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Towards circular life cycle assessment for the built environment: A comparison of allocation approaches

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Abstract
Introduction. The building sector consumes 40% of resources globally, produces 40% of global waste and 33% of greenhouse gas emissions. The transition towards a Circular Economy (CE) in the built environment is vital to achieve the Sustainable Development Goals (SDGs) of climate action and responsible consumption and production. Metrics are needed to support this transition; previous work identified Life Cycle Assessment (LCA) as the best method to analyse the environmental performance of the CE. However, current LCA methods focus on the individual system, considering a single lifecycle. Circular assessment requires a systems-perspective: buildings, components, parts and materials have multiple lifecycles. Thus, questions arise about how benefits and burdens should be allocated between systems.
Method. In this study, we compare the potential influence of applying different allocation approaches in LCA method. We calculate the environmental impacts of two 'circular building components': (1) a concrete column designed for direct reuse and (2) a recyclable roof felt. We applied four allocation approaches: (a) the cut-off approach stated in EN 15804/15978, (b) the Circular Footprint Formula (CFF) from the Product Environmental Footprint (PEF), (c) the 50:50 approach, and (d) the linearly degressive (LD) approach.
Results. The allocation approaches resulted in notable differences in impact distributions thereby incentivising different CE principles (narrowing, slowing and closing). Due to the long lifespan of building components, concerns regarding uncertainty and 'green-washing' resulting from allocation of impacts between cycles arise. However, the LD approach was, for closed-loop systems (such as the ones assessed here), found to be promising: it is simple to use; it creates incentives for narrowing, slowing and closing loops and to design for these in the future; it deals with the uncertainty, material quality and number of use cycles.
Conclusion. The comparison of allocation approaches and first recommendation on an allocation approach provides an important step towards circular life cycle assessment and, subsequently, helps promote the CE concept within the building industry.

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1. Introduction

Globally, buildings are responsible for 40% of waste generated (by volume), 40% of material resource use (by volume) and 33% of all human-induced emissions [1, 2]. Circular economy (CE) can help provide a better alternative to the current linear economy of take-make-use-dispose. CE is a regenerative approach in which resource inputs and waste generation, emissions, and energy leakages are minimised by narrowing (through efficient resource use), slowing (by temporally extended use) and closing (i.e. cycling) material and energy loops [3]. Value Retention Processes (VRPs), for example, reuse, repair, refurbish, recycle and recover are imperative for operationalizing the CE [3]. Thus, creating a circular built environment is vital to achieve the United Nations (UNs) Sustainable Development Goals (SDGs) such as 13 Climate Action and 12 Responsible Consumption and Production. In the transition towards a circular built environment, many decisions need to be made. To support the industry in making decisions, and to incentivize industry in this transition, CE decision making/facilitating tools and assessment methods are needed. There is a consensus that life cycle assessment (LCA) can assess the environmental performance of CE [4]. However, conventional LCA methods focus on analysing individual products and single life-cycles [5]. Whereas CE requires a systems-perspective in which buildings are considered as a composite of components, parts and materials which - potentially - have different and multiple use-, and life-cycles. Thus, questions arise about how benefits and burdens should be allocated between cycles. For example, a concrete column, designed for disassembly, has the potential for subsequent reuse(s) in different buildings. The evident question is hence, how should the impact of the use of the column be calculated for the first building, the second building, etc.? Many different allocation approaches exist and there is no single widely accepted approach [6]. However, the choice of allocation approach may influence the results of the LCA, and subsequently which VRPs are being promoted to achieve SDGs. LCA and CE are popularising within the building industry, for example, through building certification systems and suggested future legislations [7]. At the same time different allocations approaches are suggested for LCA. Although allocation studies exist, the examples provided in these studies often build on simplified short-lived products [8], whereas the construction sector works with complex long-lived products. Thus, selecting/developing an allocation approach for the construction sector requires testing them on sector specific products to deal with their inherent complexity in an appropriate manner. In addition, the European Union (EU) aims at net zero buildings by 2050. However, research showing the effect of the different allocation approaches on the LCA and the subsequent incentive they provide for industry to reach SDGs and net zero buildings, is lacking.

