017) measured the potential reduction of the environmental impacts of repurposing buildings entirely. However, for the reuse of building components, a consensus is needed to transparently evaluate the environmental impacts associated to each building from/in which components are reused. This requires a trans-scalar sustainability performance method from material to urban scale.

Various approaches to assess the complete life cycle impact of reused building components compete, each using different assumptions and equations when it comes to the definition of the assessment boundary and the impact allocation. For example, if one evaluates the environmental benefits of choosing reused components in a new building, *design with upstream reuse* is incentivised, while if you allocate some of those benefits to the building source of the reused components, *design for downstream reuse* is incentivised. Consequently, results of these various approaches cannot be compared, combined, and predicted reliably. Worse, assessments can easily be tailored to produce desired results.

The main characteristic of reuse is that the lifespan of a component is distributed over multiple building life cycles (Figure 2). A number of authors, norms, and standards (Ekvall and Tillman, 1997; Nicholson *et al.*, 2009; Frischknecht, 2010; Allacker *et al.*, 2017; ISO 14040, 2006; ISO 14044, 2006; BSI, 2008; EN 15804, 2019; BRE Global, 2013) have proposed various methods to assess the environmental impacts over multiple life cycles. This paper analyses the different methods proposed by widely recognised standards and rating schemes as well as previous academic studies of those standards. In order to express their differences better, the methods are applied to three different life cycles corresponding to the first, intermediate, or final use of a building component. In the first use cycle, a component is produced from virgin resources. It is supposed to be reused in consecutive intermediate cycles, which are repeated an unknown number of times. In the last use cycle, the component is landfilled, recycled or incinerated with energy recovery.

The following sections give a detailed overview of the existing methods to allocate impacts of a building component over a building use cycle. This paper proposes new equations for the *reuse* of components in the case of *buildings*. They are based on existing guides and academic literature defining equations which are most often applied to allocate impacts of recycling of products with smaller lifespans. The quality properties of the components at the end of each use cycle are considered unchanged in most methods. With no perfect maintenance of the components, Ekvall and Tillman (1997) suggest using a coefficient that corrects the quality of the components. The scope of this paper addresses the reuse of building components with no quality loss. Future research should also include quality loss of reused components while managing uncertainty in the equations.

3.1. Cut-off method (100:0)

The cut-off method (BSI, 2008) is mainly used for assessing the recycling of building products. Equation 1 uses the same logic for reuse in buildings, including the impacts of the construction and use stages (equation 1).

$$I=(1-R_1)\cdot I_P+I_C+I_U+R_1\cdot I_R+(1-R_2)\cdot I_D \quad (1)$$

where:

I	environmental impact
I_P	environmental impact of production
I_C	environmental impact of construction
I_U	environmental impact of use
I_R	environmental impact of reuse
I_D	environmental impact of disposal
R_1 and R_2	coefficients with value zero or one depending on the use cycle of the component

- For the first use cycle, $R_1 = 0$ and $R_2 = 1$
- For the intermediate use cycle, $R_1 = 1$ and $R_2 = 1$
- For the last use cycle, $R_1 = 1$ and $R_2 = 0$

The environmental impacts of each life-cycle stage (e.g. production) are counted within the life cycle in which they actually occur (e.g. the initial life cycle for production impacts, as this is the life cycle in which the materials are actually produced). This is the reason why this method is also called "100:0": 100% of the production impacts are attributed to the first use cycle of the components while the other use cycles are charged with 0% of these impacts (Frischknecht, 2010; Allacker *et al.*, 2017). The cut-off method encourages actors to reuse already used elements (*design with upstream reuse*). However, the method does not allow building designers (of the first life cycle) to benefit from the environmental gains obtained when assembling components that can be more easily reused in the future (*design for downstream reuse*). The BREEAM method provides similar results (BRE Global, 2013).

3.2. End-of-Life method (0:100)

The logic of the so-called End-of-Life (EoL) method (BSI, 2008) related to production impacts is the opposite of that of the cut-off method as shown in equation 2. Also known as the 0:100 method, it does not allocate the production impacts to its first use cycle but 100% of these impacts are attributed to the last use cycle (Frischknecht, 2010; Allacker *et al.*, 2017). The allocation of impacts in this method assumes that building components will be reused after the initial or intermediate life cycles: the environmental impacts of production and end-of-life are only accounted for in the last life cycle, which encourages actors to design for downstream reuse. However, considering the relatively long service lifetime of building components, scenarios of reuse are difficult to accurately predict.

$$I=(1-R_2)\cdot I_P+I_C+I_U+R_2\cdot I_R+(1-R_2)\cdot I_D \quad (2)$$

3.3. Distributed allocation

Based on the formula described in the Publicly Available Specification 2050 (PAS-2050) guide for the treatment of emissions associated with reuse (BSI, 2008), a distributed allocation method can be defined: this method proposes an equally distributed allocation of both production and end-of-life impacts in all life cycles (equation 3). The competitiveness offered by this method is a function of the number of use cycles, which is difficult to predict. This difficulty to predict the number of use cycles may lower the degree of reliability of the results.

$$I=\frac{I_P+I_D}{n}+I_C+I_U+I_R \quad (3)$$

where n is number of use cycles.

