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An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment

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ABSTRACT

Refurbishment is one of the most important measures for reducing the environmental impacts of the construction sector in the near future. According to the life cycle assessment (LCA) methodology for buildings, the environmental impacts of refurbishment measures should be assessed within the whole life cycle of the building and reflected in separate modules. However, in practice, refurbishment is often treated as the beginning of a new building life cycle. This leads to difficulties in correctly assessing the environmental impacts for the components that are reused or recycled after the refurbishment. The division of a building's life cycle into two separate life cycles indicates that the environmental impacts must be divided between the life cycle before and the life cycle after the refurbishment for a correct assessment of the environmental impacts and a calculation of the residual value.

We propose a newly developed methodology for calculating the environmental impacts and the residual value of refurbishment measures that also involves a division between life cycles. The new methodology is a combination of already exiting methodologies that are innovatively combined and consists of four sequential steps. In the first step, the input, output and reuse flows between the life cycles before and after the refurbishment are defined. In the second step, the environmental impacts are assessed using the chosen allocation approach (i.e., the cut-off, cut-off with module D, avoided-burden, 50:50 and the product environmental footprint (PEF)). In the third step, a maintenance scenario is implemented according to the selected reference-service-life (RSL) database. In the fourth step, the residual value is estimated. The methodology was tested on selected building components. A sensitivity analysis for different allocation approaches and RSL databases was performed to show how the choice of these parameters can influence the results. The differences between the selected allocation approaches emerge if materials with recycled content are used or if the materials are being recycled or reused at the end of their life cycle. The developed methodology reliably estimates the environmental impacts as well as the residual value of the life cycle before and after the refurbishment. We expect that this research will stimulate practitioners to avoid the negligence of previous environmental flows, bringing scientific consistency to future assessments of refurbishment measures.

1. Introduction

The construction sector's potential to reduce its environmental impacts and consequently tackle climate change are highlighted in various reports, e.g., UN Environment (UN Environment Programme, 2018; UNEP, 2020), the International Energy Agency (IEA and UNEP, 2019), and scientific papers (Röck et al., 2019). According to these findings, new buildings must become fossil-free and nearly zero energy by 2020. Existing buildings have to be renovated rapidly to increase their energy efficiency, since in Europe 80% of the buildings that will be occupied in 2050 already exist (Dixit, 2019; Röck et al., 2019; Vilches et al., 2017a). Several policy documents, for example, the European Green Deal (EC, 2020), are considering refurbishment as one of the most important tasks to reduce the construction sector's environmental impacts in the near

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future.

Life cycle assessment (LCA) is recognized as an appropriate method (Asdrubali et al., 2013; Denac et al., 2018; Ortiz et al., 2010; Ramesh et al., 2010; Sharma et al., 2011) for quantifying environmental impacts. It assesses products' and processes' environmental impacts throughout their entire life cycles in a iterative approach, divided into four steps: defining the goal and scope of the study, collecting data and analyzing the inventory, assessing the environmental impacts and interpreting the results (ISO 14040:2006, n.d.). The LCA method for the buildings sector in Europe is additionally regulated by the standards EN 15804 (EN 15804:2012 + A2:2019, n.d.) for products and components and EN15978 (EN 15978:2011, n.d.) for entire buildings. They propose a modular approach to cover the whole life cycle of the building and divide it into the production stage (comprising the stages of raw-material extraction, A1; raw-material transport, A2; production of construction materials, A3; their transport, A4; and their installation, A5), the use stage (including use, B1; maintenance, B2; repair, B3; replacement, B4; refurbishment, B5; operational energy use, B6; and operational water use, B7), the end-of-life (EoL) stage of the building (comprising the deconstruction, C1; the transport of materials, C2; the waste treatment, C3; and the final disposal phase, C4) and the stage beyond the life cycle of the building, module D (scenarios of reuse, recycling and energy recovery from obsolete materials and the environmental impacts associated with them).

The results of the LCA are the input for the residual-value calculation of separate materials and components. According to the definition of SIA 2032:2020 the residual value is the sum of the not-yet-amortized environmental emissions of embodied energy evaluated at a specific moment in the life cycle, whereas embodied energy includes the production stage (modules A1–A5), maintenance (B4) and the EoL stages (modules C1–C4) according to EN 15804. In the ideal case, the building materials and components should be amortized within the reference service period (RSP) of the building, and at this point the building should be either refurbished or demolished. This is seldom the case, however. In practice, at the end of the RSP the building materials are often not amortized and the building is demolished, and some materials are still intact (Vilches et al., 2017a). Therefore, the economic and environmental residual values of the components should be assessed. The residual value indicates how much damage is done to the environment if a certain component or material is replaced, recycled or discarded prematurely. However, the residual value is dependent on the calculation methodology and the input data (e.g., the life cycle-inventory database used, the RSL database, etc.) (Kohler et al., 2010; Severin, 2018).

A special case is the evaluation of the environmental impacts and the residual values of buildings that were refurbished. The refurbishment of a building should be assessed in module B5 according to the standard EN 15978 (EN 15978:2011, n.d.). This includes:

- production of new building components,
- transportation of the new building components (including production of any materials lost during the transportation),
- construction as part of the refurbishment process (including production of any material lost during refurbishment),
- waste management of the refurbishment process,
- the EoL stage of replaced building components.

However, several studies (Corrado and Ballarini, 2016; Ferreira et al., 2013; Häkkinen, 2012; Häkkinen et al., 2016; Oregi et al., 2015; X Oregi et al., 2017; Passer et al., 2016; Vilches et al., 2017b) indicate that the environmental impacts of a building's refurbishment are not addressed as the phase B5 of the whole life cycle, but are treated as the beginning of a new life cycle (Anand and Amor, 2017). In other words, the environmental impacts of the refurbishment materials and processes are addressed in modules A1 to A5 (the production stage of the building) of the life cycle after the refurbishment. This practice is still in line with EN 15978, which states that "if a building is refurbished and the refurbishment was not taken into account at the outset, i.e., in any previous assessment, a new assessment should be carried out, particularly where the refurbishment changes the functional equivalent (…)". While the European standard does not clearly mention how the practitioner should address the materials and components that are remaining after the refurbishment, according to ISO 14044 the reuse of previously adopted materials in a new product system (i.e., in a new building's life cycle) calls for an allocation procedure. ISO 14040 emphasizes that allocation should be avoided either by dividing the unit process into two or more independent sub-processes or by expanding the scope of the study to include the additional functions related to the co-products (ISO 14040:2006., n.d.). If allocation cannot be avoided, a division between two life cycles should be made. The recognition of an allocation need is seldom observed in published studies, especially for buildings.

To bridge the gap between the common building-refurbishment LCA practice and the international standard's requirements, it is crucial that the practitioners consider the distribution flows between previous and new life cycles (Allacker et al., 2017; Ekvall, 2000; Ekvall and Tillman, 1997; Frischknecht, 2010; Kim et al., 1997; Mirzaie et al., 2020)). There are several approaches to allocate the environmental burdens and benefits between two product systems (Allacker et al., 2017). In this paper we used the (1) the recycled-content approach, (2) the module-D approach, (3) the avoided-burden approach, (4) the 50:50 approach and (5) the PEF approach. It is important to mention that the approaches are mainly discussed for the recycling of materials or products. In the case of building refurbishment, the situation is similar to recycling, except that mostly the materials and components are being reused. Compared to recycling, this means that no additional recycling processes and their related environmental impacts are involved.

