



Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction

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Abstract

Purpose There has been a growing interest in the environmental trade-off between renovation and reconstruction. Life cycle assessment (LCA) is a widely recognized method to quantify environmental impacts of buildings. However, the existing standards do not provide guidelines for defining the reference system period (RSP) and system boundaries (SB) to allow for a fair, robust, and consistent comparison of renovation and reconstruction. Hence, this research establishes guidelines for defining the RSP and SB.

Methods From literature, existing approaches are gathered for defining the RSP when comparing buildings with different service lives and for defining the SB when an existing building is the starting point of an assessment. Eight criteria are then elaborated for defining the RSP and SB. For example, the RSP approach should differentiate between buildings from different construction periods, and the SB approach should be robust for time-related uncertainties. Therefore, the building's and building materials' service lives and replacement rates are varied; the standard deviation (σ) between the results then determines the robustness. Subsequently, the extent to which the approaches meet the predefined criteria is assessed. Finally, guidelines are established for defining the RSP and SB when comparing renovation with reconstruction.

Results and discussion Three RSP approaches are selected: the RSP is equal to (i) the RSP of new building, (ii) the difference between the total service life of the building (TSLB) and the building age, or (iii) a service life extension. Furthermore, three SB approaches are selected: (i) the environmental impact is considered at the moment of production, (ii) the moment of occurrence, or (iii) equally divided over different life cycles. As none of the SB approaches meet all predefined criteria, three partial allocation approaches are conceived based on a linear, concave, and convex model. The concave model gives the most robust results ($\sigma=0.11$), but is less consistent with the reality of emissions. The convex model is, in contrast, most consistent with the reality of emissions, but is less robust ($\sigma=0.16-0.19$).

Conclusions Based on the literature review and results, the authors recommend to define the RSP based on the difference between the TSLB and the building age for comparing renovation with reconstruction. For defining the SB in case of building materials that are retained over multiple life cycles, it is recommended to include the impact through a convex partial allocation model to compare the environmental impact of renovation and reconstruction in a robust and consistent way.

Keywords Life cycle assessment (LCA) · Renovation · Reconstruction · Reference study period · Allocation · Single-family case study

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Abbreviations

EPBD	Energy performance of buildings directive
EOL	End-of-life
ESL	Estimated service life
ESLC	Estimated service life component
FU	Functional unit
LCA	Life cycle assessment
LCI	Life cycle inventory
PEF	Product environmental footprint
PSLC	Past service life component

ReqSL	Required service life
RR	Replacement rate
RSL	Remaining service life
RSLC	Remaining service life component
RSP	Reference study period
SB	System boundaries
TSL	Total service life
TSLB	Total service life building

1 Introduction

Most residential buildings were built before the introduction of energy regulations in building codes, causing major contributions to global energy use and greenhouse gas emissions. In the context of a sustainable transition of the existing building stock towards climate neutrality, life cycle assessment (LCA) is a commonly used method to quantify the impacts of buildings on the environment throughout their life cycle. The number of studies calculating the environmental impact of buildings by means of LCA has steadily increased over the past decades. Initially, research was mainly focused on new buildings (Cuéllar-Franca and Azapagic 2012; Dahlstrøm et al. 2012), whereas the environmental assessment of renovation projects—i.e., the application of energy conservation measures—has become more prevalent over the last decade (Gustafsson et al. 2017; Vilches et al. 2017). The environmental trade-off between renovation and reconstruction—i.e., the demolition of an existing building and replacement by a new building—on the other hand, is a recently emerging topic under study (Alba-Rodríguez et al. 2017; Assefa and Ambler 2017; Gaspar and Santos 2015; Hasik et al. 2019; Meijer and Kara 2012; Verbeeck and Cornelis 2011).

In the latter context, several studies have shown that the environmental impact related to the renovation of a building is lower than that of reconstruction (Alba-Rodríguez et al. 2017; Assefa and Ambler 2017; Gaspar and Santos 2015; Hasik et al. 2019). However, the reported differences vary significantly. Hasik et al. (2019) compared the environmental impact across six impact indicators of an office building located in Philadelphia that was either renovated or reconstructed. They found that the environmental impact of renovation was 53–75% lower than reconstruction. A similar range (58–68%) was reported by Alba-Rodríguez et al. (2017) studying a multi-family building in Spain. Assefa and Ambler (2017), on the other hand, addressed a smaller difference; renovating an existing Canadian library tower resulted in 20–41% less impact compared to complete demolition and new construction. Furthermore, the renovation of a 40-year-old detached single-family dwelling located in Portugal only had a 17% lower impact in comparison with reconstruction (Gaspar and Santos 2015). In contrast, Meijer

and Kara (2012) found opposite results: reconstruction is preferred to renovation for a terraced house if renovation led to certain lower energy savings and the remaining service life was 30 years shorter than that of the reconstruction case. Likewise, Verbeeck and Cornelis (2011) stated that renovations do not necessarily result in lower environmental impacts than reconstructions, as the trade-off depends on the energy performance level achieved.

A difference in energy performance is, however, not the only aspect that can influence the environmental trade-off between renovation and reconstruction. Variations and contradictions in the results can also arise from methodological differences. Existing standards on how to perform an LCA, i.e., international standards ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) and European standards EN 15804 (CEN 2012a) and EN 15978 (CEN 2012b), do not provide uniform methodological guidelines that allow for a fair, robust, and consistent comparison between renovation and reconstruction. This entails that LCA practitioners need to make a lot of assumptions and decide on the adequate boundary conditions. In literature, methodological choices are often made for case studies to compare renovation and reconstruction (e.g., Gaspar and Santos 2015; Meijer and Kara 2012), but the implications of methodological choices on the balance between renovation and reconstruction are seldom considered in a systematic way.

In order to determine how the choice between renovation and reconstruction should be guided and supported from an environmental viewpoint, a robust methodological framework for comparing both options in a fair and coherent way is required. Hence, the objective of this research is to set up guidelines for defining the reference study period and system boundaries when the goal of the LCA is to compare the environmental impact of the renovation of an existing building with the reconstruction of a geometrically equivalent new building. This paper examines the following two research questions:

1. How should the reference study period (RSP) be defined when buildings with different service lives are to be compared? In case of a renovation, the remaining service life (RSL) of the renovated building can be taken into account as the RSP; in case of reconstruction, the estimated service life (ESL) of a new building can be considered. A renovated building will, however, most likely have an RSL that differs from the ESL of a reconstructed building.
2. How should the system boundaries be defined for removed, retained, and new building materials when an existing building is the starting point of the assessment? In case of reconstruction, all existing building materials will be demolished at the moment of the intervention. In case of renovation, some existing building materials

will be demolished while others will be retained. These retained materials may need to be replaced during the RSP. Thus, the actions on existing building materials, during the RSP, will be different for renovation and reconstruction, as will the impact. Therefore, the impact of actions that occur during the RSP (i.e., demolition or replacement) may not be neglected in the LCA to allow for a fair comparison. This is in contrast to comparative LCAs of renovation projects that often only consider newly added materials. When comparing different renovation scenarios, the actions on the existing building materials will be more similar than when comparing renovation with reconstruction. Hence, excluding existing building materials will have no or a rather limited impact on the comparison of different renovation scenarios.

To answer these research questions, a literature review was first conducted to provide insights into the state-of-the-art of existing approaches for defining the reference study period and system boundaries. Subsequently, a set of criteria was established to which the approach should comply. These criteria were based on specific methodological challenges that are related to the trade-off between renovation and reconstruction and derived from literature. The existing approaches were then examined in terms of the predefined criteria. Based on the results, guidelines for defining the reference study period and system boundaries in the context of a comparative LCA between renovation and reconstruction were established.

2 Background on existing approaches

2.1 Reference study period

According to EN 15978, the reference study period is “the period over which the time-dependent characteristics of the object of the assessment are analyzed”. Moreover, the standard describes that the required service life of a building (ReqSL) should be considered as the default value for the RSP. The reference service life of a building should be based on a reference set of in-use conditions and can be

used to predict the ESL under specific conditions. As stated in EN 15804, the ESL typically depends on the service life of the load-bearing structure, which is not replaceable or repairable. Since there are no default values included in international standards, a wide range of RSPs is found in literature. Chastas et al. (2018) reviewed 95 case studies of residential buildings and found RSPs ranging from 30 to 100 years, whereas Goulouti et al. (2020) reported values from 15 years up to 120 years. In addition, Thibodeau et al. (2019) concluded that 80% of 41 analyzed LCA studies took into account an RSP of 50 or 60 years. The technical service life of the building structure will most likely exceed 50 or 60 years; however, it is assumed that after this period, a building will have been renovated to such an extent that, apart from the structure, only few of the original materials will have remained. The consideration of longer RSPs would lead to larger uncertainties regarding future processes. In addition, different national and regional LCA frameworks and tools were developed in the context of an environmental assessment or certification schemes for new residential buildings. The RSPs considered in these frameworks vary for different countries between 50 and 120 years (Table 1).