3.4. European Commission Environmental Footprint (EC EF)

Based on the logic of the PEF equation (European Commission, 2012) used for allocating impacts of recycling and that of the BPX 50/50_adapted (AFNOR, 2011) formula proposed by Allacker *et al.* (2017) for the European Commission Environmental Footprint (EC EF) methods, equation 4 was defined to equally allocate the environmental impacts of production and disposal stages in the first and last use cycles, and those of reuse in intermediate consecutive use cycles.

$$I=\left(1-\frac{R_1}{2}-\frac{R_2}{2}\right)\cdot I_P+I_C+I_U+\left(\frac{R_1}{2}+\frac{R_2}{2}\right)\cdot I_R+\left(1-\frac{R_1}{2}-\frac{R_2}{2}\right)\cdot I_D \quad (4)$$

Such allocation encourages LCA-actors to employ reused components in their projects or to construct with the aim of reusing the components in future cycles. Similar to the EoL or distributed allocation methods, the reliability of the results is a function of the assumptions on future reuse.

3.5. Degressive

Based on Allacker *et al.*'s (2017) degressive (linearly with the recycled content and recyclability rate = 100%) method, a degressive method is also proposed in this paper adapted for the reuse of building components, as described in equation 5, using the logic of equation 3 for the allocation of the environmental impacts of the production and disposal stages and the logic of equation 4 for the reuse stages. The method is dependent on the accurate prediction of scenarios.

$$I=\frac{I_P+I_D}{n}+I_C+I_U+R_1\cdot\frac{I_R}{2}+R_2\cdot\frac{I_R}{2} \quad (5)$$

3.6. SIA 2032

According to SIA 2032 (2018) norms in Switzerland, another methodology is being developed to calculate the impact of a reused building component. At the time of reuse of the building component from its original first use (initial life cycle) to a second building (intermediate life cycle), the actual life span is compared with the expected total life span of the building component. For instance, take a window with a life expectancy of 30 years. It is used for 20 years in building 1 (initial life cycle), another 10 years in building 2 (intermediate life cycle) and 10 years in building 3 (last life cycle). Each life cycle has its own use emissions (module B). The production, construction, and end-of-life emissions (modules A and C) are divided among the three life cycles as follows: building 1 is taking into account two thirds (20 years / 30 years) of the A and C emissions, building 2 is taking into account one third (the remaining 10 years) of the A and C emissions, and building 3 is taking no emissions into account as they have already been 'paid for' by the first two buildings with the window frame exceeding the expected life span, as shown in equation 6.

$$I=\frac{l_{current}}{l_{expected}}\cdot I_P+I_C+I_U+\frac{l_{current}}{l_{expected}}\cdot I_D \quad (6)$$

where:

$l_{current}$ life span of component within life cycle n if $\sum_{i=1}^{current} l_i \leq l_{expected}$

$l_{current}$ 0 if $\sum_{i=1}^{current} l_i > l_{expected}$

$l_{expected}$ expected total life span of the component

The method supports design for downstream reuse, but by doing so, does not penalize the premature disassembly of buildings. It also supports design with upstream reuse, but assumes we can use components beyond their expected lifespan.

3.7. E+C-

Energie plus, Carbone moins (E+C-) is an experimental label developed by the French government to promote buildings with net positive energy and a low carbon footprint, in preparation of the new energy regulation RE2020 (CSTB, 2020). The label does not yet address the assessment of the impact of the reuse of materials. In the meantime, certification scheme *Certivéa* (2020) recommends to consider reused materials as if there were no new materials in a typical LCA of the building in which the materials are reused. This method assumes that all A – C impacts of the materials (including production and end-of-life impacts) are allocated to the initial life cycle and a zero impact is accounted for in the intermediate and last life cycles. The approach is likely to change throughout the experimentation and was therefore not included in the analysis of this paper.

3.8. Summary

Figure 2 summarizes the discussed methodologies according to the life cycle stages defined by the European Norms for three typical life cycles of a building component: (a) the initial, (b) an intermediate, and (c) the last one. These life cycles can be seen as separate scopes for LCAs performed by (a) designers allowing downstream reuse but not achieving upstream reuse, (b) designers achieving upstream reuse and allowing downstream reuse, and (c) designers achieving upstream reuse without allowing downstream reuse of the component.