The current approach for assessing environmental impacts neglects the materials and components that remain in the building after the refurbishments. Neglecting materials and components used prior to the refurbishment is scientifically questionable, according to the requirements outlined in ISO 14044. If only the materials substituted during the refurbishment are considered in an LCA study, we produce a gap at the end of the building's new life cycle, where all the materials (the materials reused during the refurbishment and the newly added materials) are "discarded", an issue already highlighted in the study of Vilches et al. (2017a). Additionally, no information about which impacts have already been considered in the past, carries the risk that some of the impacts are double-counted. For example, a material that has already been described as burden-free at the beginning, because it consists of recycled content. If we do not have this information in the later stages, we can also assign it the benefits of recycling at its EoL. Thus the benefit of recycling is assigned twice to the same material (Frischknecht, 2010). It is crucial that the impacts which are considered before and which are considered after the refurbishment of the building are clearly indicated.

The solution to the presented problems is a newly developed methodology for the assessment of the environmental impacts and the residual value of components and materials before and after a refurbishment. The methodology builds on the LCA methodology and the SIA2032 standard that is used to evaluate the residual value. These are upgraded by the allocation approaches of the impacts between the life cycle before and after the refurbishment. For the allocation of the impacts, different existing allocation approaches can be used, which are chosen based on the scope and goal of the study. The connection of the various existing methodologies into a new methodology is innovative and allows a reliable estimation of the environmental impacts and the residual value at a certain moment in time. This information facilitates decisions about the further use of different components and materials.

The new methodology is verified on two different case studies where the sensitivity to various allocation approaches and selected reference-service-life databases was also assessed.

2. Methods and materials

The following subsections describe the stages of this research. First, the four-step methodology for the assessment of the environmental impacts and the residual value of refurbished buildings is described in detail in subsection 2.1. The subsection 2.2 describes the validation of the methodology on two case studies (two different building components of a multi-family building).

2.1. Methodology description

The newly developed calculation approach to measure the refurbishment measures' environmental impact and residual value has four steps (Fig. 1). In step 1, the inputs and outputs of the building's life cycle before and after its refurbishment are determined. For each life cycle we must indicate which inputs are virgin materials and which consist of recycled materials. Similarly, this step also defines which materials are disposed of at the end of the life cycle, which materials are recycled and which are reused (e.g., reuse of the structural components after the refurbishment). The scope of the study should be chosen so that it shows the relationship between the first and the second life cycles. This step establishes a logical background for the calculations performed in step 2.

Step 2 is the most time consuming. The environmental impacts of the materials, components or buildings are calculated and distributed between the life cycle before the refurbishment and the life cycle after the refurbishment using the chosen allocation method. The connection between the first and second life cycles and the choice of the allocation schemes is an important topic, especially when materials are reused or recycled. The allocation approaches between the life cycles of a building lead to very different results (Allacker et al., 2017).

The cut off (also called the 100:0 or the recycled content) approach considers that the environmental impacts of the production phase for a product are attributed to the first use of this product and follow the "polluter pays" principle (Gervasio and Dimova, 2018). The second use of the product only bears the environmental impact of collection and the preparation of the product for its subsequent use. In some cases, the collection is also attributed to the first use of the product. However, the materials that are used for the second time do not bear any environmental load from the primary production process (Allacker et al., 2017; Frischknecht, 2010; Gervasio and Dimova, 2018). The cut off approach with module D tries to introduce the circularity stimulus to the previous approach by the introduction of module D. This is the phase beyond the system boundary of the building's life cycle that includes possible benefits or loads due to recycling, reuse and energy recovery. However, in module D the difference in quality of the material before and after the recycling process is not assessed. The avoided burden approach (also called the End-Of-Life approach or 0:100) considers the benefits of the potential recycling or reuse and accredits it in the first life cycle. The 50:0 approach divides the burdens and benefits equally between the first and second life cycles. It allocates 50% of the benefits of using recycled materials in the production stage and 50% of the benefits of recycling at the EoL stage to the observed life cycle. It can be seen as a compromise between the recycled content and the avoided-burden approach. The Product Environmental Footprint (PEF) approach builds on the 50:50 approach and introduces two factors: one to take into account the downcycling of materials, and the other to introduce the market demand for recycled products (Gervasio and Dimova, 2018). However, these factors are sometimes difficult to determine due to a lack of data (Spirinckx et al., 2018). The graphical presentation of the approaches is in Fig. 2.

The ISO standards do not dictate which to adopt, relying on the practitioner's judgement to determine their appropriateness. The results of this step are the absolute environmental values of separate life cycles, and these are an input for the calculation of the residual value. For the materials that are replaced or kept during the following life cycle, additional information is needed for the calculation of the residual value, which is provided in the next step. The formulas for the allocation are derived from Gervasio and Dimova, and Allacker et al. (Allacker et al., 2017; Gervasio and Dimova, 2018). To facilitate the interpretation of results, the total environmental impact for each allocation approach was further subdivided into the subcategories proposed in Table 1: A, production; C, EoL; and D, beyond the building life cycle. These subcategories are divided into parts that represent impact virgin (environmental impact of the virgin materials), impact recycled content (impact related to the use of recycled materials), impact disposal (environmental impact of disposal), impact EoL (environmental impact of EoL), recycling impact (environmental impact of the recycling) and credit module D (environmental impact avoided because of the benefits of reuse, recycling, incineration with waste recovery).

In step 3, a timeline with the replacement times and maintenance actions for each component or material is established according to the selected reference service life (RSL). Materials and building components have different RSLs and are amortized at different times of the observed reference service period (RSP) of a building. For the determination of the RSL various sources can be used (Grant and Ries, 2013). Often, they are acquired from RSL databases. Generally, the data for various materials or components differ from one database to another. In a previous study we found that due to different replacement rates, the environmental impact can vary significantly (Potrč Obrecht et al., 2019). In the developed methodology, this step provides the information about the replacement rate and maintenance procedures and consequently also about the remaining RSL of the building materials and components.

Finally, in step 4 the data from the two previous steps are used to calculate the residual value of the material, a component or a building. The environmental values calculated in step 2 are linearly distributed accordingly to their remaining RSL (which was determined in step 3). The residual value is calculated following the approach presented in SIA:2032 (Severin, 2018). As already mentioned, the residual value of a material, component or building is the sum of the not-yet-amortized environmental emissions of embodied energy evaluated at a specific moment in time, whereas the embodied energy includes the production stage (modules A1–A5), maintenance (B4) and the EoL stages (modules C1–C4) according to EN 15804 (EN 15804:2012 + A2:2019, n.d.; Severin, 2018). The residual value of a material component of a building

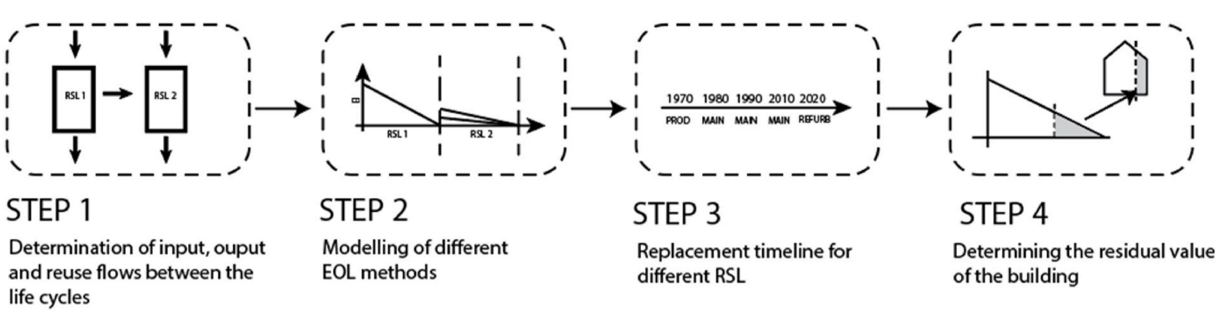

Fig. 1. Methodology for the assessment of environmental impacts and the residual value of components and materials before and after a refurbishment in four steps.