The determination of the RSP becomes even more complex in the context of a comparative assessment between renovation and reconstruction. In case of reconstruction, the obvious choice is to take into account the ESL of a new building. In case of renovation, on the other hand, an existing building with a certain age serves as the starting point of the assessment. Therefore, the RSP should depend on the expected RSL of the existing building after renovation. One would expect that the load-bearing structure of a new building lasts as long or even longer than an already existing structure since it conforms to current regulations, has no past service life, and due to technological innovations improving the durability of materials. Palacios-Munoz et al. (2019) predicted service lives of concrete structures by applying degradation models related to corrosion and concluded that a new concrete structure could have a service life more than two times longer than that of an existing structure. Moreover, when taking into account that the existing building was built 60 years ago, the results showed that the new structure could have an ESL more

Table 1 RSPs considered for new residential buildings in national or regional LCA frameworks or tools

Country	Framework/tool	RSP	Reference
DE	eLCA	50 years	(Rössig n.d.)
FR	HQE Performance	50 years	(Association HQE 2015)
BE	TOTEM	60 years	(OVAM 2021)
UK	BRE Global	60 years	(BRE Global 2008)
NL	MPG	75 years	(Nationale Milieudatabase 2020)
FR	I3E Rénovation	100 years	(Sié et al. 2017)
DK	LCAbyg	120 years	(Birgisdottir and Rasmussen 2019)

than six times longer than the RSL of the existing structure. If no degradation models are available, it should be assumed that the TSL of new buildings is at least equal to the TSL of existing structures. A renovated building will, thus, most likely have a shorter RSL than the ESL of a reconstructed building (Palacios-Munoz et al. 2019; Thibodeau et al. 2019). As the RSP should be defined in the functional unit (FU) to allow for fair comparisons, the RSPs of renovation and reconstruction should be identical. But which RSP should then be considered?

Thibodeau et al. (2019) discussed two options when dealing with different RSPs. Both options involved choosing one RSP over the other. On the one hand, the considered RSP in both scenarios can be equated to the shortest RSP. For the longest-lasting scenario, the EN 15978 rule can be applied (i.e., full allocation of modules A and C) and partial allocation of module B considering a factor RSP/ReqSL or all impacts (i.e., modules A, B, and C) can be partially allocated pro rata of the RSP. On the other hand, the longest RSP can be opted for as default RSP. This approach, however, implies that an additional scenario (i.e., renovation or demolition/reconstruction) has to be developed for the shortest lasting scenario and involves high uncertainties regarding future impacts.

If the RSP would be equated to the RSL of the renovated building, no guidelines are available on how to determine this RSL. Based on literature and existing LCA frameworks regarding renovation, three main approaches can be distinguished for the determination of the RSP (Fig. 1):

1. The RSP is identical to the default RSP for new buildings.
2. The RSP is equal to the total expected service life of the building (TSLB) minus the building age.
3. The RSP is related to a certain service life extension due to renovation.

The first approach is the most commonly applied practice in existing LCA frameworks, tools, and studies (Assefa

and Ambler 2017; OVAM 2021; Vilches et al. 2017). It is assumed that the RSL of the existing building is identical to the RSP assumed for new buildings, regardless of the building age. The Belgian tool TOTEM, for example, assumes a default RSP for new buildings of 60 years (OVAM 2021). When a renovation case is entered into the tool, the environmental impact is also calculated over a 60-year study period. The second approach, on the other hand, takes into account the current building age by subtracting it from the TSLB. In the I3E Rénovation project, it was assumed that the RSP is equal to the full building service life (i.e., 100 years) minus the difference between the renovation and construction year (Sié et al. 2017). If a renovation took place 30 years after construction, the RSP considered for the LCA study would be 70 years. The same principle was applied by Assiego De Larriva et al. (2014). This approach, however, is found less frequently in existing studies compared to the first approach. Furthermore, this approach implies that very old buildings would have no or a very small RSL. With a TSLB of 100 years, a building built before 1922 cannot be considered for renovation at present day in that approach. Finally, the third approach assumes that a renovation will prolong the original ESL of the building (Nationale Milieudatabase 2020; Worm et al. 2017; Klunder 2004). Hence, the expected service life extension is considered as the RSP. This approach is applied in the Dutch determination method MPG (i.e., MilieuPrestatie Gebouwen, or in English: Environmental Performance of Buildings) (Nationale Milieudatabase 2020). There, it is assumed that the total service life (TSL) of a renovated building will be longer than initially considered in case of a new build. However, no clear guidelines have been defined on how to determine the RSL. It is stated that a default value in the case of renovation will not be sufficient, since the RSL depends on various parameters such as the current condition of the building, type of renovation, and environmental and external factors (e.g., weather, pollution, and maintenance). Within that framework, W/E Adviseurs

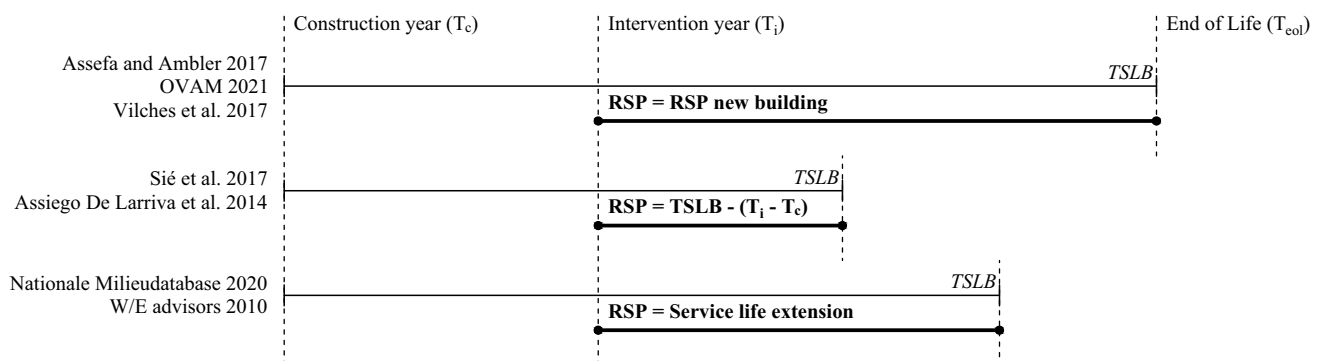


Fig. 1 Approaches found in literature for the determination of the RSP for renovation

(2010) performed an LCA study comparing the renovation of an office building with a reconstruction scenario assuming a service life extension of 25 years in case of a light renovation, whereas 40 years was considered in case of a thorough renovation.

2.2 System boundaries

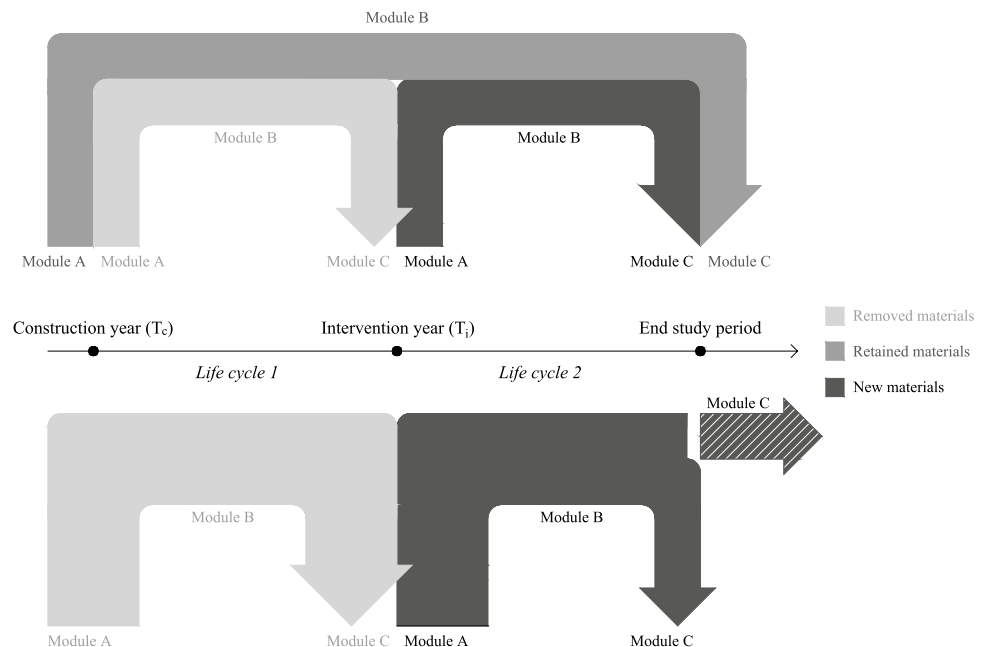
ISO 14040 defines the system boundaries as “a set of criteria specifying which unit processes are part of the product system”. Related to building products and buildings (CEN 2012a, b), the system boundaries determine which of the following life cycle stages (or modules) are included in an LCA: product stage (module A1–A3), construction process stage (module A4–A5), use stage (module B1–B7), end-of-life (EOL) stage (module C1–C4), and all benefits and loads beyond the system boundaries (module D). Renovation can be categorized as a substage of the use stage, i.e., “refurbishment” (module B5). This module should include the impacts of the production and transportation of new building components, construction and waste management of refurbishment processes, and EOL stage of replaced building components. However, module B5 is rarely applied to consider environmental impacts associated with the renovation of an existing building (Thibodeau et al. 2019). Module B5 is mainly introduced in the standard to perform scenario analyses on new buildings. The standard in fact states that a new assessment should be carried out if the renovation of an existing building was not included in a previous assessment. Consequently, this principle initiates a new life cycle at the moment of intervention. This hampers the determination of the system boundaries in comparison with new construction

on an empty plot since there is an overlap between two life cycles in case of renovation as well as reconstruction.

As illustrated in Fig. 2, parts of the existing building materials will be removed and parts will be retained at the moment of the intervention in case of renovation. In case of reconstruction, on the other hand, all the existing building materials will be removed at the intervention moment. Consequently, there will be different actions on the existing building materials when comparing both scenarios. Hence, it is an important challenge to define consistent system boundaries for removed, retained, and new building materials. Based on a literature review by Vilches et al. (2017) on LCAs of energy refurbishments, there is no consensus on which life cycle stage or modules of these existing building materials should be included in the assessment (i.e., the second life cycle).