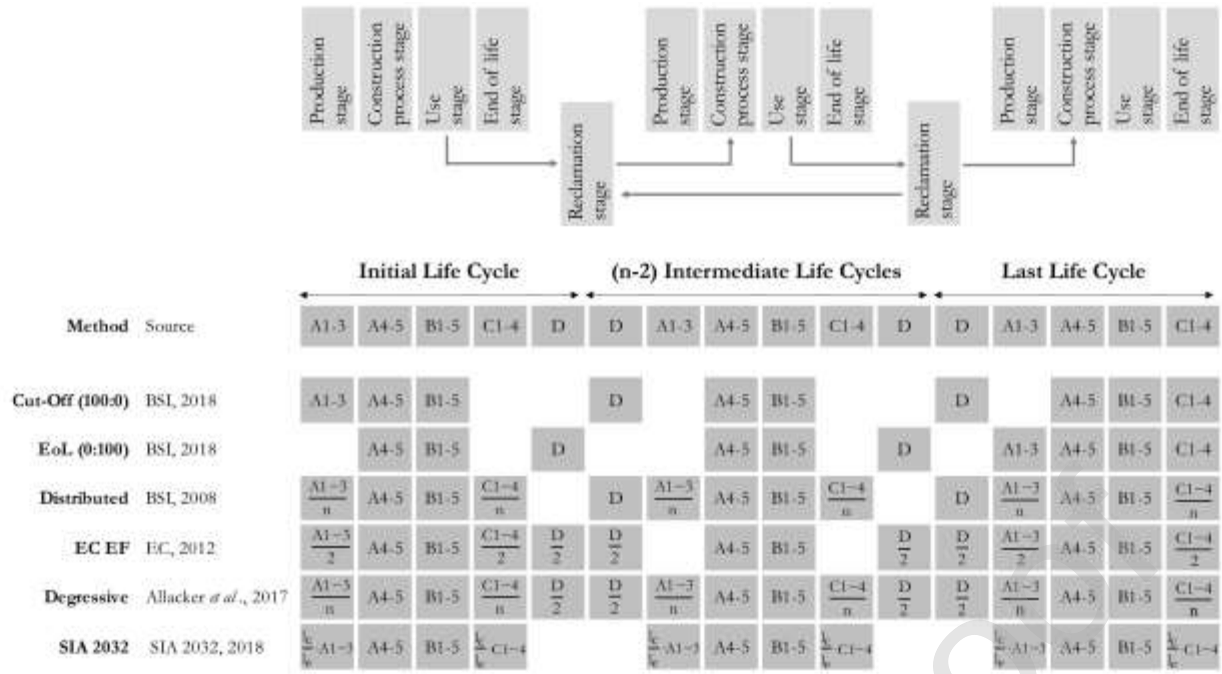

Figure 2: Overview of allocation of the environmental impacts of building components onto n use cycles

4. Differences between existing assessment methods evaluated through a case study

This paper analyses the Kopfbau Halle 118, called K.118 in the rest of this paper, designed by Baubüro in situ and built in Winterthur, Switzerland (Figure 3). The design process started in 2017 and the building is to be delivered in 2021. K.118 is chosen as a case study as it is almost completely built with reused components, including its load-bearing system. Baubüro in situ provided all data on material quantities, types, and origins. Figure 4 illustrates the sources from which materials are reclaimed for the construction of K.118.

Figure 3: Design of K.118 and dismantling of façade elements leading to the choice of the red colour for the façade (Baubüro in situ, 2018)