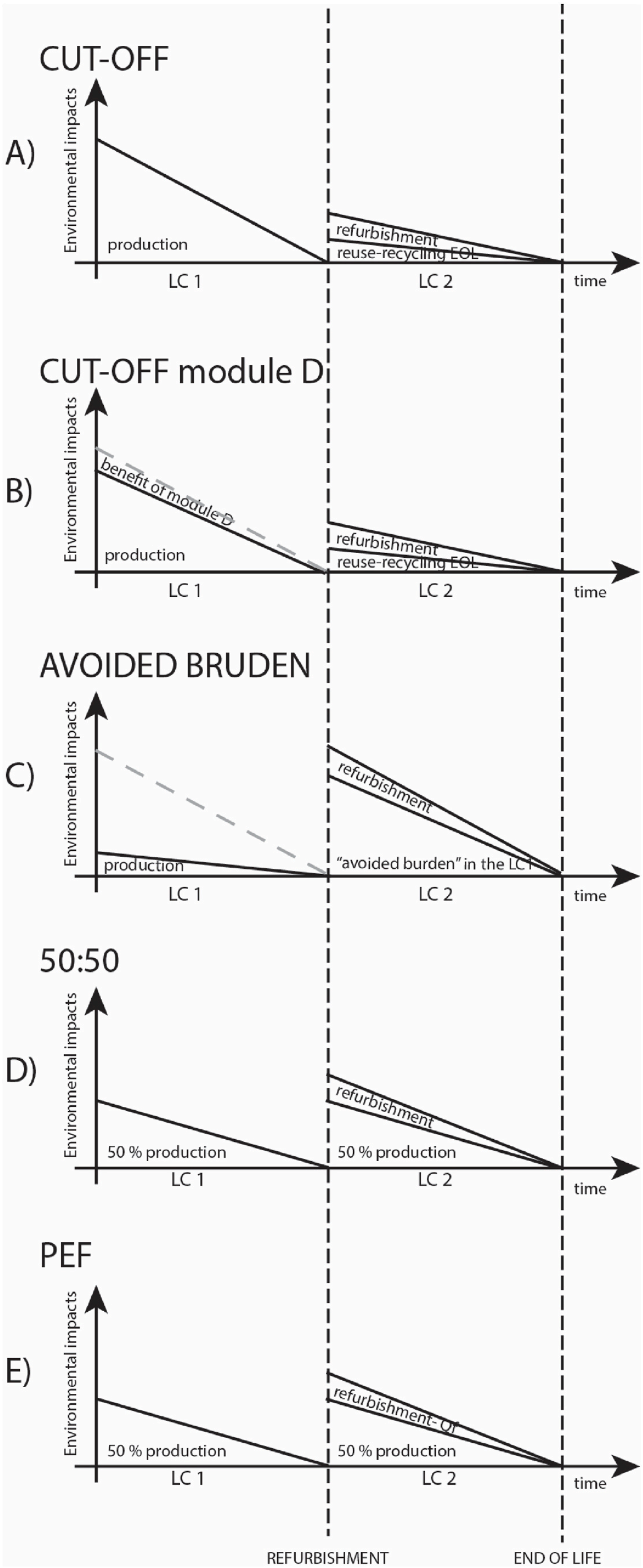

Fig. 2. Graphical representation of the allocation approaches: A) Cut-off: LC1 has all the environmental impacts (EI) of the production; LC2 has the EI of the refurbishment measures and the EI of the recycling and reuse; B) Cut-off with module D: LC1 has all the environmental impacts (EI) of the production and the benefits of module D; LC2 has the EI of the refurbishment measures and the EI of the recycling and reuse; C) EoL LC1 has all the environmental impacts (EI) of recycling and reuse, LC2 has the EI of the refurbishment measures and the avoided burdens in LC1; D) 50:50 LC1 has half of the environmental impacts (EI) of production, LC2 has the EI of the refurbishment measures and half of the environmental impacts (EI) of production; E) Product Environmental Footprint (PEF): LC1 has half of the environmental impacts (EI) of production, LC2 has the EI of the refurbishment measures weighted by the quality factor Qf and half of the environmental impacts (EI) of production.

Table 1
Formulas for calculating life cycle modules according EN 15978 for the different allocation approaches.

	Formulas				
Modules EN 15978	A-production		C-EoL	D-beyond the building life cycle	
Allocation approach	EI virgin	EI rec content	EI disposal	EI EoL rec	EI, rec, open loop (credit module D)
CUT-OFF	(1-R1) Ev	R1*Erec	(1-R2)*Ed	0	0
CUT-OFF + D	(1-R1) Ev	R1*Erec	(1-R2)*Ed	(R2-R1) *Erec,eol	-(R2-R1)*E*v
AVODIED BURDEN	Ev	0	(1-R2)*Ed	R2* Erec, eol	-R2*E*v
50:50	(1-R1/ 2)Ev	R1/ 2*Erec	(1-R2/2)* Ed	R2/ 2*Erec, eol	-R2/2* E*v
PEF	(1-R1/ 2)Ev	R1/ 2*Erec	(1- R1/2- R2/2)*Ed	R2/ 2*Erec, eol	-R2/2* E*v* (Qprod,out/ Qprod,in)

Where:
Ev = emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material.
E*v = emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.
Erec = emissions and resources consumed (per unit of analysis) arising from the production process of the recycled material, including collection, sorting and transportation processes.
ErecEoL = emissions and resources consumed (per unit of analysis) arising from the recycling process at the EoL, including collection, sorting, transportation and recycled material production processes.
Ed = emissions and resources consumed (per unit of analysis) arising from disposal of waste material (e.g. landfilling, incineration and pyrolysis).
R1 = recycled content of the materials.
R2 = recycling share at the end of the life cycle.
Qprod,out/Qprod,in = difference in the quality of the primary Qprod,in and secondary materials Qprod,out.

can be determined at any point during the observed life cycle period. The formula for the calculation of the residual value is based on SIA 2032:2020:

$$RV = \sum_i EI_i - \frac{EI_i}{y_{RSL}} \times y_{USE}$$

where.

- RV = residual value
- EI = environmental impact of the production and EoL phases of the material
- y_{RSL} = estimated RSL in years
- y_{USE} = years in use

2.2. Method validation by case study

The application and verification of the methodology are presented for two selected components of a typical Slovenian, multi-residential building from 1980. The components were deliberately selected so that they differ greatly in composition, the use of recycled materials and refurbishment measures. The first component is the slab between the stories (Table 2 and Fig. 3). This component was selected because it contains a material that has recycled content already in the first life cycle (the reinforcing steel).