Various LCA studies of renovation projects only assess the environmental impact of new building materials, omitting all impacts (modules A, B, and C) of existing building materials that are retained or removed (Beccali et al. 2013; Lasvaux et al. 2015). The “exclude the past” approach is based on the assumption that the environmental impact of existing building materials is a result of a past decision, already took place and cannot be undone (Rasmussen and Birgisdottir 2016), or that there is a lack of information on the original impact of these materials (Obrecht et al. 2021a). The advantage of this approach is that it avoids the risk of double counting. On the other hand, since a previous assessment of an existing building is seldom performed, this approach can ensure that impacts will never be counted. The literature review by Vilches et al. (2017) confirms that existing building materials are often excluded from LCA studies of energy refurbishments; the impact of existing

Fig. 2 System boundary diagram of renovation (top) and reconstruction (bottom)



building materials on the use stage after renovation, on the other hand, is occasionally included. For example, Hasik et al. (2019) proposed a framework for defining the system boundaries when comparing renovation and reconstruction. This framework includes all impacts (modules A, B, and C) of new building materials and the impact of only the use stage (module B) of retained building materials. The impacts of the initial production, construction, and EOL (modules A and C) of retained building materials are excluded from the system boundaries, along with all impacts (modules A, B, and C) of removed materials.

As stated by Hansen and Peterson (2002), identical processes in all scenarios can be omitted when performing a comparative LCA. Including or excluding the environmental impact of existing building materials will not affect the order of preference when comparing different renovation scenarios. However, in case of a comparative LCA between renovation and reconstruction, the actions on existing building materials will be different (i.e., full demolition versus partial demolition) and so will the impacts. A study by Zimmermann et al. (2020), which analyzed scenarios for preservation, renovation, and reconstruction, recommended an extended framework for defining the system boundaries compared to the previously mentioned research. The system boundaries included two additional modules related to existing building materials: module C of both removed and retained materials. They concluded that the full demolition of an existing school building accounted for 12% of the total environmental impact over a 50-year study period. This impact was not considered in the study by Hasik et al. (2019). This highlights the importance of defining consistent system boundaries for removed, retained, and new building materials. Furthermore, the Belgian LCA tool TOTEM considers the same system boundaries as Zimmermann et al. (2020) (OVAM 2021). The environmental impact linked to the use stage after intervention and EOL stage (modules B and C) of retained building materials is taken into account, along with the environmental impact from the demolition, waste transport, waste processing, and disposal (module C) of removed building materials. The impacts of module A are zero for existing building materials. For new materials, all impacts (modules A, B, and C) are included.

Existing building materials that are retained will be present in a building before and after an intervention moment. As mentioned above, a new life cycle is introduced at the moment of intervention when renovation was not considered in a previous assessment (CEN 2012b). Consequently, retained building materials are produced during the first life cycle (i.e., before the intervention moment) but will still exist during the second life cycle (i.e., after the intervention moment). As a result, several studies included the environmental impact of existing building materials through allocation (Wijnants et al. 2015; Rasmussen and Birgisdottir 2016; Obrecht et al. 2021b).

According to ISO 14044, allocation is “partitioning input or output flows of a process or a product system between the product system under study and one or more other product systems”. If the definition for allocation is adapted to the specific context discussed above, allocation can be seen as “the partitioning of the environmental impact related to one life cycle stage or module over multiple life cycles”.

ISO 14044 recommends avoiding allocation by dividing the process into two or more subprocesses or expanding the system to include the additional functions into the system boundaries. For the context under study, expanding the system boundaries could mean including the environmental impacts of the existing building before intervention in the current scope, as done by Meijer and Kara (2012). If allocation cannot be avoided, an allocation model should be established based on physical or other relationships (or specifically for reuse and recycling, the number of subsequent uses). The LCA standards, however, do not provide more specific guidelines regarding allocation models. In the context of recycling and reuse, the allocation of impacts over multiple life cycles has been discussed frequently (Eberhardt et al. 2020; Koffler and Finkbeiner 2018; Lei et al. 2021), but there is no generally accepted allocation approach. Both Wijnants et al. (2015) and Rasmussen and Birgisdottir (2016) took into account a linear depreciation model (also called annual or straight-line depreciation) for assessing the environmental impact of existing building materials. The model determines which existing building materials have not yet reached the end of their ESL at the moment of the intervention and allocates the residual impact to the current life cycle. This residual impact is calculated according to the ratio of the remaining service life of the component (RSLC) to the estimated service life (ESLC), later referred to as the “residual factor”. This allocation model is also applied in the Dutch MPG method (Nationale Milieudatabase 2020). In case of retained materials, a residual environmental load is allocated to the current life cycle; this concerns the impact of production, construction, and EOL (modules A and C) multiplied by the residual factor. In addition, the impact linked to the use stage after the intervention (module B) is taken into account completely. Moreover, a residual environmental load is calculated for existing building materials that are removed at the intervention moment; this concerns the impact of production and construction (module A) multiplied by the residual factor. The EOL impact (module C), on the other hand, is fully allocated to the current life cycle. There is, however, a lack of scientific literature dealing with partial allocation of environmental impacts in the context of a comparative LCA of renovation and reconstruction.

Both Wijnants et al. (2015) and Rasmussen and Birgisdottir (2016) compared the “exclude the past” approach to partial allocation through linear depreciation. Both studies concluded that the approach does not change the overall conclusions

regarding the preference for renovation or reconstruction. However, it can be noticed in the study of Rasmussen and Birgisdottir (2016) that the “excluding the past” approach favors renovation more over reconstruction than partial allocation. In case of partial allocation, the embodied impact related to renovation represented 40–50% of the embodied impact related to new construction. The ratio was only 20–30% when existing building materials were assumed burden-free. If other materials with, e.g., a different ESLC or another TSLB and RSP were assumed, the difference between renovation and reconstruction could further decrease; consequently, the selected approach could entail opposite results in terms of preference for renovation or reconstruction.

3 Methodology

3.1 Selection of existing approaches

3.1.1 Reference study period

Based on the literature review in Section 2.1, three existing approaches were selected for defining the RSP (Fig. 3):

1. RSP_new: the RSP is identical to the default RSP for new buildings. In this research, the default RSP for new buildings is set to 60 years, one of the most commonly used RSPs (Thibodeau et al. 2019).
2. RSP_remaining: the RSP is equal to the TSLB minus the building age. For this paper, it is assumed that the TSLB is 100 years, similar to the French I3E Rénovation project (Sié et al. 2017).
3. RSP_extension: the RSP is related to a service life extension due to renovation. Due to the lack of scientific research on the effect of a renovation on the ESL of a building, a service life extension of 40 years is con-

sidered. This is analogous to what is assumed by W/E Adviseurs (2010) for a thorough renovation.

3.1.2 System boundaries

Based on the literature review in Section 2.2, three existing approaches were selected for defining the system boundaries (Fig. 4):

1. SB_production: modules A, B, and C of new materials and module B of retained materials are taken into account. In other words, the environmental impact of modules A and C is considered in the life cycle in which the building material is produced.
2. SB_occurrence: module C of removed materials, modules B and C of retained materials, and modules A, B, and C of new materials are taken into account. In case of reconstruction, module C of new materials is considered only when the new material has reached its EOL before the end of the study period. In other words, the environmental impact of modules A and C is considered in the life cycle in which the impact actually takes place (i.e., the moment of occurrence). Module A is considered in the life cycle in which the production and construction occur, whereas module C is considered in the life cycle in which the EOL occurs.
3. SB_continuous: the environmental impact of modules A, B, and C is equally divided over different life cycles relative to the ESLC. In case of the first life cycle, the impact is multiplied by the ratio of the past service life of the component (PSLC) to the ESLC (in this study referred to as “past factor”), while the impact is multiplied by the residual factor for the subsequent life cycle. In case of renovation, it is assumed that the building will be demolished at the end of the study period, as the TSL of the building structure is then reached. The impact of retained

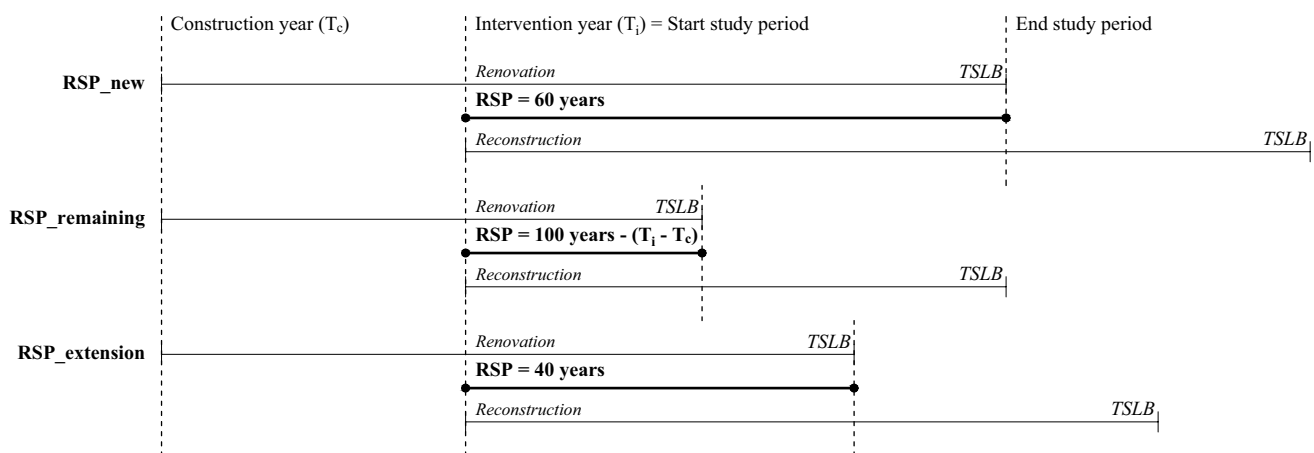


Fig. 3 Existing approaches for the definition of the RSP selected in this research