In this study, we compare the effect of different allocation approaches on the LCA outcomes and the subsequent incentive they provide for industry. The paper is structured as follows. First, we identify and clarify existing LCA methods for dividing burdens in circular systems. Second, using these approaches, we calculate the environmental impact of two exemplary 'circular building components': (1) a concrete column design for reuse and (2) a recyclable roof felt. Third, we compare the effect of these approaches on the LCA outcomes and derive the incentive they create. Finally, we reflect on our finding and make a first recommendation on an allocation approach for CE LCA.

2. Background on allocation approaches in LCA

A challenging aspect of LCA is how to deal with multifunctional processes or secondary functions such as the CE principles of reuse, recycling and energy recovery. These result in shared processes and functions between more than one product system. Although some general LCA recommendations have been provided by different recognized standards such as ISO 14040 [9], ISO 14044 [10], EN 15804 [11] and 15978 [12] several approaches still exist and are applied.

The ISO 14040 is aimed at all types of products [9]. It recommends a hierarchical procedure for solving multifunctionality. Partitioning the environmental impacts between multiple product systems – i.e., allocation – should be avoided by: (1) dividing the processes into sub-processes and 'cutting off' the sub-processes providing the secondary function or by (2) 'system expansion' were all functions of the product system are integrated into the system boundary through avoidance of impacts. If allocation cannot be avoided, (3) an allocation approach should be applied. How burdens and benefits are divided between systems can be based on different parameters. The ISO 14044 suggests allocation (in the following order of preference) using (a) the underlying physical relationship (e.g., mass), (b) other relationships (e.g., economic value), or (c) number of subsequent uses of the recycled material. The array of different existing allocation approaches can broadly be grouped into three common approaches: 0:100 ('end-of-life recycling'), 100:0 ('cut-off') and 50:50 ('equal share') [6]. However, research literature describes these approaches in different ways (i.e. emphasizing different processes and impacts to be allocated between life cycles). For example, the 100:0 approach is both used for allocation of EoL impacts [8] and to address allocation of avoided burdens from substituted materials [13].

The ISO 14040 remains flexible and only provides general guidelines. Yet, more detailed and prescriptive standards have been developed. The current European LCA practice for construction products and buildings is based on the European standards EN 15978 and EN 15804. In the EN 15804 and 15978, multifunctionality is handled through system expansion where the net environmental benefits and burdens of reuse, recycling and energy recovery are integrated in the system; burdens and benefits are divided by calculating the avoided impact from the most likely corresponding technology and/or practice. The net benefits and burdens are reported separately in module D. Furthermore, impacts from production, use and EoL are calculated using the 'cut-off' allocation approach.

The International Reference Life Cycle Data System (ILCD) recommends that the choice of how to handle multifunctional processes or secondary functions should be based on the decision context (i.e. the type of decision to be made based of the LCA study). For most decision contexts system expansion is recommended over allocation [14].

As inconsistency and incomparability exist between existing LCA methods, the European Commission (EC) has developed a common methodology, Product Environmental Footprint (PEF) for all types of products. The EC recommends the use of the PEF to member states to support the assessment and labelling of products [8]. Herein, a single end-of-life (EoL) formula – known as the Circular Footprint Formula (CFF) – is suggested. The CFF builds on existing approaches. The formula aims to enable the assessment of all EoL scenarios possible including reuse, recycling, incineration with/without energy recovery and final disposal via landfill – for both open and closed loop systems – in a consistent and reproducible way [15]. Existing allocation approaches favour either ingoing or outgoing secondary materials, whereas the CFF tries to accommodate both by covering recycled content at the input side and recyclability at EoL [15]. Additionally, the CFF considers the change in material quality between cycles. The CFF uses all three allocation principles: 100:0, 0:100 and 50:50. Which applied depends on the material, the market situation of the material (i.e., whether there is a high or low supply and demand). The CFF thereby integrates a systems perspective [15]. CFF also uses system expansion [15].