The second component selected for the illustration of the methodology is the outer wall (Table 3 and Fig. 4). In this case material's thermal insulation was added during the refurbishment.

A sensitivity analysis was performed along with the validation to show the dependence of the residual value on the following parameters:

- allocation approaches,
- RSL databases

In step 1, the flows between the life cycles before (LC1) and after the refurbishment were determined (LC2). For the calculation of the allocation, it is important to know the recycled content of the input materials and the reuse, recycling, incineration or landfill rates of the materials at the end of each life cycle.

After defining the flows (inputs, outputs and reuse) between the life cycles before and after the refurbishment (step 1), we calculated the environmental impacts of the individual materials. The input information for the assessment of EI is presented in the Appendix.

In step 3, we compared three different databases containing data about the RSL of building components and materials. The first database is *Pravilnik o vzdrževanju stavb* and is used in Slovenia; the second database is derived from *Bewertungsystem für Nachhaltinges Bauen* (Bbsr, 2011) and is often used in Germany; and the third database is from

Table 2
Life cycle Inventory (LCI) of the slab.

	SLAB 1m2	
	Thickness [cm]	Mass [kg]
Sawn wood	1.5	8,4
Precast cement floor	5	110
EPS	3	0.6
Reinforced concrete	15	360
Base plaster	1.5	24
Alkyd paint	/	0.28

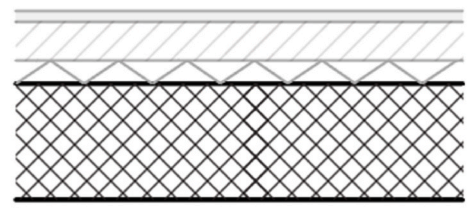

Fig. 3. Slab.

Table 3
Life cycle Inventory (LCI) of the wall.

EXTERIOR WALL 1m2		
	Thickness [cm]	Mass [kg]
Cover coat	1.5	28
Rock wool	30	30
Concrete brick	29	440
Adhesive mortar	/	30.45
Base plaster	0.015	24
Alkyd paint	/	0.28

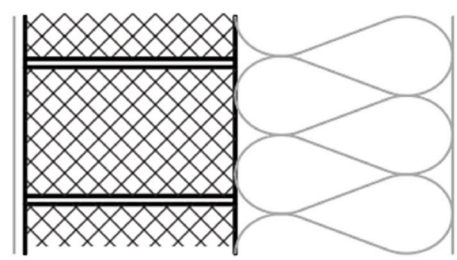

Fig. 4. Exterior wall.

SIA2032:2020 (Severin, 2018) and is used in Switzerland. The comparison will show how the residual value of a building can vary depending on the RSL database used for the study.

In step 4, the residual value was calculated for each life cycle (the LC1 before the refurbishment and the LC2 after the refurbishment) after two arbitrarily selected periods. It is estimated that each of the life cycles has a RSP of 60 years. The first calculation of the residual value was performed after 30 years (on the half of the observed RSP). The second calculation is made after 50 years (10 years before the end of RSP) of the individual life cycle.

The methodology can be applied to every material, component or building and can be used for every environmental impact category. In the study we present results for the greenhouse-gas emissions (GWP impact category) since it is the most prominent indicator. The database used in the study is Ecoinvent 3.6 (Wernet et al., 2016). The characterization factors used for the calculation are derived from IPCC 2013 (Heijungs et al., 2013).

3. Results

3.1. Step 1

Initially, in step 1, the basic flows between the first and second life cycles were determined. The material flows between the first and second life cycles are illustrated for the slab and the exterior wall in Fig. 5. The figures show which virgin materials were used, their recycled content, which materials are recycled or reused, and also how individual materials were treated at the end (landfill or incineration).

3.2. Step 2

The GWPs for the slab were calculated with five different allocation methods (cut-off, cut-off with module D, avoided burden, the 50:50 and the PEF) for the first life cycle of the building component (LC1) and the life cycle after the refurbishment (LC2). The results are illustrated in Fig. 6. The differences between LC1 and LC2 only emerge for materials that are reused after the refurbishment, i.e., the reinforcing steel and the concrete. In the cut-off approach no credits for reuse were assigned, as in the case of the cut-off with module D. In the avoided-burden approach the credits are the same as the negative value of the virgin impact, while in the 50:50 and PEF approaches they are halved when compared to the previous two approaches. In the second life cycle the credits are given because the reinforced steel and the concrete are recycled at the end. In the case of steel, 95% is recycled for steel production. The recycled concrete is used instead of gravel, in other words it is downcycled. Therefore, the credits gained for the recycling of concrete are also minimal.

For thermal insulation, base plaster and paint, which are completely disposed at the EoL, no allocation exists so the impacts are the same in LC1 and life cycle 2, since the same amounts are used in both life cycles. They also receive no credits, because they are disposed at the EoL. For the cast cement floor and sawn timber, which are recycled at the EoL, the impacts in LC1 and LC2 are the same because everything is handled within the observed life cycle, and hence there is no allocation between the life cycles.

The application of the methodology on the outer wall provided similar insights (Fig. 7). The differences are noticeable for the materials, which are reused in LC2 after the refurbishment, i.e., adhesive mortar and concrete bricks. Again, in the first life cycle those two materials get credit for being reused in all the allocation approaches, except for the cut-off approach. On the other hand, the differences are minor for the materials used only in one life cycle. These materials have a similar impact for different allocation approaches in both life cycles. The only difference between the approaches is how they treat the recycling at the end of each life cycle. This means that the results for different allocation approaches differ from each other, but are the same in the life cycle before and after the refurbishment. It is also important to notice that in LC2 the thermal insulation was added. This material addition influences the residual-value calculation.

3.3. Step 3

For each component, maintenance and replacement scenarios were established according to three different RSL databases: SLO, BNB and SIA. In the case of the slab, it is necessary to regularly repaint the ceiling and also replace the floors once during the period of the life cycle, which is 60 years. In the case of the floor replacement, the EoL of the previous floor is included. In the refurbishment phase everything except the concrete and the reinforcing steel was replaced (Fig. 8).

The exterior wall has to be regularly repainted on the inside and the cover coat has to be replaced once in the observed period according to the data in the three different databases. When the cover coat was replaced in the first cycle (before the refurbishment), the impact of the disposal of the old cover coat is also included in the environmental impacts of this action. During the refurbishment, thermal insulation is added to the exterior wall. In LC2 the walls were regularly repainted and after a certain period the base plaster on the inside was exchanged. When replacing the base plaster the impacts of the disposal of the old base plaster were also taken into account. Additionally, the exchange of the thermal insulation requires that the cover coat is replaced. The impacts of the disposal of the old thermal insulation and the cover coats were also considered.