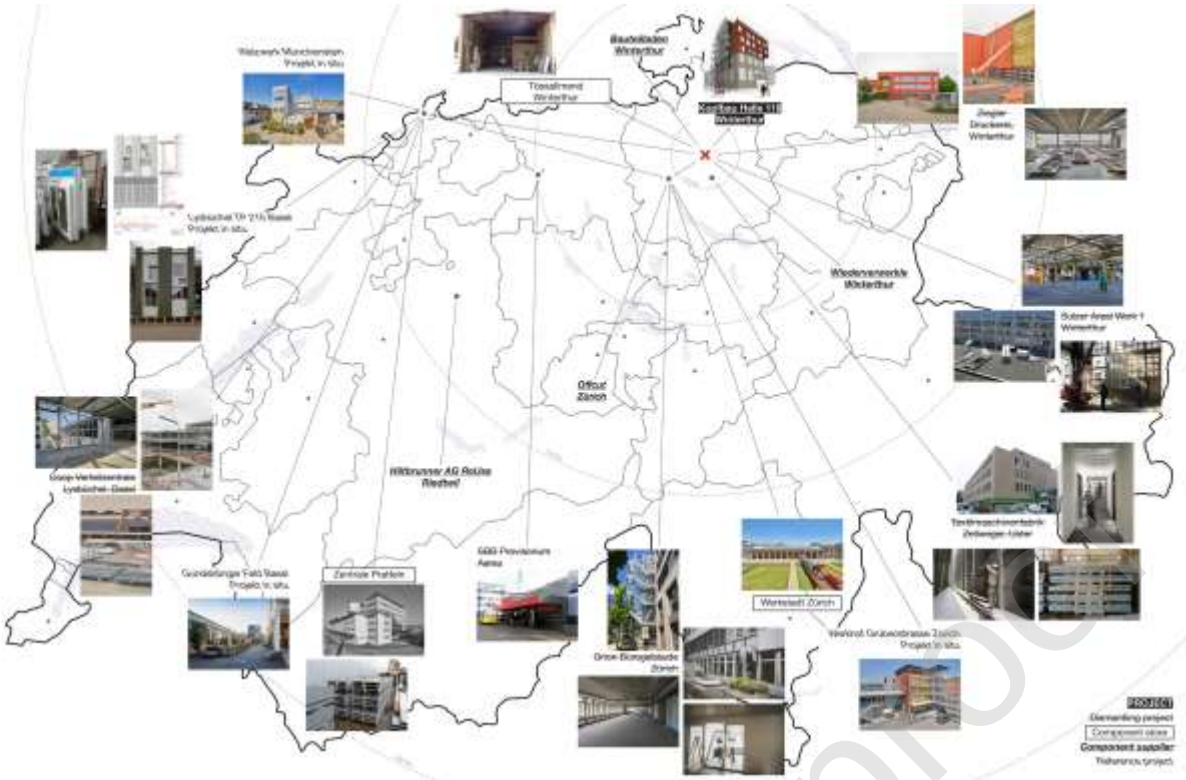

Figure 4: Map with demolition sites where the materials of K.118 come from, storage sites, and reference projects (Baubüro in situ, 2018)

While the environmental benefits of reuse have been discussed by Hoxha and Fivet (2018), this paper studies the differences of the results of the K.118 case study with the different existing allocation methods. To illustrate the difference among the six methods discussed in section 3, we evaluated the environmental impact of all building components of K.118. Original plans, material weight, and transportation mode were used to calculate the embodied carbon of the components. The Global Warming Potential (GWP, expressed in kg_{CO2e}/unit) of the equivalent new building components with their expected lifespans, were calculated with data from ecoinvent and KBOB, based on the life-cycle stages of a conventional LCA according to EN 15804. The bill of materials contained the building components illustrated in Table 1. For each building component, a detailed description was given with the material quantities as shown in Table 2 for one of the floor types.

Table 1: Building components in the bill of materials of K.118

Exterior walls	AW1	Existing, interior insulation and planking
	AW2	Existing, interior insulation, no planking
	AW3	Raised straw bale wall
Floors	Bo1	Misapor insulated floor
	Bo2	Floor overhang of the extension
Roof	DA1	Roof structure
Intermediate floors	ZWD1	Gallery floor
	ZWD2	Existing floor
	ZWD3	New floor
Interior walls	IW1	Limestone wall
	IW2	New concrete wall
	IW3	Interior lightweight wall construction

Fire protection	KIW	Fire protection, concrete-filled steel beam
Windows	F	Windows

Table 2: Example of the bill of materials for one floor building component

Bo1	**Floors**		
Nr:	Bo1	Description:	Misapor insulated floors
Art:	Floors	Layer against:	Earth
Use in:	All	Section:	1 (homogeneous)

Layer	**Thickness**	**Lifespan**	**Layer composition / materials**	**Volume**	**Density**
[-]	[m]	[a]	[-]	[m^3/m^2]	[kg/m^3]
1	0.03	60	H118 hard concrete, single-layer, 27.5 mm, RC quality new (KBOB 2014)	pro m^2	pro m^2
2	0.18	60	H118 construction concrete, CEM II/B, 60 kg/m3 of steel (KBOB 2014)	0.18	2342
3	0.3	60	H118 foam glass granulates, Misapor scraps (KBOB 2014)	0.3	170