Next to the standards, other more unconventional approaches exist. For example, in the development of the CFF 11 different allocation approaches where assessed among others the linear degressive (LD) allocation approach [8]. In this approach, impacts from virgin material production are allocated linearly degressively to all use cycles, allocating the highest share of impact to the first cycle where the production happens. Likewise, the final disposal impact is allocated linear degressively to all use cycles, allocating the highest share of impacts to the last cycle where the disposal happens. This approach uses the 50:50 approach for impacts from reuse and recycling processes between use cycles. In other words, the reuse and recycling impacts of a material are equally allocated between the first and subsequent use cycle(s) of the material. The LD approach is not yet integrated in existing standards but has been discussed by other researchers [8]. The approach appears promising for CE as it accounts for the number of times a material will be reused and recycled. Although, this is uncertain and difficult to predict in doing so the LD approach implicitly considers changes in material qualities.

In comparison to the 50:50 approach described above, Eberhardt et. al [16] suggested a modified version of the approach where all impacts of reusable concrete elements are equally shared between the use cycles to not benefit one cycle over another.

Each of the abovementioned approaches have limitations in relation to CE. In (1) by 'cutting off' the secondary functions – which are central to the CE concept – these functions are excluded. As it is uncertain what resources are avoided in the future through the recycling, reuse and recovery, in (2) ‘system expansion’, suitable substitutes to perform system expansion cannot always be found and it has proven difficult to develop a common approach for this methodology. Furthermore, system expansion only avoids reuse or recycling from the second cycle: any further cycles are neglected. Also, as system expansion integrates secondary functions in the product system, it becomes difficult to differentiate the impact between different products [8]. (3) Allocation can be based on an array of different parameters as there is currently no single, widely accepted modelling approach [6]. However, allocation is for the purpose of assessing multiple cycles favourable as it can help answer questions arising about how benefits and burdens should be allocated between cycles. Hence, in this paper we compare four allocation approaches: two prevalent approaches: (a) the cut-off approach stated in EN 15804/15978 [11, 12] and (b) CFF from the Product Environmental Footprint (PEF) [15]: and two unconventional approaches (c) the 50:50 approach [6] and (d) the LD approach [8].

3. Methods

In this section, we calculate the environmental impact of two exemplary ‘circular building components’, using the four allocation approaches selected in section 2.

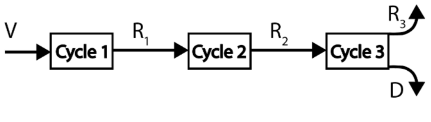
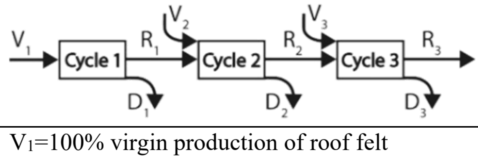
3.1. Exemplary circular building components: case descriptions

The two exemplary circular building components assessed include: (1) a long-life, concrete column with a high(er) uncertainty of subsequent reuse and (2) a short-life, roof felt with less uncertainty of future recycling [17]. Concrete elements are often difficult to separate without damaging the element, as they are casted together. Therefore, they are commonly crushed into concrete gravel (used as road filling); the reinforcement steel is recycled into new steel products at EoL. The Finnish company, Peikko, produces large bolted mechanical steel connections for concrete elements that enables disassembly for reuse in subsequent buildings, thereby prolonging the elements’ service life and avoiding environmentally burdensome production of new concrete elements [17]. We assumed that the concrete column can be used three times 80 years. Roof felt is most commonly disposed of through landfill, energy recovery or recycling for asphalt roads. However, the Danish roof felt manufacturer, Viva Tagdækning A/S, can extract and recycle 90% of the bitumen and slate through shredding and heating into new roof felt [17]. Although 10% virgin material needs to be added to each cycle to continue cycling the roof felt, the recycling process is theoretically eternal. To be able to assess the roof felt, and compare it to the case of the column, the system has been limited to three cycles of each 20 years.