3.4. Step 4

The results of the residual-value calculation are illustrated in Fig. 9. Generally, the residual value is higher after 30 years than after 50 years. In the cut-off approach, the residual value should be lower in LC2, because during the refurbishment some materials were reused. For example, in the case of the slab, the concrete and the reinforcing steel are reused, while in the case of the exterior wall the bricks are reused. However, in the case of the wall, the thermal insulation is added and consequently the impacts are sometimes higher in LC2. In the case of the cut-off with module D, the residual values are lower for each RSL database, compared to the previous approach. This is because the benefits of module D for recycling or reusing the materials at the end of life are also included in the calculation of the overall impacts. On the other hand, the avoided-burden approach has higher impacts in LC2. As for the wall, the impacts are considerably higher because additional thermal insulation was added. If we compare the results of the 50:50 and the PEF approaches, they are similar for the separate RSL databases. For the slab they are also similar for LC1 and LC2.

Generally, the residual value in LC1 is the lowest in the case of the avoided-burden approach, where the impacts are shifted to the life cycle after the refurbishment. This approach clearly rewards the recycling and reuse at the EoL. Also, the cut-off with module D has small residual values in the first LC, because the materials are credited for recycling and reuse at the EoL. In the 50:50 and PEF approaches these credits are distributed between LC1 and LC2. Therefore, the residual values are higher than those obtained with the cut-off with module D. The highest residual values were observed in the case of the cut-off approach.

In LC2 it is important to note that in the case of the exterior wall the residual values are higher because a new material, namely the thermal insulation, was added during the refurbishment. Otherwise, the impacts would be similar for both life cycles in the case of the 50:50 and PEF approaches, smaller in the case of the cut-off and cut-off with module D approaches and higher in the case of the avoided-burden approach.

The differences in the results caused by using different RSLs, namely, the SLO, BNB and SIA databases, are difficult to compare. In the case of the slab, the RSL are similar for the SLO and BNB database, while the use of the SIA RSL values results in smaller residual values. In the case of the wall, the residual values are the highest if we use the SLO database, and

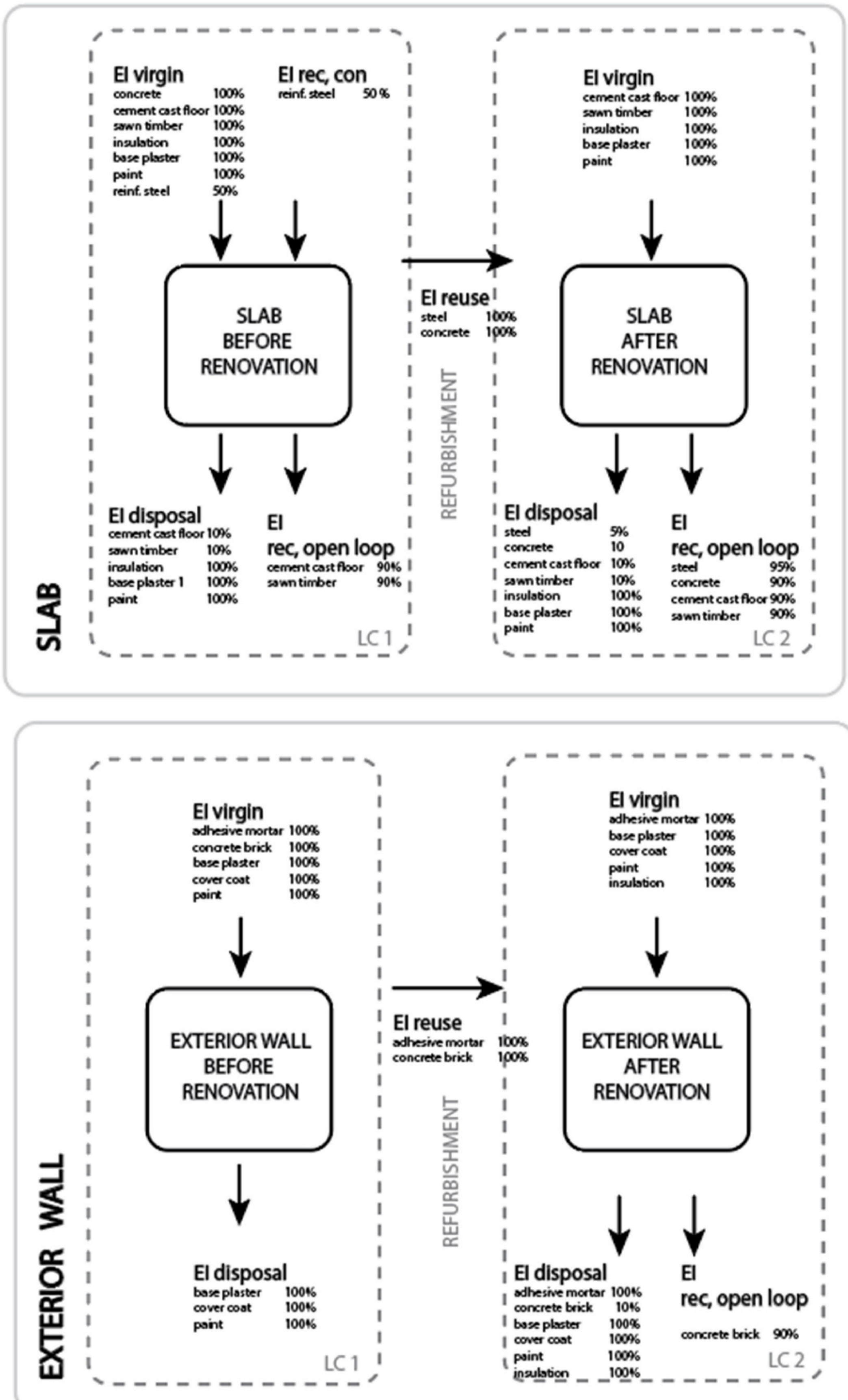

Fig. 5. Step 1 - Distribution of the environmental impacts (EI) between the life cycle before the refurbishment (LC1) and life cycle after the refurbishment (LC2) of the slab and exterior wall.