For each material used in the K.118 building, the data described in Table 3 is collected, based on the bill of quantities, information obtained from the architect, KBOB or SIA values. A simplified LCA methodology is followed in order to be reproducible and to illustrate the differences between the methods discussed in this paper. The production stage impacts (A1-3) are calculated by multiplying the material quantities (expressed in units such as m^3 or kg) with KBOB's value for the production impacts ($kgCO_2$-eq/unit). The construction process stage impacts (A4-5) are calculated by multiplying the material weight (t) with the distance from the manufacturer to the construction site (km) and the transport mode coefficient ($kgCO_2$-eq/t.km) for the transport impacts and by taking a percentage of the production impacts for the construction impacts, according to Hoxha *et al.* (2016). The use stage impacts (B1-5) are calculated based on the expected lifetime of each element in order to account for the number of replacements of a product during the lifetime of a building. The end-of-life stage impacts (A1-3) are calculated by multiplying the material quantities (expressed in units such as m^3 or kg) with KBOB's value for the end-of-life impacts ($kgCO_2$-eq/unit). The benefits and loads of reuse impacts (D) are calculated by multiplying the material weight (t) with the distance from the deconstruction site to the storage site and then on to the new construction site (km) and the transport mode coefficient (kgCO2-eq/t.km) for the transport impacts and adding twice the construction impacts (A5) for the dismantling and remounting impacts.

Table 3: Data used for LCA calculation, example of an OSB panel used in K.118

	Values	**Source**
Description	OSB	in situ
Unit	kg	unit
A1-3 ($kgCO_2eq$/unit)	0.487	KBOB
C1-4 ($kgCO_2eq$/unit)	0.127	KBOB
Specific Quantity (m^3/m^2)	0.012	in situ
Surface element (m^2)	262.21	in situ
Absolute Quantity (m^3)	3.15	specific quantity * surface element
Density (kg/m^3)	605	KBOB
Quantity (Unit)	1904	density * absolute quantity
Distance manufacturer to construction site (km)	300	in situ
Distance demolition site to storage site (km)	2	in situ
Distance storage site to construction site (km)	2.7	in situ
Distance demolition site to construction site (km)	4.7	in situ
Transport mode	Truck	in situ
Transport mode coefficient ($kgCO_2$-eq / t.km)	0.11	KBOB
Expected lifetime of element (yr)	30	SIA
Building lifetime (yr)	50	hypothesis

The results for stages A1-3 and C1-4 are obtained from the coefficients available in KBOB. The results for stages A4-5, B1-5, and D are calculated based on transport distances, transport modes, and percentages of the production and end-of-life emissions (e.g. the use stage B4 for replacement). Figure 5 illustrates the impacts for the six allocation methods and assuming three different scenarios: building components are used in their first life-cycle, in any intermediate life-cycle, or in their final life cycle. This is a theoretical exercise, as in practice not all building components would be reused in exactly the same buildings throughout all their life-cycles.