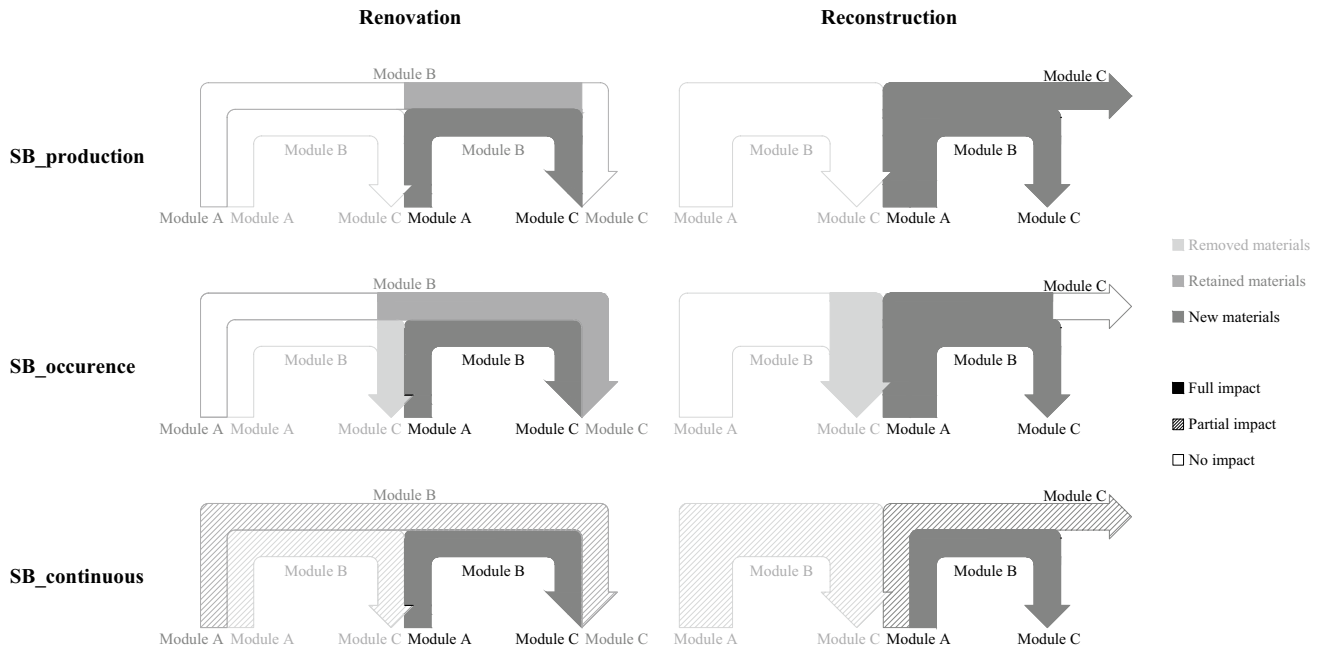


Fig. 4 Existing approaches for the definition of the system boundaries selected in this research

(replaced in the second life cycle) and new materials that still have a certain RSL at the end of the study period will be fully allocated to the current life cycle. In contrast, the impact of removed materials at the beginning of the second life cycle will be linearly distributed over the two life cycles if these materials have not yet reached their EOL (similar to the Dutch MPG method to discourage early demolition). Moreover, in case of reconstruction, the impact of new materials will be partially allocated to the current life cycle if certain materials have not yet reached their EOL at the end of the study period. Otherwise, the full impact is allocated to the life cycle in scope.

Note that module B4 is split into module A of the new material and module C of the removed material. The impact of both modules will be considered independently according to the approach considered.

3.2 Definition of criteria

This section establishes a set of criteria to which the framework for defining the RSP and the system boundaries should comply, based on methodological challenges found in literature. The literature review showed that the TSL of a renovated building should be equal to or smaller than the TSL of a reconstructed building. As a result, the RSL of a renovated building will be shorter than the ESL of a new building; studies analyzing either renovation or reconstruction used both service lives for defining the RSP. Consequently, the following three criteria are set for the definition of the

RSP in order to compare renovation and reconstruction consistently:

1. C1: assume an identical RSP for renovation and reconstruction.
2. C2: assume an identical TSLB for a renovated and reconstructed building.
3. C3: differentiate between buildings constructed at different moments in time.

On the other hand, it is essential to define consistent system boundaries for removed, retained, and new building materials to compare the environmental impact of renovation and reconstruction in a coherent, fair, and robust way. The following five criteria are set for the definition of the system boundaries:

4. C4: distinguish between retained, removed, and new building materials.
5. C5: allocate the highest impact to the moment of occurrence.
6. C6: take into account residual values to discourage early demolition and encourage long-term use or reuse.
7. C7: consider the uncertainty of past and future environmental impacts.
8. C8: robust approach for time-related uncertainties. In other words, the trade-off between renovation and reconstruction should be minimally influenced by the system boundary approach when time-related uncertainties such as the TSLB, RSP, ESLC, and replacement rate are varied.

3.3 Case description

The environmental impact of a renovation and reconstruction case study with an identical geometry and energy performance is compared to assess the robustness of the system boundary approaches for time-related uncertainties (i.e., C8). The case study in scope is a two-story-high, uninsulated terraced single-family dwelling with a horizontal extension, of which the geometry is based on a representative dwelling built in the nineteenth century in Ghent, Belgium. The gross floor area of the case study is 114 m². In addition, the building envelope assemblies are derived from the Belgian TABULA archetypes (Cyx et al. 2011). The original façade is composed of an uninsulated brick cavity wall ($U=1.70$ W/m²K), windows with single glazing and a wooden window frame ($U=5.00$ W/m²K), and two uninsulated external doors ($U=4.00$ W/m²K). The pitched roof of the main building consists of an uninsulated wooden roof construction with roof tiles ($U=1.95$ W/m²K), whereas the flat roof of the horizontal extension and slab on grade are both uninsulated concrete structures ($U=3.50$ W/m²K and $U=0.77$ W/m²K, respectively). The internal walls are composed of hollow clay bricks finished with gypsum plaster and equipped with wooden doors.

In case of renovation, one renovation strategy per building envelope component is proposed. Some materials will be retained (i.e., mainly the building structure), whereas others will be demolished (i.e., mainly finishing layers). In addition, the existing envelope components will be insulated (i.e., the addition of new materials) to such an extent that they comply with the maximum U values that are imposed by the EPBD regulations for new buildings in Flanders (e.g., 0.24 W/m²K for external walls, roof, and slab on grade). The addition of insulation does not change the useful floor area, as it is applied to the outside of the building envelope. In case of reconstruction, identical compositions of the different envelope components are adopted. Moreover, the geometry of the reconstructed building is identical to the renovated building. It must be noted that the renovation of an existing building has more restrictions and less optimization potential in terms of, e.g., window-wall ratio, thermal bridges, compactness compared to a new building. These aspects are however not considered in this paper.

Additional information (e.g., area, state—removed, retained, and new—, and thickness of layers) on the building envelope and internal construction assemblies can be found in the supplementary material. Note that it is assumed that the HVAC installations will be renewed analogously. As identical processes in all scenarios can be omitted when performing a comparative LCA, their impact is not considered in this paper.

3.4 Method for LCA

The goal of the LCA study is to compare the renovation of an existing building with the reconstruction of a geometrically equivalent new building. The focus of the LCA in this paper is on the second life cycle. This life cycle starts at the intervention moment (i.e., renovation or reconstruction) and ends at the end of the RSP. In addition, the functional unit is defined as the renovated or reconstructed building with a gross floor area of 114 m² over a certain RSP. The RSP will, however, vary depending on the approach considered (see Section 3.1.1). Note that in this research, it is assumed that the geometry of the renovated building is identical to the reconstructed building. However, it might be that the geometry (e.g., useful area) after renovation or reconstruction of an existing building changes and is not identical. How should the FU be defined to allow for fair comparisons between different geometries? This is also an important methodological challenge that needs further research. However, setting up guidelines regarding the FU when dealing with different geometries falls outside the scope of this research.

The environmental impacts are calculated via the software SimaPro version 9. For the life cycle inventory (LCI), generic environmental data are derived from the Ecoinvent 3.8 “cut-off” database. Moreover, transformation processes that apply to the European context (“RER” or “Europe without Switzerland”) are opted for to ensure geographical representativeness. If no European data are available, processes representative of Switzerland (“CH”) are adapted to the European context. To translate data from the LCI phase into environmental impacts, the EN 15978 + A2 method is used with PEF (Product Environmental Footprint) normalization and weighting factors. Moreover, the results are converted into a single score, expressed in millipoints (mPt), which requires weighing. Weighing is a subjective and controversial step, but it facilitates easy decision-making and comparison between different scenarios. In addition, this impact assessment method is chosen over a single issue method since more than one environmental problem is considered.