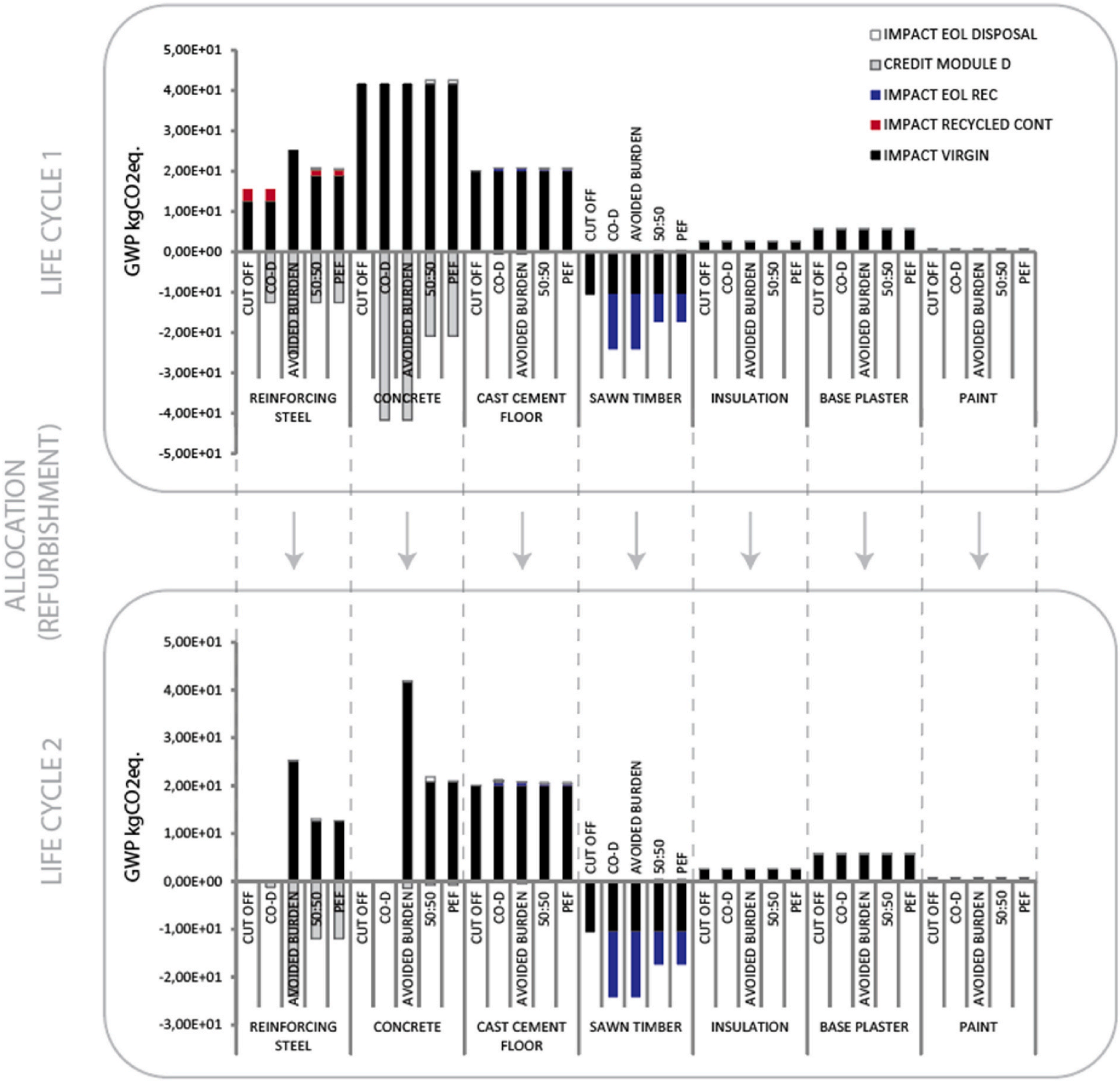

Fig. 6. Step 2 - GWP results for different allocation approaches before the refurbishment (LC1) and after the refurbishment (LC2) for the slab.

the lowest if we use the BNB database. On the other hand, when looking at the residual value after 50 years for the LC2, the residual value is higher if the BNB database is used. This proves that the results can be very different depending on which database we use and therefore it is very important to include data about the RSL and the maintenance of different materials in the study to ensure transparency and reproducibility.

Due to the different environmental impacts for production, reuse, recycling and disposal of each material, it is impossible to make direct comparisons between allocation approaches. Therefore, only general conclusions about the choice of the allocation approaches and RSL databases can be made.

4. Discussion

Today's approach to calculating the environmental impacts of refurbishments focuses only on the life cycle after the refurbishment. Consequently, an allocation of the impacts is not possible and there is a gap in the information for the materials that remain in the building after the refurbishment. On the other hand, neglecting the life cycle before the refurbishment could lead to incorrect conclusions. The proposed methodology helps to allocate the environmental impacts according to the scope, and it reduces the information uncertainties related to the life cycle before the refurbishment.

The allocation of environmental impacts before and after the refurbishment is seldom discussed in the literature (Allacker et al., 2014, 2017). On the other hand, the discussions about the allocation approaches are far more often at the level of commercial products (Frischknecht, 2010). This is most likely due to the products' shorter service lives, which makes the need for allocation more understandable than at the building level, where the service periods are relatively long. The newly developed calculation methodology for environmental impacts and residual value before and after a building's refurbishment enables a more comprehensive determination of the results, since no previous environmental exchanges are ignored. In an LCA of building refurbishment, the previous life cycle is usually ignored, and consequently, as previously discussed, the benefits of refurbishment could be overestimated. With the increasing demand for refurbished buildings to allow for high energy efficiency, the effect of that negligence will become progressively larger – which holds the potential to disturb the

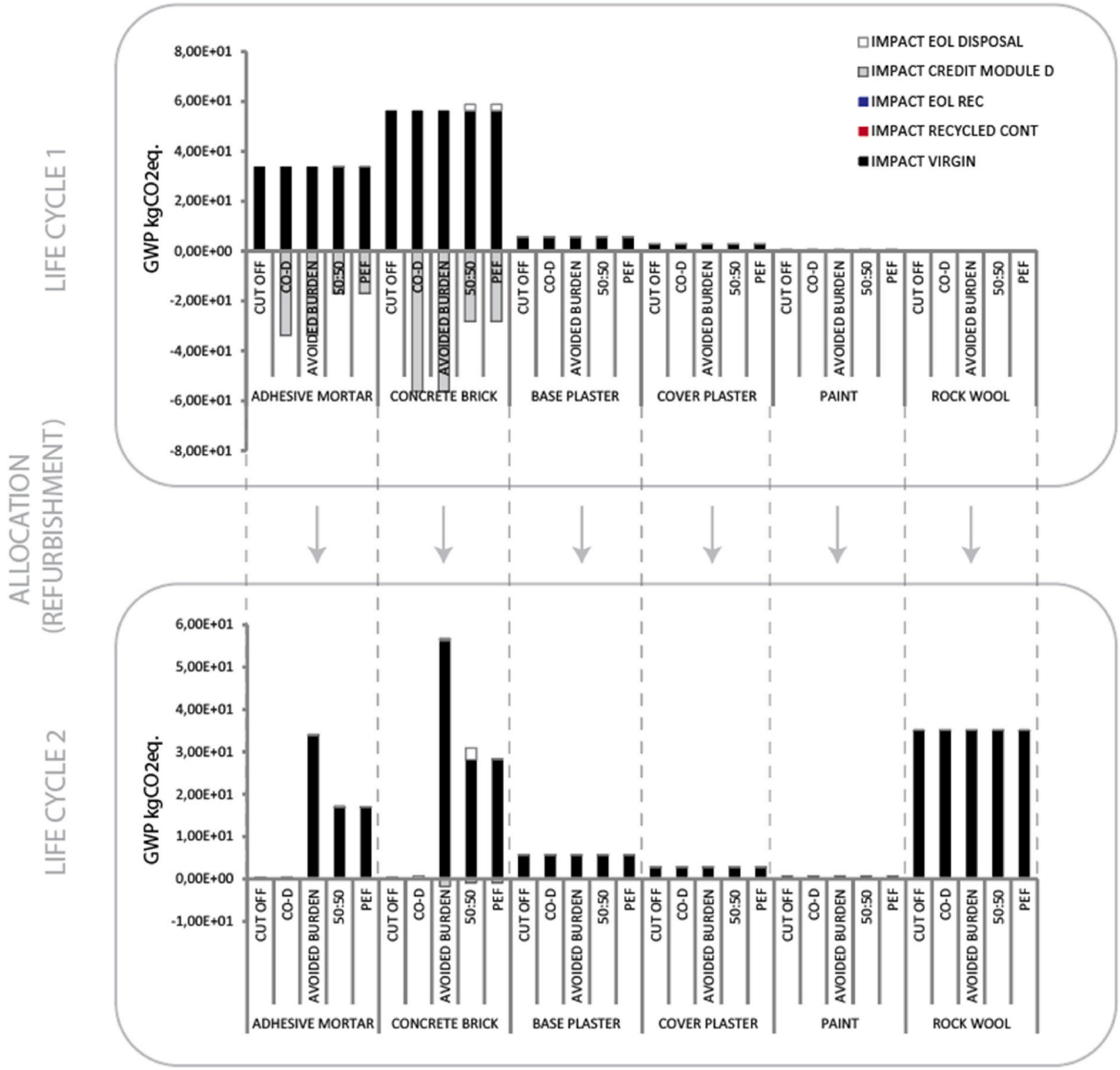

Fig. 7. Step 2 - GWP results for different allocation approaches before the refurbishment (LC1) and after the refurbishment (LC2) for the wall.

reduction predictions to meet the targets set for 2050.