3.2. Life cycle assessment

Table 1 gives and overview of the life cycle inventory of the column and the roof felt.

Table 1. Life cycle inventory of the column and the roof felt.

	420x420x3500mm Peikko prefabricated concrete column (reuse)	**1 m^2 Icopal Top 500 P roof felt (recycling)**
Service life	3x80 years (240 years)	3x20 years (60 years)
Bill of materials	Concrete: 1489 kg Reinforcement: steel 76 kg Steel connections: 26 kg	Bitumen: 4 kg Polyester felt: 0.2 kg Slate: 1.1 kg
Flow diagram		
Scenario/ Impact	V=100% virgin production of column $R_{1,2}$=480 km (longest travel distance in Denmark) freight lorry transportation of column to subsequent reuse R_3=90% concrete and 99% steel recycling D=10% and 1% concrete and steel landfill	V_1=100% virgin production of roof felt $R_{1,2,3}$=90% bitumen and slate recycling $D_{1,2,3}$=100% polyester incineration and 10% bitumen and slate landfill $V_{2,3}$=100% polyester felt and 10% bitumen and slate virgin production

Abbreviations: V=production, R = reuse/recycling, D = disposal

In conventional LCA, either the overall cascading system (cycle 1, 2 and 3 in Table 1) or a single cycle is assessed (e.g. cycle 1 in Table 1) depending on the system boundaries. In this study we focus on assessing the environmental impact of both the cycling system in terms of reuse and recycling and how the cycling affects the individual cycles of that system.

Table 2. Allocation of the reusable and recyclable material fractions of the column and the roof felt.