The life cycle stages included in this research are shown in Fig. 5. Transport (A4) and EOL (C1–4) scenarios are acquired from OVAM (2021) which are representative of the Belgian context. Building activities (A5) are in this research limited to a 5% material surplus to take into account, e.g., storage, cutting losses, and careless handling during the construction stage. The impact of construction activities themselves is not included. Only one stage regarding the use stage is considered in this study, i.e., the replacement stage (B4). Some materials or products will have a shorter lifespan than the study period. These materials or products will be replaced by the same material because they can no longer

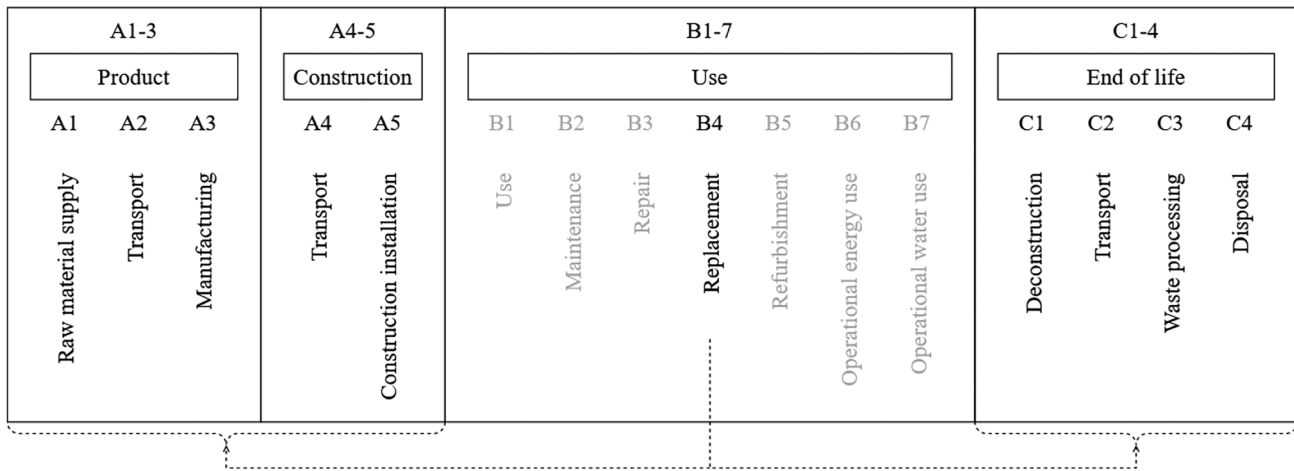


Fig. 5 Building life cycle stages included in the research based on EN 15978 (CEN 2012b)

fulfill their function or because of aesthetic reasons. The replacement stage includes the production and transportation of the replaced building material including construction waste (A1–A5) and the EOL impact of the removed building material (C1–C4). The ESL of individual components is based on Vissering (2011). The ESL of the structural elements is set equal to the TSLB. To check the robustness of the system boundary approaches, the TSLB, ESLC, and method to calculate the number of replacements will be varied. This is further discussed in Section 4.2. Furthermore, the ESLC and material quantities required to renovate or reconstruct the single-family dwelling in scope are listed in the supplementary material. Note that the operational energy use stage (B6) is not included in the analysis. This stage is considered equal for both cases, as the U values of the respective components are the same. In reality, the operational energy use will most likely differ to some extent, as the implementation of renovation measures entails more complexity with regard to, e.g., building junctions compared to new build.

4 Evaluation of existing approaches

4.1 Reference study period

C1 and C2: assume an identical RSP and TSLB for renovation and reconstruction As the RSP should be defined in the functional unit, the RSP of renovation and reconstruction should be equal. Moreover, the authors recommend assuming an identical TSLB for renovation and reconstruction. On the one hand, a reconstructed building can have a longer TSLB than a renovated building due to, e.g., the improvement of the materials' durability over time (Palacios-Munoz

et al. 2019). On the other hand, a renovation can entail a service life extension, leading to a longer TSLB than that of the reconstructed building. However, the reconstructed building might be renovated in the future, obtaining the same service life extension. Due to these uncertainties, it is recommended to assume an identical TSLB.

For the three different RSP approaches, an identical RSP and TSLB for renovation and reconstruction can be guaranteed. This was already illustrated in Fig. 3. In case of RSP_new, the RSP is equal to the RSP for new buildings, which is assumed to be 60 years in this research. The TSLB of the renovated building is then equal to the sum of the RSP and building age. The same TSLB is assumed for the reconstructed building. RSP_extension is quite similar to RSP_new, but the RSP is equal to a 40-year service life extension. The TSLB for both cases is again the sum of the RSP and building age. These approaches might seem contradictory, as reconstruction leads in both cases to a longer service life compared to the default assumed for new buildings. To allow for a coherent comparison between renovation and reconstruction, this would imply that the reconstructed building also needs to be renovated after a certain period to obtain the same service life extension. This, however, requires scenario modeling of future actions to take into account uncertainties. On the other hand, it can be assumed that these interventions fall outside the system boundaries and should hence not be accounted for. In case of RSP_remaining, the RSP is not fixed but varies according to the building age. The TSLB is again assumed to be identical for the renovated and reconstructed building. With a TSLB of 100 years and a building age of, e.g., 60 years, the RSP will be 40 years. As mentioned before, with this approach very old buildings might not have an RSL, rendering renovation unlikable. However, this can be mitigated by including the TSLB as a

variable parameter in the analysis, as the TSLB depends on many factors. Note that in each approach, the TSLB of the reconstruction scenario is longer than the RSP. Therefore, an appropriate allocation approach should be searched for that takes this RSL into account (i.e., C6).

C3: differentiate between buildings from a different construction period To check C3, three construction years are assumed: 1940, 1960, and 1980. The timelines of the selected RSP approaches are listed in Table 2 per construction year (T_c). It is assumed that the intervention takes place in 2020 (T_i). The end of the study period (T_e) depends on the RSP and/or TSLB. When different construction years are considered, only RSP_remaining differentiates between buildings constructed at different moments in time. The RSL of the existing building will be longer for more recent buildings, whereas it will be shorter for older buildings. In contrast, RSP_new and RSP_extension indirectly assume the same RSL regardless of the construction year.

4.2 System boundaries

C4: distinguish between retained, removed, and new building materials All three system boundary approaches make a distinction between retained, removed, and new building materials. A schematic representation of the system boundaries for the different material states is shown in Fig. 6. An additional division is made between new building materials that are removed at the end of the study period and those not removed at the end of the study period. In case of renovation, it is assumed that all building materials are demolished at the end of the study period as the TSLB will be reached; in contrast, new building materials that still have an RSL in the reconstructed building are retained. This distinction makes no difference in the division of impacts according to SB_production, as all impacts are considered at the moment of production. For the other two approaches, this distinction does result in a different impact per life cycle. In case of

SB_occurrence, the impact of module C is only considered in the current life cycle if the EOL stage occurs between the intervention moment and the end of the study period. In the case of SB_continuous, the impact of new building materials that still have an RSL at the end of the study period will be partially distributed over the current and next life cycle for reconstruction, whereas the impact will be fully considered in the current life cycle for renovation.

C5: allocate the highest impact to the moment of occurrence C5 implies that the highest impact should be considered when the impact actually occurs, as this reflects the reality of emissions most accurately. This is also in line with the European LCA standards (CEN 2012a, b). Only SB_occurrence considers the highest impact at the moment of occurrence. On the one hand, if SB_production is applied, the EOL impact is not considered at the moment of its occurrence, but at the moment of production. On the other hand, if SB_continuous is implemented, the impacts of modules A and C are equally distributed over the ESLC; the highest impact is thus not necessarily considered in the life cycle in which the respective life cycle stage takes place.

C6: take into account residual values As the methodology should consider an identical RSP and TSLB (i.e., C1 and C2), the TSL of the reconstructed building will be longer than the RSP, because the RSP depends on the RSL of the renovated building. The system boundary approach should take into account the residual value of the reconstructed building in order to compare renovation and reconstruction in a fair and equivalent way. On the other hand, reconstruction typically involves the demolition of materials that—at the moment of the intervention—have not yet reached the end of their potential service life. These removed materials thus also have a certain residual value, which is nullified. Consequently, C6 implies that the definition of the system boundaries should discourage early demolition and encourage long-term use or reuse by considering residual values. Only SB_continuous meets this criterion, as a residual value is calculated as a function of the ESLC. It must, however, be noted that this criterion is the most subjective. In contrast to, e.g., cost estimates where a residual value is something physical, emissions occur when they actually happen. Therefore, it is suggested that the residual value at the end of the study period in case of reconstruction should be reported separately to take into account the uncertainty of the RSL, similar to module D which addresses the benefits and loads of reuse, recovery, and recycling.

C7: consider the uncertainty of past and future environmental impacts Current production and waste processes are commonly assumed for past or future processes due to the lack of data. However, production and waste processes evolve, rendering the results of past and future processes uncertain and

Table 2 Timelines of the three existing approaches for defining the RSP for different construction years

	T_c	T_i	T_e	TSLB	RSP	
RSP_new	1940	2020	2080	140	60	
	1960			120		
	1980			100		
RSP_remaining	1940	2020	2040	100	20	
	1960			2060		40
	1980			2080		60
RSP_extension	1940	2020	2060	120	40	
	1960			100		
	1980			80		