The environmental impacts can be distributed between primary and secondary product systems in various ways and double counting should be avoided (Allacker et al., 2014; Eberhardt et al., 2020; Frischknecht, 2010; Schrijvers et al., 2016; Weidema, 2000). Different allocation methods have been developed and each of them has its own theoretical background as well as strengths and weaknesses. Some of the approaches promote the use of recycled materials (e.g., cut-off), some promote recycling at the EoL (e.g., avoided-burden approach) or try to distribute the impacts across both life cycles (e.g., 50:50 and PEF) (Allacker et al., 2017; Gervasio and Dimova, 2018). The cut-off approach is most commonly used, since it is easy to apply and reduces the uncertainties connected to future recycling and reuse scenarios. It awards the use of recycled materials. On the other hand, it does not promote the use of materials with recycling potential within the system. This weakness is partly reduced with the introduction of the module D, which sums the benefits and the burdens of recycling, reuse and incineration. This module was optional in the previous version of the EN15804 (EN 15804:2012 + A2:2019, n.d.), but has become mandatory in the latest version (EN 15804:2012 + A2:2019, n.d.). With EN 15804's amendment, it has become more comparable with the PEF approach and should promote the circular use of materials, which is also in line with the sustainable development goals of the UN (United Nations, 2019). The avoided burden approach awards the creation of recycled materials but neglects the benefits of using recycled materials. The 50:50 approach is a compromise between the cut-off and avoided burden approach. It credits both the use of recycled materials as the recycling potential of the materials. The PEF builds upon the 50:50 approach and introduces factors for the quality differences between primary and secondary materials. Since each of the allocation approaches has its own purpose, the choice of the allocation approach should be aligned with the goal and scope of the study. Since the idea of a circular economy is not promoted by all the allocation approaches equally, it is assumed that the PEF method and the cut-off method with module D, which include the aspects of circularity, will prevail over the other methods.

For a proper impact allocation between the life cycles, it is crucial to define the scope and the boundaries of the life cycles before and after the refurbishment. In this study we have determined the scope and the relations between the life cycles before and after a refurbishment (e.g., Figs. 8 and 9) (Xabat Oregi et al., 2017). In these figures we have indicated which inputs and outputs are related to which life cycle and which of the materials are reused or recycled at their EoL. So, basically, a clear

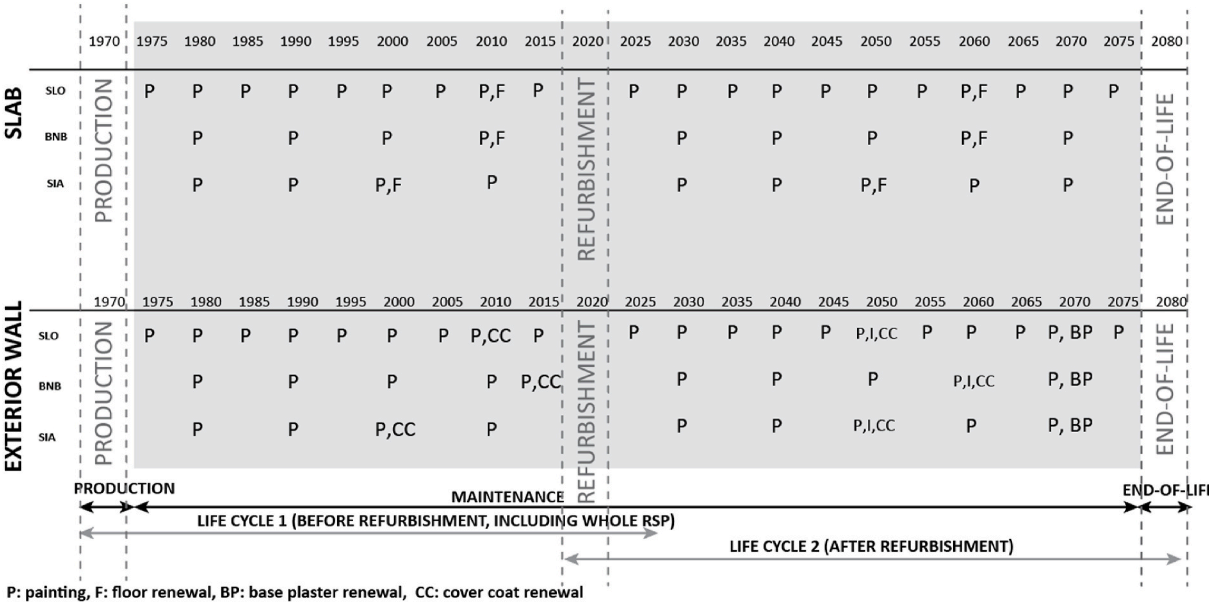

Fig. 8. Step 3 - The maintenance and replacement timeline for the slab and the exterior wall.

definition of the scope should prevent errors by allocating the impacts and the possibility of double counting.

We also found that the calculation of some of the allocation methods requires specific input information, like the difference in the quality of the virgin and the recycled material or the impact of virgin materials that will be replaced by the recycled materials, etc. This information is generally difficult to find in the literature and therefore presents a great challenge when the allocation of the impacts is modelled (Eberhardt et al., 2020). Often the information is available only for closed-loop recycling (the material is recycled into the same material with the same quality, e.g., steel), but generally the information is lacking for open-loop recycling (the recycled materials are used for other purposes, e.g., crushed concrete is replacing gravel). To calculate the environmental impacts, these data should be provided. This data gap is a potential area for future research.

During the study, impacts related to the EoL (modules C) and phases beyond the life cycle of the building according to EN15978 (EN 15978:2011, n.d.) (module D-reuse, recovery, recycling, energy export) were assessed. Reporting these impacts became mandatory for environmental product declarations (EPDs) in 2019 according to EN 150804:2012+A2:2019, which also proves the increasing importance of the circular economy in the construction sector. Gathering the information about the EoL processes and the reuse, recycling and recovering processes is very challenging and introduces great uncertainties into the LCA (Ng and Chau, 2015). We have observed several authors with the same experience (Spirinckx et al., 2018). The EPDs are ordered by manufacturers, which have information and control relating to the production process, but generally they do not have any control over what happens to their product during the construction, use and the EoL stages. Therefore, generic data for the disposal and the recovery process are often used (Lasvaux et al., 2015). Recently, a guidance document with basic principles and recommendations for describing the dismantling, post-use, and disposal stages of construction products were developed (Agency, 2020). It proposes the establishment of documents where the manufactures of the construction products and the disposal practitioners (recyclers, waste-management companies, etc.) exchange information, determine the recycling and recovery prerequisites or conditions, etc. These documents should provide realistic and comparable life cycle-assessment data for modules C and D for buildings and so close the current information gap in this area.