Allocation approach	420x420x3500mm Peikko prefabricated concrete column (reuse)	1 m^2 Icopal Top 500 P roof felt (recycling)
Cut-off	**Cycle 1** = $V+R_1$ **Cycle 2** = R_2 **Cycle 3** = R_3+D Where R_3 is allocated to the subsequent cycle	**Cycle 1** = $V_1+R_1+D_1$ **Cycle 2** = $V_2+R_2+D_2$ **Cycle 3** = $V_3+ R_3+D_3$ Where R_3 is allocated to the subsequent cycle
50:50	**Cycle 1** = $V+0.5 \cdot R_1$ **Cycle 2** = $0.5 \cdot R_1+0.5 \cdot R_2$ **Cycle 3** = $0.5 \cdot R_2+0.5 \cdot R_3+D$ Where 0.5·R3 is allocated to the subsequent cycle	**Cycle 1** = $V_1+0.5 \cdot R_1+D_1$ **Cycle 2** = $V_2+0.5 \cdot R_1+0.5 \cdot R_2+D_1$ **Cycle 3** = $V_3+0.5 \cdot R_2+0.5 \cdot R_3+ D_3$ Where 0.5·R3 is allocated to the subsequent cycle
CFF	**Cycle 1,2,3** = $(V+(1-A) \cdot r_2 \cdot ((R_1+R_2+R_3)-R_3^* \cdot (Q_{sout}/Q_p))+(1-r_2) \cdot D)/3$ Where A is the allocation factor, r_2 is the share of the material (90% concrete and 99% steel) that will be recycled at EoL, R_3^* is the impact assumed to be substituted by 90% concrete and 99% steel recycling, Q_{sout} and Q_p is the quality of the outgoing secondary material and primary material respectively.	**Cycle 1** $_{\textbf{bitumen/slate}}$ = $V_1+(1-A) \cdot V_1 \cdot (Q_{sin}/Q_p)+(1-A) \cdot r_2+(R_1-V_1^* \cdot (Q_{sout}/Q_p))+(1-r_2) \cdot D_1$ **Cycle 2** $_{\textbf{bitumen/slate}}$ = $(1-r_1) \cdot V_2+r_1 \cdot (A \cdot R_1+(1-A) \cdot V_2 \cdot (Q_{sin}/Q_p))+(1-A) \cdot r_2 \cdot (R_2-R_2^* \cdot (Q_{sout}/Q_p))+(1-r_2) \cdot D_2$ **Cycle 3** $_{\textbf{bitumen/slate}}$ = $(1-r_1) \cdot V_3+r_1 \cdot (A \cdot R_2+(1-A) \cdot V_3 \cdot (Q_{sin}/Q_p))+(1-A) \cdot r_2 \cdot (R_3-R_3^* \cdot (Q_{sout}/Q_p))+(1-r_2) \cdot D_3$ Where A is the allocation factor, r_1 is the share recycled content in the production (90% bitumen and slate), r_2 is the share (90% bitumen and slate) that will be recycled at EoL, $R_{2,3}^*$ is the impact assumed to be substituted by 90% bitumen and slate recycling, Q_{sin}, Q_{sout} and Q_p is the quality of the ingoing/outgoing secondary material and primary material respectively. **Cycle 1,2,3** $_{\textbf{polyester}}$ = $V_{1,2,3}+r_3 \cdot (D_{1,2,3}-L \cdot X_{ER,heat} \cdot E_{SE,heat}-L \cdot X_{ER,elect} \cdot E_{SE,elec})$ Where L is the lower heating value, r_3 is the share of material (100% polyester) that will be used for energy recovery at EoL, $X_{ER,heat/elec}$ is the efficiency of the heat/electricity energy recovery process and $E_{SE,heat/elec}$ is the impact assumed to be substituted by the heat/electricity energy recovery.
LD 56/33/11	**Cycle 1** = $0.56 \cdot V+0.11 \cdot R_3+0.11 \cdot D+0.5 \cdot R_1$ **Cycle 2** = $0.33 \cdot V+0.33 \cdot R_3+0.33 \cdot D+0{,}5 \cdot R_1+0{,}5 \cdot R_2$ **Cycle 3** = $0.11 \cdot V+0.56 \cdot R_3+0.56 \cdot D+ 0.5 \cdot R_2$ Where R_3 is counted as disposal	**Cycle 1** = $0.56 \cdot V_1+0.11 \cdot R_3+0.11 \cdot D_3+0.5 \cdot R_1$ **Cycle 2** = $0.33 \cdot V_2+0.33 \cdot R_3+0.33 \cdot D_3+0{,}5 \cdot R_1+0{,}5R_2$ **Cycle 3** = $0.11 \cdot V_3 + 0.56 \cdot R_3 +0.56 \cdot D_3 + 0.5 \cdot R_2$ Where R_3 is counted as disposal

Abbreviations: V=production, R = reuse/recycling, D = disposal, CFF: Circular Footprint Formula, LD: Linear degressive

The embodied carbon of each component was assessed following the LCA methodology stated in EN 15978 however applying each of the selected allocation approaches. Table 2 gives an overview of how impacts are allocated when applying these allocation approaches to the two exemplary circular building components. The modelling was carried out in openLCA v1.9.0 software, using the CML-IA baseline characterization method. The functional unit was set to provide the function of each component across three component life cycles based on the components service life as stated in Table 1. The life cycle inventory (LCI) of the background system was based on Ecoinvent 3.4 APOS database [18] using system processes to get aggregated results. APOS already uses an allocation principle in the background system. However, APOS is the best option for controlling the allocation approach in the foreground system. The foreground system was compiled using the manufacturers' product specifications stated in Table 1. The system boundaries include production of the building materials, waste recovery for reuse, recycling or incineration, and disposal by landfilling at EoL. Credits for potential reuse, energy recovery and recycling of materials and components in a next product system is an inherent part of the CFF approach but has been excluded from all other approaches to avoid double counting between cycles. LD requires the knowledge of how many times a product is being cycled. In other words, the use cycles need to be determined in advance. Thus, to maintain the mass balance of the system, R_3 is for LD counted as part of the systems' final disposal instead of associating the recycling with a potential 4th cycle.