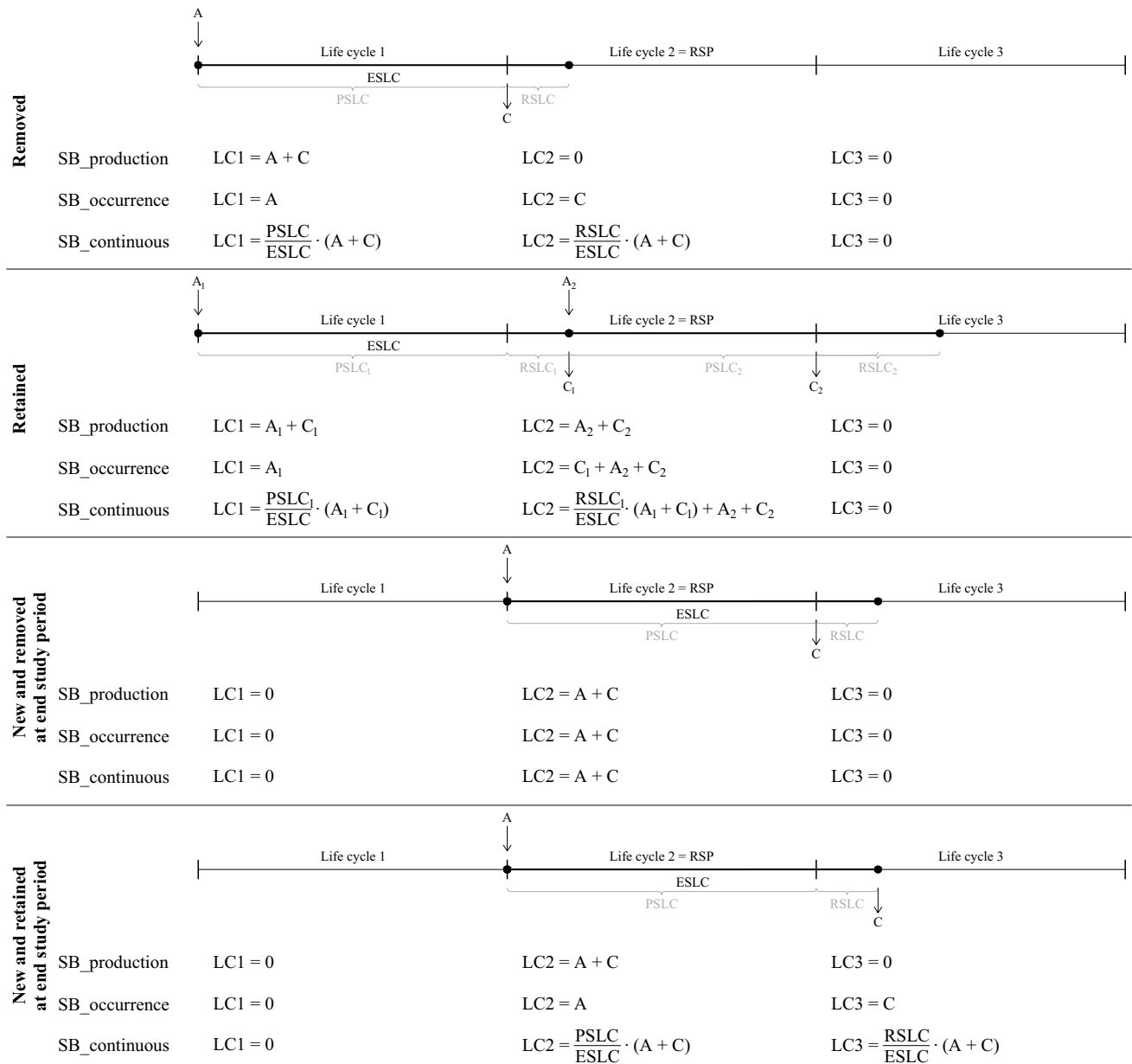


Fig. 6 Schematic representation of existing allocation approaches for removed, retained and new materials

unreliable. Therefore, the system boundary definition should consider this uncertainty by assigning a more limited impact to past and future processes compared to current processes. Accordingly, SB_occurrence only takes into account impacts that occur during the RSP. No assumptions are thus made on impacts that took place during the previous life cycle or will take place in the next life cycle. Of course, assumptions are made about materials that will be replaced or removed in the future during the RSP. SB_production considers impacts that will happen in the next life cycle (i.e., EOL impact of new materials that will be retained in a reconstructed building).

Moreover, particular impacts that are certain are excluded (i.e., EOL impact of removed materials at the moment of the intervention). In case of SB_continuous, impacts of past and future processes are included to the same extent as current processes, as their impact is equally distributed over the ESLC.

C8: robust approach for time-related uncertainties This section assesses the robustness for time-related uncertainties of the selected system boundary approaches. More specifically, an approach is searched for in which the trade-off between

renovation and reconstruction is minimally influenced by varying time-related parameters. The following three parameters are varied:

- The TSLB is varied from 100 to 180 years per 20-year interval. For defining the RSP, RSP_remaining is applied, i.e., the RSP is equal to the TSLB minus the building age. The analysis is conducted for the three aforementioned construction years: 1940, 1960, and 1980.
- The ESLC of the different building materials is changed to $(ESLC - 0.5ESLC)$ and $(ESLC + 0.5ESLC)$. In this way, early and late replacements are simulated.
- The replacement rate (RR) is equal to the ratio of the TSLB to the ESLC minus one. However, when the equation results in a fractional number, two main methods can be found in literature to calculate the RR. On the one hand, prorating is used, which takes into account the decimal RR (Nationale Milieudatabase 2020; Radhi and Sharples 2013). This method is, however, not in line with EN 15978 in which it is stated that only a full number of replacements are allowed. As a result, the RR is often rounded to an integer number. Most studies use upper-value rounding (Ott et al. 2017; Rössig n.d.). Nonetheless, EN 15978 states that if the RSL of the building is relatively short proportionate to the ESLC, the likelihood that a replacement will take place should be considered. In the Belgian TOTEM tool (OVAM 2021), it is assumed that a replacement will only take place if the RSL of the building is larger than or equal to half the ESLC. If not, the fractional number is rounded down. To test the robustness of the system boundary approaches, the RR is calculated according to the following two assumptions: a replacement will always take place (i.e., upper-value rounding), or a replacement will only occur if the RSL of the building is larger than or equal to half of the ESLC.

First, the three parameters are varied one-by-one with the reference parameters being a TSLB of 100 years, the default ESLC and a RR based on the assumption that a replacement will only occur if the RSL of the building is larger than or equal to half of the ESLC. In order to assess the robustness of the system boundary approaches, the results are expressed as the ratio of the environmental impact of reconstruction to the environmental impact of renovation. If this ratio is higher than one, the environmental impact of renovation is smaller than reconstruction. If the ratio is smaller than one, the opposite is true. In this research, we are not interested in the absolute value of this ratio, but in the relative difference between the ratios when the above described time-related uncertainties are varied. Therefore, the standard deviations (σ) between the ratios derived from the variations are calculated for each system boundary approach.

The results of the robustness analysis are shown in Fig. 7 for the three time-related parameters and three construction periods considered. When the TSLB is varied, the ratio of the environmental impact of reconstruction to renovation ranges between 1.24 and 2.74, 1.19 and 2.26, and 0.97 and 1.24 in case of SB_production, SB_occurrence, and SB_continuous, respectively. When the ESLC is varied, the ratios vary between 1.27 and 2.76, 1.22 and 2.27, and 0.79 and 1.35, respectively. Finally, when varying RR, the ratios vary between 1.59 and 2.98, 1.46 and 2.42, and 0.97 and 1.21. It can be noticed that the standard deviations in the ratios of the environmental impact of reconstruction to renovation are the largest in case of SB_production for each construction period and varied parameter, with $\sigma_{\max} = 0.65$. The lowest standard deviations, on the other hand, can be found for SB_continuous, with a $\sigma_{\max} = 0.13$.

Secondly, all parameters are varied simultaneously, as they are interdependent. The standard deviations are listed in Table 3. It can be concluded that SB_continuous is the most robust approach ($\sigma = 0.08$ – 0.10) followed by SB_occurrence ($\sigma = 0.21$ – 0.41). The trade-off between renovation and reconstruction is the most influenced by varying the three defined time-related uncertainties in case of SB_production ($\sigma = 0.27$ – 0.57). In addition, the largest deviations are noticed for the construction year 1940.

4.3 Summary

A summary of to what extent the existing approaches for defining the RSP and system boundaries meet the predefined criteria is provided in Table 4. It can be noticed that RSP_remaining complies with all the predefined criteria regarding the determination of the RSP (C1–C3), whereas none of the system boundary approaches fulfills the predefined criteria (C4–C8).

5 Guidelines for defining the RSP and system boundaries

5.1 Reference study period

The RSP is based on the ESL of the new building in case of reconstruction, whereas the RSL of the existing building is used to determine the RSP in case of renovation. The RSP of renovation and reconstruction should be identical and defined in the functional unit to allow for fair comparisons. However, the ESL of a new building will be greater than the RSL of an existing building, leading to different possibilities to define the RSP. As choosing the longest RSP would involve high uncertainties regarding future impacts, it is recommended to consider the RSL of the existing