Since the choice of the different RSL databases can have a major influence on the results when observing the entire life cycle of a building, it is very important that each study indicates which RSLs were used for the calculation or refer to the selected RSL database (Potrč Obrecht et al., 2019). We have noticed that the RSL for the same materials can be very different in selected RSL databases, although the geographical circumstances are similar. Further research has to be devoted to this field to test the uncertainties and differences that result from these parameters (Goulouti et al., 2020; Hoxha et al., 2017).

5. Conclusion

Today, the environmental impacts of a building's refurbishment are not addressed as the a sub-stage of the whole life cycle according to EN 15978, but are calculated as the new life cycle of a building. This is possible within the current standard, if no assessment has been carried out prior to the refurbishment or if the functional equivalent changes during the refurbishment. Since the majority of the buildings have not been assessed yet, this actually applies for almost all cases. Consequently, the impacts have to be distributed among the life cycles before and after the refurbishment correctly. Therefore, a new methodology has been developed to assess the environmental impacts and the residual value of buildings, which also includes the allocation of the impacts between the life cycles before and after the refurbishment, as well as the maintenance scenarios according to the RSL. The new methodology combines already exiting methodologies into a novel approach that has not been applied before. It enables a more correct distribution of the environmental impacts between the life cycles.

The allocation approach and the RSL are the variable parameters of the methodology. The sensitivity analysis of the allocation approaches showed that differences between the assessed environmental impacts and residual values emerge if materials with recycled content are used or if the materials are being recycled or reused at the end of their life cycle. For materials with no recycled content and for those disposed of at the end of the observed life cycle, there is no significant difference caused by the selection of the allocation approach. The results indicated that greater differences between the allocation approaches were visible in the second life cycle after the refurbishment, where larger shares of reused and recycled components were present. The sensitivity study also confirmed that the choice of the RSL database has a great influence on the maintenance scenarios (replacement rates) and leads to different residual values of the materials and components, and consequently also

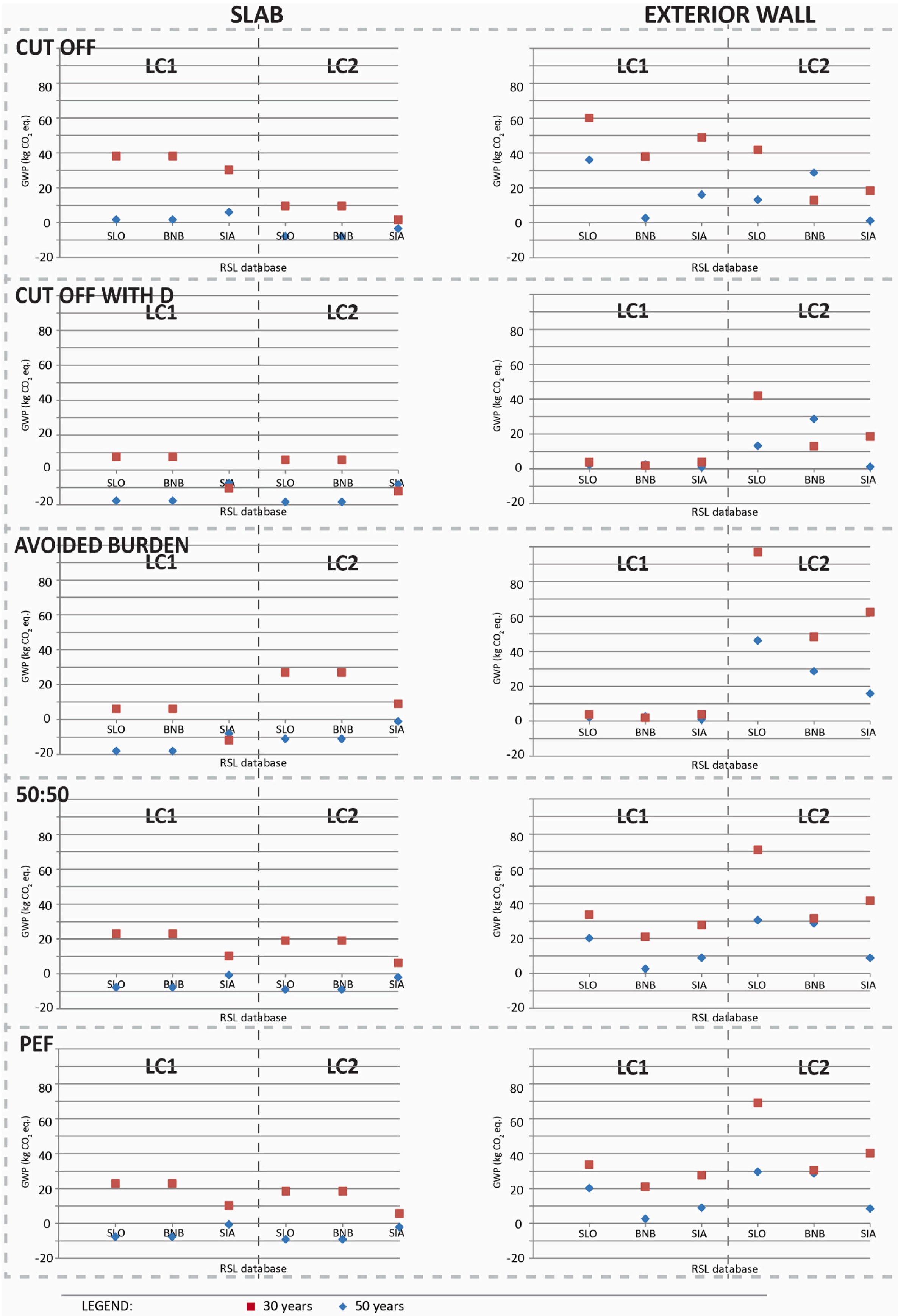

Fig. 9. Step 4 - Residual value of the slab and the exterior wall calculated with different allocation approaches after 30 and 50 years of the observed RSP for the life cycles before (LC1) and after the refurbishment (LC 2).

of buildings. For this reason, it is crucial to indicate which RSL database is used in the estimation procedure.

Due to the ambitious targets set by European governments to reduce the built environment's contribution to climate change, the refurbishment of buildings and also the recycling and reuse of materials are strongly encouraged and will become everyday practice. Hence, the application of the developed methodology will become progressively necessary. In this sense, we believe that our developed approach will not only improve environmental impact assessments and contribute to the circular economy of the construction sector, but it will bring scientific consistency to the future estimation of refurbishment measures. It is expected that this research will encourage professionals to avoid the negligence of previous environmental flows, relying on the very nature of LCA: a strong methodological framework able to consider broad scopes and connections between different product systems.

CRediT authorship contribution statement

Tajda Potrč Obrecht: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Sabina Jordan:** Supervision, Writing – review & editing. **Andraž Legat:** Supervision, Writing – review & editing. **Marcella Ruschi Mendes Saade:** Writing – original draft, Writing – review & editing, Supervision. **Alexander Passer:** Supervision, Writing – review & editing.

Declaration of competing interest

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.129527.

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