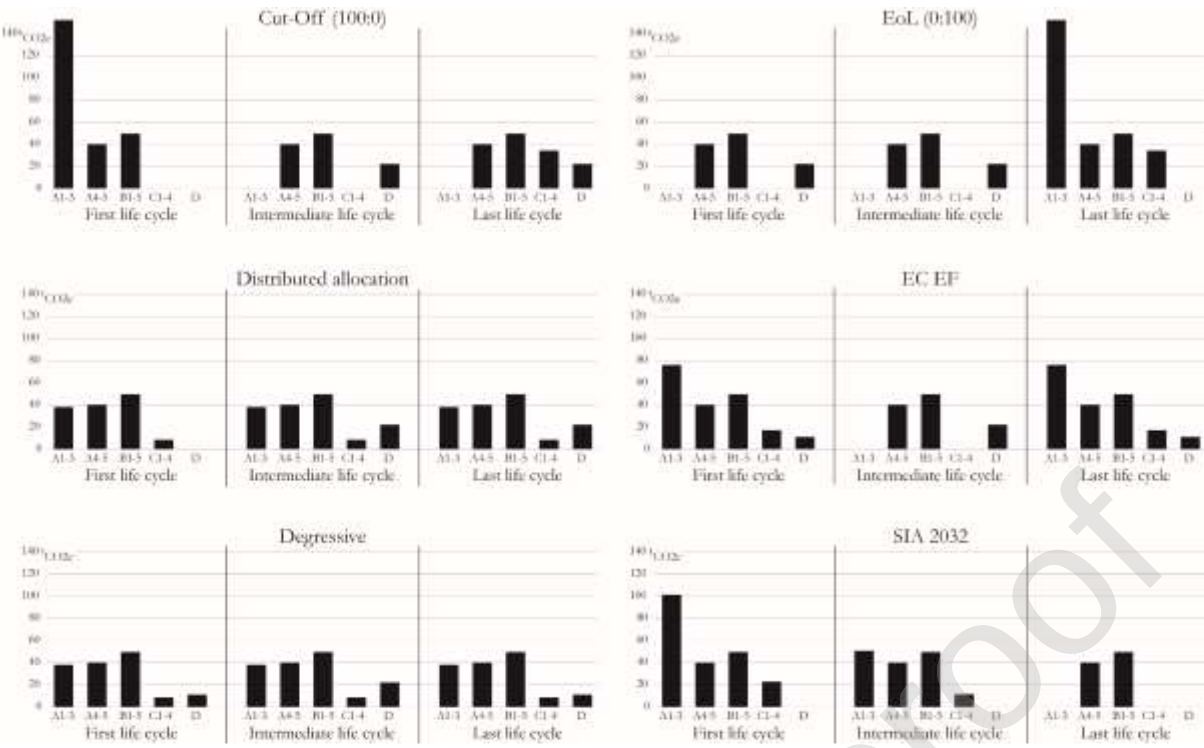

Figure 5: GWP of the K.118 building as if it was built with entirely new materials and reused entirely at its end-of-life (first life cycle), as if it was built entirely with reused materials and reused entirely at its end-of-life (intermediate life cycle), and as if it was built entirely with reused materials but not reused at all at its end-of-life (last life cycle); for each assignment method

Results show the diversity of allocation methods for the GWP of the building. The Cut-off method allocates the environmental impacts of the production stage (A1-A3) to the first life cycle, but the environmental impacts of the end-of-life stage (C1-C4) of reused building components to the last life cycle. The intermediate life cycle is then only charged with the impacts of transport and construction (A4-5), of use (B1-5), and of refurbishment (D). The aim of the cut-off method is to give reliable results by allocating the impacts of components at the moment when they occur, but numbers do not support the development of buildings with components that can be reused in the future. The EoL method allocates both production and end-of-life impacts to the last life cycle. The aim is to give an incentive for designing for reuse in the future, not to reuse already existing components. The distributed allocation (PAS-2050) method distributes the impacts of production and end-of-life stages in proportion to the number of life cycles of the building components, to incentivise design with upstream reuse and for downstream reuse. However, the number of life cycles of building components is difficult to predict. The EC EF method allocates the impacts of production and end-of-life stage to the first and last life cycle, sharing them in a 50:50 ratio, to remediate the difficulty to predict the number of life cycles. The degressive method is a mix of the distributed allocation (PAS-2050) and the EC EF method. Results from the SIA 2032 norms follow a specific distribution that is function of the expected lifespan of each component.

As further illustrated on Figure 6, there is also a diversity of GWP values across the three typical life cycles scenarios. In other words, the interpretation of these results will vary widely according to the chosen allocation method and according to assumptions made regarding the previous and future life cycles of building components.

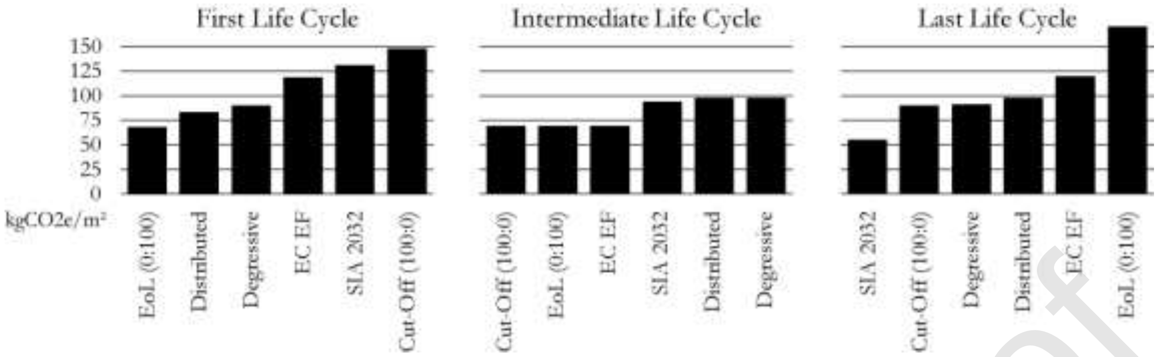

Figure 6. Global Warming Potential per gross floor area of the entire K.118 building for each typical life-cycle.

As shown in Figure 6, values of GWP per GFA vary in the ratio of one to two (increase of 94 $kgCO_2eq/m^2$) when considering first life cycle and of one to three (increase of 115 $kgCO_2eq/m^2$) for last life cycle. All methods give similar global values for intermediate life cycles; and those values are globally smaller than for the first and last life cycle, meaning that, when averaging over all allocation methods, reuse always leads to beneficial numbers if building components are said to be in an intermediate life-cycle.

Stages A4-5 (transport, construction & installation process) and B1-5 (use, maintenance, repair, refurbishment, replacement) always provide the same values whatever the chosen allocation method. However, stages A1-3 (raw material supply, transport, manufacturing), C1-4 (de-construction/demolition, transport, waste processing, disposal), and D (reuse potential) show a large variation of values across the allocation methods. As shown in Figures 5 and 6, the SIA 2032 method is the most beneficial one when considering end-of-life scenarios and the EoL method remains the most beneficial when considering first-use scenarios.