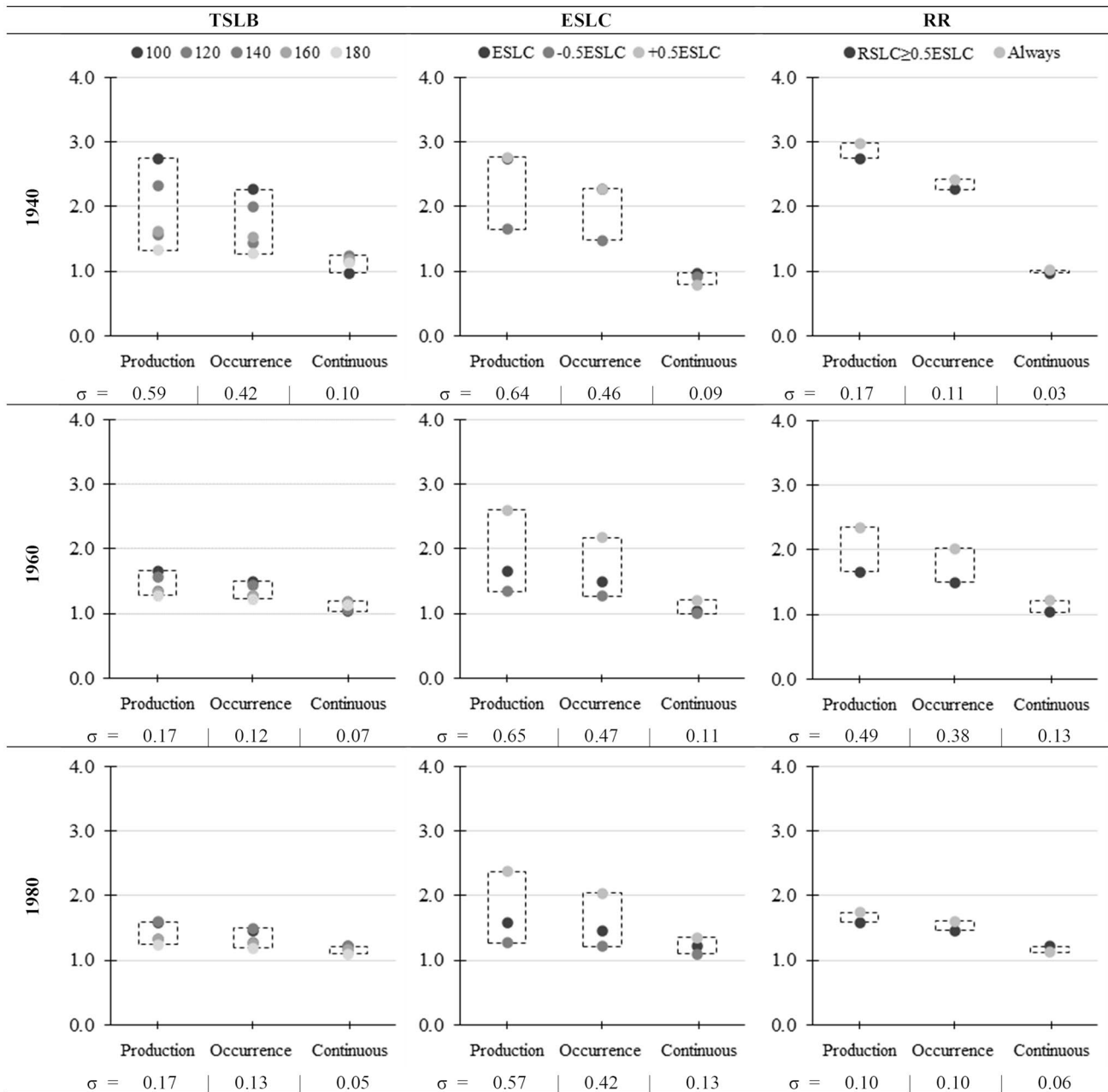


Fig. 7 Reconstruction to renovation ratios and standard deviations (σ) for each system boundary approach per construction year when the defined time-related parameters varied one-by-one

building. In addition, the TSL of the reconstructed building should be at least equal to the TSL of the renovated building. Finally, the definition of the RSP should allow distinguishing between buildings constructed at different moments in time to avoid older buildings having a longer TSL than more recent buildings.

The existing approach in which the RSP is defined based on the difference between the TSLB and the building age (i.e., RSP_remaining) met these predefined criteria and is,

therefore, found most suited for conducting a comparative LCA between renovation and reconstruction. However, it is recommended to consider the TSLB as an uncertain parameter in a sensitivity analysis, as there is a lack of scientific literature dealing with this parameter. Additionally, this approach should be combined with an appropriate system boundary approach that credits RSLs, as the TSLB of a reconstructed building will be longer than the RSP.

Table 3 Standard deviations between the reconstruction to renovation ratios for each system boundary approach per construction year when the defined time-related uncertainties are varied simultaneously

	SB_production	SB_occurrence	SB_continuous
1940	0.57	0.41	0.10
1960	0.34	0.25	0.08
1980	0.27	0.21	0.08

5.2 System boundaries

There are several criteria with which the approach for defining the system boundaries should comply. The approach should differentiate between retained, removed, and new materials, allocate the highest impact to the moment of occurrence, take into account residual values, consider the uncertainty of past and future processes, and should be robust for time-related uncertainties. None of the existing system boundary approaches complied with all the criteria. SB_production met almost none of the criteria. In contrast, the other two approaches supplement each other. Consequently, an approach for defining the system boundaries is searched for that combines both, i.e., a partial allocation approach that allocates the highest impact to the moment of occurrence.

Allacker et al. (2017) described a linear degressive allocation approach, which was developed in the context of recycling. The approach allocates the highest share of impacts to the first product/life cycle and the lowest share to the last product/life cycle, instead of equally distributing the impacts over the number of products/life cycles (SB_continuous). The share of impacts decreases linearly as a function of the number of products/life cycles. On the other hand, the impact due to the final disposal is allocated in a linear progressive way, allocating the highest share of impacts to the last product/life cycle. The linear degressive approach is included in this research as an additional system boundary approach that combines partial allocation and allocating to the moment of occurrence. However, it is adapted

to the context of a comparative LCA between renovation and reconstruction, sharing the impact over different life cycles as a function of the ESLC, instead of dividing the impact over the number of products/life cycles. Distributing the impact as a function of the ESLC is considered more appropriate for this type of research, as there are only two consecutive life cycles that do not necessarily have the same duration. The production and construction impact (module A) decreases linearly as a function of the ESLC, whereas the EOL impact (module C) increases linearly. The adapted linear degressive approach is schematically presented in Fig. 8 for the allocation of module A for removed, retained, and new building materials. A schematic representation of this approach for the allocation of module C can be found in the supplementary material.

Besides the linear model, two additional models are derived: a concave and convex model (Fig. 9). Each model assumes a reduction of the production and construction impact (module A) as a function of the ESLC (or for module C an increment). The concave model assumes a lower initial impact (module C: final impact) and a more slowly declining (module C: increasing) trend than the linear one, whereas the convex model assumes a higher initial impact (module C: final impact) and a faster declining (module C: increasing) trend than the linear one.

The three conceived degressive allocation approaches can be expressed as a mathematical function, listed in Table 5. The functions are established in such a way that the area under the curve from zero to the ESLC is equal to one. This implies that the total impact over the ESLC always adds up to 100%. Per material life cycle (i.e., the interval from zero to ESLC), a factor is determined by which the environmental impact will be multiplied. This factor varies between 0 and 1 depending on the start and the end of a life cycle. Note that variations on the concave and convex models are possible; the selected models in this research serve as an example.

All conceived degressive allocation approaches differentiate between removed, retained, and new building materials (C4), allocate the highest impact to the moment

Table 4 Overview of the extent to which the RSP and system boundary approaches meet the predefined criteria

	<i>RSP_new</i>	<i>RSP_remaining</i>	<i>RSP_extension</i>
C1: identical RSP for renovation and reconstruction	+	+	+
C2: identical TSLB for renovation and reconstruction	+	+	+
C3: differentiate between buildings from a different construction period	–	+	–
	<i>SB_production</i>	<i>SB_occurrence</i>	<i>SB_continuous</i>
C4: distinguish between retained, removed, and new materials	+	+	+
C5: allocate the highest impact to the moment of occurrence	–	+	–
C6: take into account residual values	–	–	+
C7: consider the uncertainty of past and future environmental impacts	–	+	–
C8: robust approach for time-related uncertainties	–	–	+

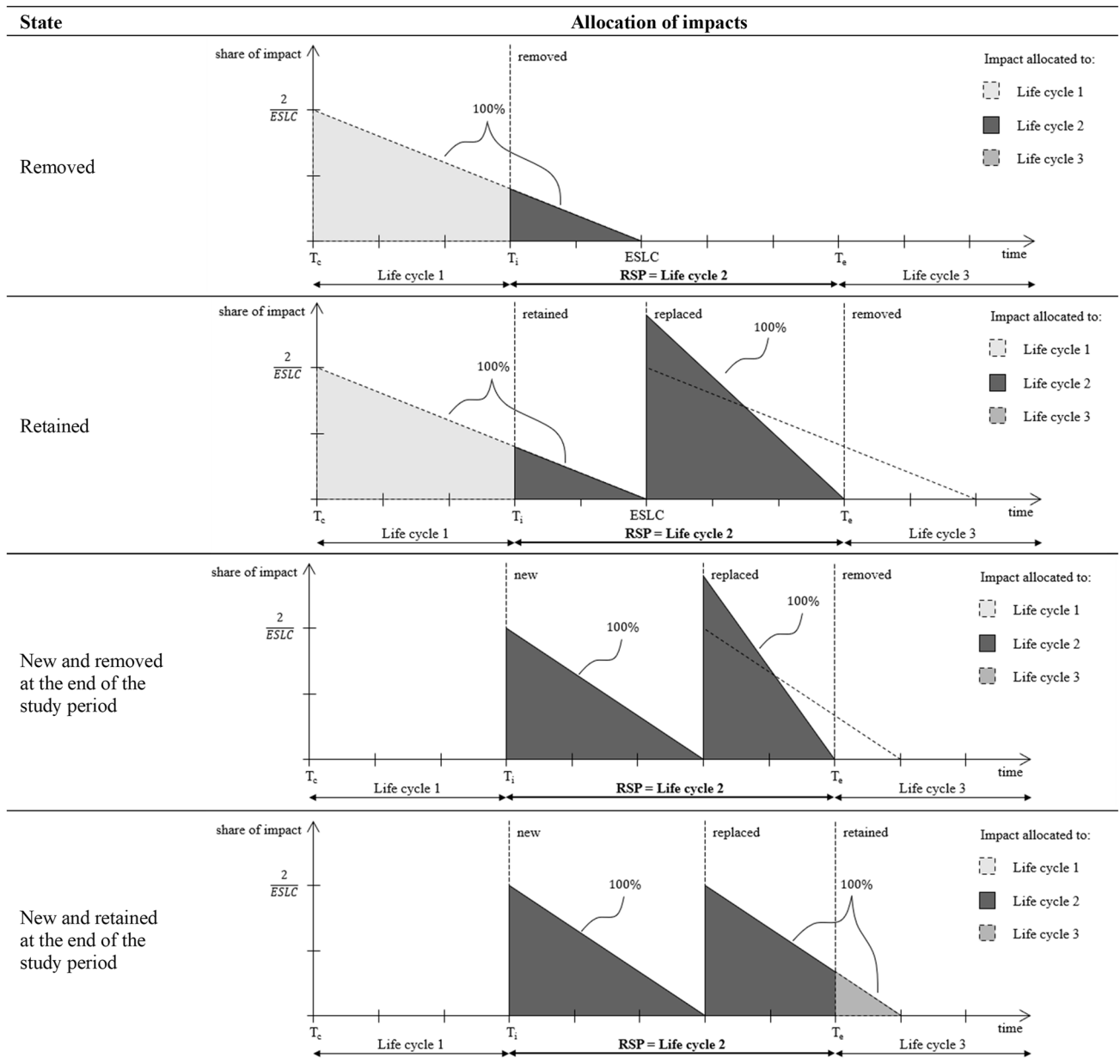


Fig. 8 Schematic representation of the linear degressive approach for the allocation of module A for removed, retained, and new building materials