4. Results

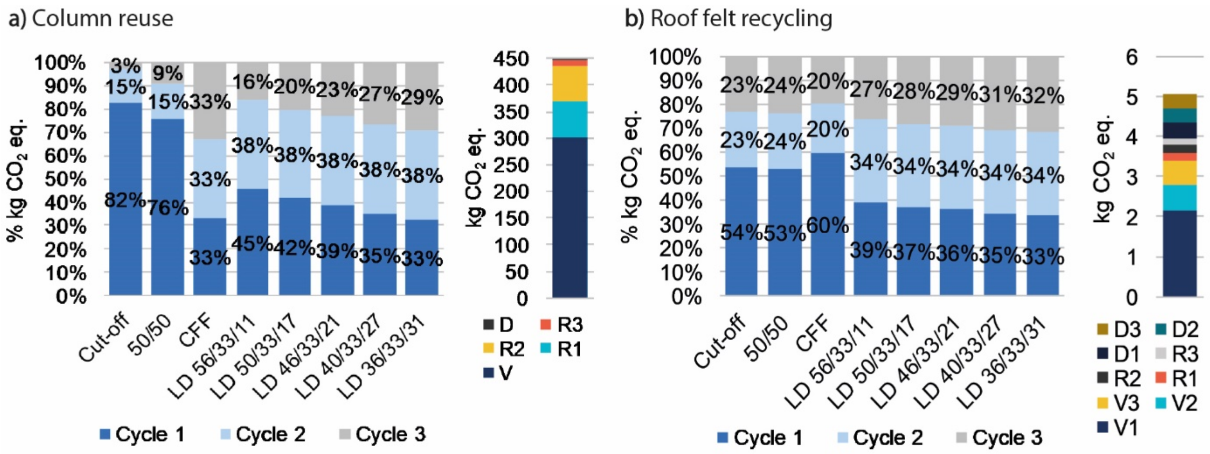


Figure 1. Percentage impact distribution using different allocation approaches and absolute impacts (using the cut-off approach) of a) the column and b) roof felt. See abbreviations in Table 1.

The embodied carbon distribution – resulting from applying the different allocation approaches to the column and roof felt system – is shown in Figure 1. The impact distribution is calculated in % to ease comparing the results of different allocation approaches. For both the column and roof felt the highest impact comes from production. The different allocation approaches have similar results for both the column and the roof felt, except for the CFF as it has a different approach for reuse and recycling. Thus, we found there is no significant difference between the shorter- and longer-lived building product. As the CFF uses the 50:50 approach suggested by Eberhardt et. al [16] in reuse situations, the CFF approach shows an even impact distribution between the three cycles for the concrete column. However, for recycling, such as for the roof felt, the CFFs distributes impacts dependent on the different factors inherent in the equation (see Table 2). These are factors such as the allocation factor, share of ingoing and outgoing secondary material and change of material quality over each use cycle. Both cut-off, 50:50 and LD for the column, as well as cut-off, 50:50, CFF and LD for the roof felt, allocates the highest impact share to the first cycle. Although LD allocates the highest impact share to the first cycle, LD does not allocate as much impact to the first cycle as the other approaches. Viewing the results of different LD distribution percentages show that the lower the percentage share for the first cycle is, the more even the impact distribution gets between the cycles.

5. Comparison of allocation approaches and their incentives in a CE

In this section, we compare the effect of the allocation approaches on the LCA outcomes and derive the incentive they create.