Of particular note, the results would include even more uncertainty in reality when all building components have a different life history.

5. Discussion

5.1. Life-Cycle Assessment (LCA)

As exemplified in the previous section, LCA quantification methods do not provide consistent values when assessing buildings whose components have or will have multiple life-cycles. Hence, they hinder consistent and objective comparisons across scenarios. In other words, they are not sufficient to compare *design with upstream reuse* strategies against *design from downstream reuse* strategies.

A number of critical features that are specific to reuse are not included in the boundaries of current conventional assessments or are not considered in the establishment of embodied carbon coefficients as discussed in sections 5.2 to 5.6. The following sub-sections discuss additional features specific to the assessment of environmental benefits of reuse.

5.2. Embedded use value

The efficiency of a reuse strategy also depends on the ratio achieved between the actual function of the product and its embedded potential. For instance, reusing a high-performance column from a high-rise building in a low-rise lightweight building such as a garden shed wastes the structural capacity of the column, potentially preventing the column from being reused at its best elsewhere. In other words, the utilization of the reused component – i.e. how much of the qualities embedded in the component are used wisely – should also be included in the assessment.

All methods analysed in this paper assume a perfect "demand-supply" coordination. For example, when a small column is needed for a garden shed (demand), a small column from a dismantled low-rise storage unit (supply) is reused, while in reality there may only be a large column from a dismantled high-rise office building available (imperfect "demand-supply" coordination). None of the existing methods addresses this discrepancy. In the K.118, this imperfect "demand-supply" coordination is illustrated by Figure 7: the window frames found (a) are slightly larger than the façade openings, leading to an adapted design (d). This shortcoming is also related to the 'ratio of use' over the lifespan of a component, as addressed in the SIA 2032 method.

Figure 7: (a) Window frames reused from the demolition site, (b) dismantling of window frames, (c) storage, (d) adapted design for use of these window frames in K.118 (Baubüro in situ, 2018)

Critical indicators of reuse such as versatility can hardly be quantified. Although critical, they are generally poorly addressed or simply omitted due to a (current) lack of relevant metrics. Versatility is here understood as the ability of a product to serve other functions than the one for which it is designed or previously used. For instance, it describes whether a highway girder can become a beam in a house, as was the case in the Big Dig House (Single Speed Design, 2009) or whether a gas pipeline's structure can be reused for making a truss, as was the case for the London Olympics Stadium (Allwood and Cullen, 2012). Currently, there is no method that attempts to quantify versatility irrespective of the nature of the product. The service life of a reusable product and its number of cycles decrease rapidly if the nature of its new uses has a high damage-risk. Moreover, the reuse of products also influences the service life of other products in the system.

5.3. Storage and transformation

In order to adjust supply with demand, reusable components must circulate and be stored in between two use cycles (Ghyoot *et al.*, 2018). This implies either the creation of additional infrastructure (Anggadjaja, 2014) or the use of existing retail stores (Diyamandoglu and Fortuna, 2015). The environmental impacts related to long-term storage are specific to the assessment of reuse. Storage impacts should consider the impact of the construction and maintenance of the storage facility, its operational impact, and land use. The usefulness of a product is in line with the magnitude of its storage impacts since less-demanded products will have to be stored for a longer time. It is expected that the generalization of Building Information Modeling (BIM) will allow records of recently disassembled components to be shared more easily and favour faster redistribution of components (Akbarnezhad *et al.*, 2014). The storage of the window frames for K.118 is illustrated in Figure 7.c.

On top of storage impacts, transformation impacts should be considered when the product is not already in shape to fulfil its new function. In the example of the window frame in K.118, the design team studied the possibility of cutting the window frame to fit the opening size in the new building. However, the energy needed for the transformation was considered too high. If it had to be treated in another facility before it is reused, additional impacts would occur. Moreover, Gorgolewski (2008) shows that reused building components sometimes require coverings because of architectural aesthetics, which increase impacts and costs.

5.4. User-owner separation

The common assumption is that the user of the product is its owner, and both remain the same throughout its service life. However, reuse strategies are potentially put in place together with sharing dynamics. Such a paradigm would call for multiple but simultaneous levels of assessment: owner, distributor, and user. For example, the reuse of the window frame in K.118 could be bought or leased by the owner of the K.118 building. Rios and Grau (2019) discuss a product-service system (PSS) model as a shift from selling products (e.g. a window frame) to selling services (e.g. a façade opening) to incentivize a circular economy. If a method that favours *design for downstream reuse* is used, the first owner of the reused window benefits from the emission savings; while if a method that favours *design with upstream reuse* is used, the second owner who reuses the window benefits from the same savings.