Fig. 9 Scheme representing the three degressive approaches based on a linear (left), concave (middle), and convex (right) model to allocate module A. A progressive trend is assumed for module C

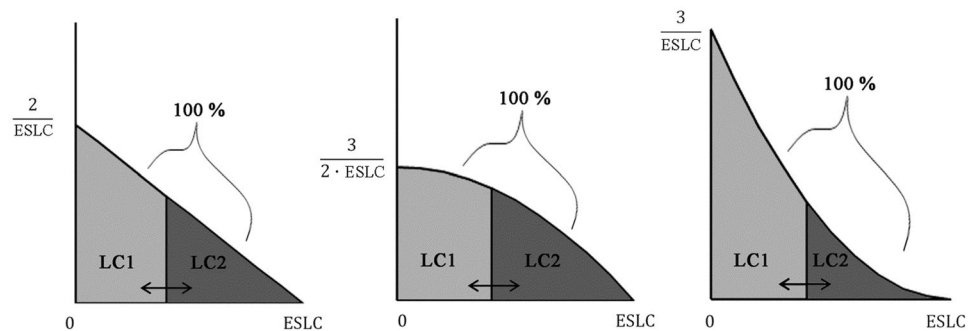


Table 5 Function of the three conceived degressive approaches for allocating module A and C

Degrassive allocation	Module A: $f(x)$	Module C: $f(x)$
Linear	$-\frac{2}{ESLC^2} \cdot x + \frac{2}{ESLC}$	$\frac{2}{ESLC^2} \cdot x$
Concave	$-\frac{3}{2 \cdot ESLC^3} \cdot x^2 + \frac{3}{2 \cdot ESLC}$	$-\frac{3}{2 \cdot ESLC^3} \cdot x^2 + \frac{3}{ESLC^2} \cdot x$
Convex	$\frac{3}{ESLC^3} \cdot x^2 - \frac{6}{ESLC^2} \cdot x + \frac{3}{ESLC}$	$\frac{3}{ESLC^3} \cdot x^2$

of occurrence (C5), take into account residual values (C6), and consider uncertainties of environmental impacts of past and future processes (C7). In order to know if the approaches also give robust results (C8), the proposed allocation models are applied to the renovation and reconstruction case study, and the time-related uncertainties are again varied as in Section 4.2. The results associated with the one-by-one variation of the defined time-related parameters can be found in the supplementary material, whereas Table 6 lists the standard deviations between the reconstruction to renovation ratios when the parameters are varied simultaneously for both the existing and conceived system boundary approaches. From the results, it can be concluded that the degressive approach according to the concave model is the most robust ($\sigma = 0.11$) of the three degressive approaches conceived, followed by the approach according to the linear model ($\sigma = 0.12$ – 0.13). The standard deviations vary between 0.16 and 0.19 when the convex model is applied. Compared to the three existing system boundary approaches, the results lie in between SB_continuous ($\sigma = 0.08$ – 0.10) and SB_occurrence ($\sigma = 0.21$ – 0.41).

The conceived degressive allocation models combine the advantages of SB_occurrence and SB_continuous; these models are more robust than SB_occurrence and take into account residual values, but also assign the greatest impact to the moment of occurrence and considers uncertainties of environmental impacts of past and future processes, which was not the case when SB_continuous was applied. When comparing the three conceived degressive models, the concave model is most robust for time-related uncertainties (C8). However, this model is less consistent with the reality of emissions (C5). The convex model, on the other hand, is

the least robust (C8) but follows most closely the reasoning that the highest impact should be attributed at the moment of occurrence and thus most closely reflects the reality of emissions (C5). The linear degressive model is situated in between the concave and convex models. Since one degressive allocation model scores better on one criterion, whereas another model scores better on another criterion, it is not possible to state in an unambiguous way which allocation model is more interesting. For this reason, a scoring system is used to evaluate both the three existing system boundary approaches and the three conceived degressive approaches.

For each criterion with which the framework for defining the system boundaries should comply (C4–C8), the system boundary approaches are ranked. Based on this ranking, a score from 0 to 5 is assigned per criterion. For example, SB_production was the least robust allocation approach, followed by SB_occurrence. The most robust approach, on the other hand, was SB_continuous. Consequently, a score of 0, 1, and 5 is assigned, respectively. In addition, the degressive approaches get a score of 2, 3, and 4 based on the results listed in Table 6. The higher the score, the greater the extent to which the approach fulfills the criterion. If approaches score identically on a certain criterion, the points are distributed in such a way that they always add up to 15 points. For example, SB_production and SB_occurrence do not take into account residual values (C6), and thus, both get a zero score. SB_continuous and the three degressive approaches do comply with this criterion to the same extent; accordingly, the 15 points are equally distributed over the four remaining approaches assigning a score of 3.75 to each approach. Once all approaches have been assessed for each criterion, the results are enumerated and expressed as a single score. Moreover, it is assumed that each criterion has equal importance, so no weighting is applied. The results of the scoring system are listed in Table 7. SB_production has the lowest total score, whereas SB_convex scores the highest, followed by SB_linear. It can thus be concluded that the convex degressive approach is the most interesting system boundary approach to compare the environmental impact of renovation and reconstruction in a robust and consistent way.

Table 6 Standard deviations between the reconstruction to renovation ratios for the existing and conceived allocation approaches per construction year when the time-related parameters are varied simultaneously

	SB_production	SB_occurrence	SB_continuous	SB_linear	SB_concave	SB_convex
1940	0.57	0.41	0.10	0.12	0.11	0.17
1960	0.34	0.25	0.08	0.13	0.11	0.19
1980	0.27	0.21	0.08	0.13	0.11	0.16

Table 7 Overview of the extent to which the existing and conceived system boundary approaches meet the predefined criteria based on a scoring system

	SB_production	SB_occurrence	SB_continuous	SB_linear	SB_concave	SB_convex
C4: distinguish between retained, removed, and new materials	2.50	2.50	2.50	2.50	2.50	2.50
C5: allocate the highest impact to the moment of occurrence	0.00	5.00	1.00	3.00	2.00	4.00
C6: take into account residual values	0.00	0.00	3.75	3.75	3.75	3.75
C7: consider the uncertainty of past and future environmental impacts	0.00	5.00	1.00	3.00	2.00	4.00
C8: robust for time-related uncertainties	0.00	1.00	5.00	3.00	4.00	2.00
<i>Total score</i>	<i>2.50</i>	<i>13.50</i>	<i>13.25</i>	<i>15.25</i>	<i>14.25</i>	<i>16.25</i>

6 Conclusion

The aim of this research was to set up guidelines for defining the reference study period and system boundaries when the goal of the LCA is to compare the environmental impact of the renovation of an existing building with the reconstruction of a geometrically equivalent new building. Firstly, a literature review was carried out, from which two methodological challenges emerged in the context of a comparative LCA between renovation and reconstruction. On the one hand, how should the RSP be defined when buildings with different service lives are to be compared? On the other hand, how should the system boundaries be defined for removed, retained, and new building materials when an existing building is the starting point of the assessment? From existing research and national LCA frameworks, three existing approaches regarding both the definition of the RSP and system boundaries were distinguished. Secondly, a set of criteria was established to which the framework for defining the RSP and the system boundaries should comply. Subsequently, the existing approaches were examined to assess the extent to which they met the defined criteria. The approaches for defining the system boundaries did not comply with all defined criteria. Consequently, some additional approaches were devised.

Based on the literature review and the results, following guidelines are set up for the definition of the RSP and system boundaries, respectively. The RSP of renovation and reconstruction should be identical and defined in the functional unit to allow for fair comparisons. In addition, the TSL of the reconstructed building should be equal to the TSL of the renovated building. Finally, the definition of the RSP should allow distinguishing between buildings constructed at different moments in time. It is, therefore, recommended to define the RSP based on the difference between the TSLB and the building age.

On the other hand, the approach for defining the system boundaries should differentiate between retained, removed,

and new materials, allocate the highest impact to the moment of occurrence, take into account residual values, consider the uncertainty of past and future processes, and should be robust for time-related uncertainties. For defining the system boundaries in case of building materials that are retained over multiple life cycles, it is recommended to include the impact through a convex partial allocation model to compare the environmental impact of renovation and reconstruction in a robust and consistent way. This partial allocation model shares the impact over different life cycles as a function of the ESLC according to a convex degressive and progressive function, respectively, for modules A and C.

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Declarations

Competing interests The authors declare no competing interests.

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