In order to reach SDG 13 *Climate Action* and net zero buildings in EU by 2050, reducing current emissions, resource use and waste should be incentivised through implementing different CE principles (narrowing, slowing and closing) now, and to design for these in the future. The results of applying different allocation approaches to circular designed building components in LCA indicates that different CE principles are being promoted due to differences in the impact distribution. The approaches that allocate a large share of impacts to the first cycle, such as the CFF for the roof felt and the cut-off approach, promotes use of secondary materials in the production (as subsequent cycles receive much less impact by recycling and reusing). In the case of the concrete column using cut-off, the initial user will have no incentive to slow loops, for example through designing the column for disassembly; the first user receives 80% of the column's total impacts originating from the column's production even though the first user has taken measures to ensure long term reusability. In comparison, the second and third users of the column only receive 17% and 3% respectively creating a great incentive for reuse. Similar results are visible for the roof felt. By equally sharing the impacts between the cycles, as for the CFF of the column a much stronger incentive is created for the first user to slow and close loops, as an up-front reduction is received. The LD approach can be said to provide an 'in-between' solution as it uses the 50:50 approach to allocate reuse and recycling impacts equally between the cycles, and allocates most of the production impact to the first cycle where the impact is happening as well as allocating most of the disposal impact to the last cycle where EoL is occurring. Thus, some benefit for designing for reuse and recycling is given up-front.

So, which method would be most suitable for circular LCAs? Because of the long-life span of the concrete column, the CFF approach is questionable: allocating impacts to potential cycles 80, 160 and 240 years into the future may lead to 'green washing' by industry. There is a high uncertainty whether the column will be reused at that time. Thus, impacts may eventually be unaccounted for. The LD approach, to some extent, deals with the sensitivity and uncertainty related to the product's long-life span: it allocates impacts according to when they happen in the system. However, LD can also be misused by adding cycles that do not exist (which lowers the impact per use cycle). As seen from Table 2, the CFF approach contains many parameters. This makes the CFF more comprehensive, but also complex to use. Although, some parameters can be looked up in an appendix, some materials are absent. Thus, a default value (or estimate) must be used in the calculation. Moreover, there is no guidance on how to estimate changes in material quality over multiple cycles, leaving it up to the assessor to produce a reasonable assumption. This may yield it difficult to ensure a harmonized, common practice of the formula. Also, the CFF does not comply with the mass balance due to the quality-correction of environmental impacts. The difference concerning mass balance may suggest that the purpose of the approach is not to show absolute impacts but stimulate a certain behaviour (e.g., promoting recycling at the front-end as seen for the roof felt example). However, absolute results are necessary in the design stage to provide a sound decision base. All in all, we found that, for closed-loop systems (such as the ones assessed here), the LD is preferable for the following reasons: it is simple to use, creates incentives for narrowing, slowing and closing loops (now and to design for it in the future), and it deals with the uncertainty, number of cycles (i.e. time perspective) and material quality (implicitly from the number of cycles) of cycling systems.

6. Discussion and conclusion

In this paper we compared the effect of different allocation approaches on the LCA outcomes and the subsequent incentive they provide for industry. We calculated the environmental impacts of two 'circular building components': (1) a concrete column designed for direct reuse and (2) a recyclable roof felt. We applied four allocation approaches: (a) the cut-off approach stated in EN 15804/15978, (b) the Circular Footprint Formula (CFF) from the Product Environmental Footprint (PEF), (c) the 50:50 approach, and (d) the linearly degressive approach. We found that the allocation approaches show notable variations in impact distributions between cycles. Subsequently, these approaches incentivize different CE principles. For closed-loop systems, such as the ones defined here, we concluded that the LD approach is preferable: it is simple to use, motivates narrowing, slowing and closing loops (now and to design for it in the future) and deals with uncertainty, number of cycles and material quality.

The proposed LD approach in CE LCA can have significant implications in both LCA practice and the circular approach in the building sector. Current LCA standards – and many derived practice tools -

do not apply LD allocation. Furthermore, the LD approach in LCA might lead to different design strategies becoming superior in terms (e.g.) CO_2 emission reductions. For example, the building sector now often focusses on reusing building materials to increase circularity, and less on designing for future reuse. However, more cases are needed to validate the results presented in this paper and to investigate which impact distribution for the proposed LD method is fair and desirable. Yet, the results of this study provide an important step towards CE LCA and, subsequently, supporting the CE concept within the built environment.

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