5.5. Reusability

Another essential critical indicator which is currently hardly quantified is the ability to be dismantled or remounted. Reusability measures the repair and transformation required during assembly and disassembly. Although the quantification of this measure is not properly defined, it is known that damage is caused by different factors: fragility of elements (Gorgolewski, 2008);

poorly designed connectors (Hechler *et al.*, 2012); and dependence of elements with each other (Durmisevic, 2019). For example, in the K.118 building, a stone element was stored in order to be reused in a floor, but the element turned out to be much weaker than foreseen (Figure 8).

Figure 8: Unexpected damage on reused component in K.118 (Baubüro in situ, 2018)

This indicator is essential as downstream reuse can only happen if components can be dismantled and remounted. Moreover, dismantling often introduces damage. In all existing case studies, additional material was needed to ensure the assembly. Although indicators of reusability can be independent from LCAs, they should help reduce uncertainties when assessing the environmental impacts of scenarios of future reuse.

5.6. Design complexity

Reuse might increase complexity at three construction stages: design, assembly, and disassembly; which ultimately affects the impacts of all life cycle stages. Design complexity is directly related to the complexity of the assembly and disassembly processes since both are functions of the geometry of the components and their connections (Guy and Ciarimboli, 2008). The design complexity of reuse imposes an excellent coordination of construction actors (Gorgolewski, 2008) and usually suffers from a lack of drawings and details of elements (Kuehlen *et al.*, 2014), a lack of codes and standards for reuse (Guy and Ciarimboli, 2008), and gaps between demand and supply (Gorgolewski, 2008), which may convince designers to manufacture new materials rather than explore reuse options. Current developments of material passports are addressing this challenge directly (Madaster, 2019; Durmisevic, 2019) as well as recent publications of guidelines (Ghyoot *et al.*, 2018; Baker-Brown, 2017). Still, design complexity cannot be fully quantified, irrespectively of the nature of the product. The time-consuming process of disassembly and reassembly is often a barrier for choosing reuse over demolishment and rebuilding.

6. Conclusion

This paper reviewed the most commonly accepted quantification methods for the LCA of recycled/reused products and applied them to the environmental impact assessment of reused building components, showing that the current practice of assessment of reuse in buildings prevents results from being compared in a reliable way. New equations based on existing LCA methods conducive to recycling and reuse have then been applied to a case study while differentiating the first life cycle, the intermediate ones, and the last one. Based on an analysis of these methods and discussions with the designer of the case study, a series of current challenges to the proper quantification of reuse were presented. They stem from three observations: no holistic distribution of impacts is possible, current boundaries of assessment are too restricted, and qualitative aspects such as versatility or reusability are hard to quantify. In conclusion, we propose the following methodological inputs in order to address these drawbacks.

The LCA should be broken down systematically into three distinct assessments whose impacts cannot be summed up or isolated: one considering the first life cycle of the building or building component, one considering any intermediate life cycles, and one considering the last life cycle. This goes hand in hand with the inclusion of storage impacts, transformation impacts, and embedded use values in the boundaries of the assessment. Moreover, evaluations should be systematically refined with uncertainty analyses, which would call for additional research on reuse. Indeed, on the one hand accurate data on GWP is still missing, on the other hand current functional units do not allow the analysis of impacts related to not just material quantities but also components geometry, topology, and connectivity. For instance, one will have to probabilistically quantify material degradation when dismantling and reassembling sub-components, now and over future decades. Moreover, risks of non-reuse scenarios should be considered in these analyses.

Future work should explore the above recommendations to develop quantitative and qualitative criteria for the environmental impact assessment of reused components in buildings. We recommend further development of the equations provided for the evaluation and allocation of impacts to also include factors of embedded use value, storage and transformation, user-owner separation, reusability and design complexity.

Current LCA methods are not adapted yet to the reuse practice and do not include a qualitative judgement of the environmental benefits or loads of reuse. GWP could be expressed in kg_{CO2e} per year of use to do so. If policies are to be written for enforcing a transition to a circular economy in cities, discrepancies in the results for reused components from one methodology to another need to be solved. A proposed solution is to design a web-diagram with a score for *design with* *downstream reuse*, a score for *design with upstream reuse*, a score for life cycle 1, scores for life cycles 2 to n-1, and a score for life cycle n. These results should be calculated by building component sets rather than for an entire building as the building will often be composed of reused and new materials.

Whereas the adoption of a circular economy by the construction industry is an urgent matter for environmental, social, and economic reasons, all considerations in this paper restate that much remain to be done before robust assessments of reuse scenarios exist, hence before reuse scenarios can be compared and lead to an improvement of the way cities are built.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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