How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978

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Abstract

Purpose EN 15804 and EN 15978 are the established standards to calculate the environmental impact of building products and buildings. Despite the importance of circular building, many life cycle assessment (LCA) studies based on EN 15804/15978 are not set up to evaluate circularity. This paper aims to research how an LCA study should be developed that can determine the environmental impact of a circular versus a linear building element within the methodological framework of EN 15804/15978.

Methods First, it is clarified how the methodological framework of EN 15804/15978 considers different circular principles. There is a particular focus on the concept of multi-cycling and module D. Second, and as the main objective of this paper, it is analyzed which scenarios throughout the lifespan of a building element should be modelled. The focus lies on combining characteristic transformation and end-of-life scenarios into characteristic life cycle scenarios and examining if this provides sufficient insight into the possible environmental impact. This is illustrated by an LCA study of a linear and circular facade system. When representing the results of the LCA study it is analyzed how the inclusion of module D changes the results.

Results and discussion To account for the concept ‘multi-cycling’ the authors propose to consider multiple use cycles (i.e. transformations) within one life cycle instead of considering several life cycles. This is done through module B5 Refurbishments. Module D is important to stimulate recycling and reuse at the end of life. However, the concept of module D must be handled with the necessary care to provide correct information. Characteristic life cycle scenarios are determined for a more robust understanding of the possible environmental impact of a building element by modelling only a limited amount of scenarios. For the facade systems, the considered transformation scenarios are more determining for their environmental impact than the choice of end-of-life scenario, especially when module D is not considered.

Conclusions By setting up an LCA study that can evaluate the important circular principles and consider characteristic life cycle scenarios, detailed insight into the environmental impact of circular versus linear building elements can be obtained. The proposed approach leads to more robust LCA studies of circular versus linear building elements.

Keywords Circular building, Life Cycle Assessment (LCA), Building element, EN 15804, EN 15978, Scenario modelling

1 Introduction

1.1 LCA studies and the evaluation of circularity

Within the building sector, EN 15804 (CEN 2019) and EN 15978 (CEN 2011) are established as the standards to determine the environmental impact of building products and buildings, respectively. The circular building strategy is identified as the key strategy to reduce the environmental impact of the building sector (European Commission 2019) and life cycle assessment (LCA) is recognized as the method that can determine the environmental impact of circular building solutions (De Wolf et al. 2020; Eberhardt et al. 2019a, 2020a; Lei et al. 2021). However, the majority of the existing LCA studies based on EN 15804/15978 are focused on evaluating our linear way of building and are not set up to evaluate circular principles. If an LCA study accounts for the important circular principles it will stimulate circularity throughout the whole life cycle of a building solution, e.g. encourage the use of existing over new materials, stimulate multiple uses of materials and reward reuse and high-quality recycling at the end of life. Furthermore, LCA studies considering multiple possible life cycle scenarios are limited. This is because the long lifespan of a building makes it difficult to determine which future scenarios should be modelled and the fact that circular building solutions enable more scenarios (transformations, reuse, recycling,…) than linear solutions is generally not considered. To comply with the circular design principles ‘independent layers’ and ‘reversible connections’, building solutions might require additional materials, which can result in a higher initial environmental impact. Therefore, it is crucial to take future scenarios into account and evaluate which scenarios should take place for the initial investment to pay off, i.e. under which boundary conditions are circular building solutions the most environmentally beneficial?

1.2 Existing research

Literature on how to evaluate circularity through LCA is limited. Existing research mainly tackles the question how to evolve from analyzing one life cycle to analyzing multiple life cycles. More specifically on how the burdens and benefits regarding circular building should be allocated over multiple life cycles. In this context Eberhardt et al. (2020a) compare four different allocation approaches: (a) the EN 15804/15978 cut-off approach, (b) the Circular Footprint Formula, (c) the 50:50 approach and (d) the linearly degressive (LD) approach. They conclude the LD approach is promising to evaluate the impact of open and closed-loop systems within a closed-loop supply chain. In an earlier paper Eberhardt el al. (2019b) propose a formula for reusable materials within the logic of EN 15804: the total impact (modules A to D) is divided by the amount of expected life cycles. In further work of Eberhardt this allocation approach is not addressed anymore but the focus is on the LD approach (Eberhardt el al. 2020a, b; van Stijn 2021). Other literature on how EN 15804/15978 can account for multiple cycles does currently not exist to the best knowledge of the authors.

EN 15804/15978 is often considered to only be able to promote the use of reused or recycled components while other circular principles such as recycling and reuse at the end of life are not stimulated (Eberhardt el al. 2020a; Lei et al. 2021; Rajagopalan 2021; Rasmussen et al. 2019). However, given the importance of EN 15804/15978 and the concept of circularity within the building sector, it is necessary to determine how an LCA study that can evaluate the important circular principles should be set up based on these standards. No detailed research exists on this topic at present.

Studies taking into account multiple scenarios throughout the life cycle of a building element exist, but are not standard practice. Paduart et al. (2013) and Vandenbroucke et al. (2015) consider multiple frequencies of adaptions to building elements to determine how many adaptions during their lifespan are necessary for the circular building element to have a lower environmental impact than the linear alternative. Other studies taking into account multiple scenarios mainly focus on the end-of-life phase (Di Maria et al. 2018; Hossain et al. 2018). For an LCA study of internal walls Buyle et al. (2019) model five possible end-of-life scenarios going from ‘business-as-usual’ to ‘maximized reuse’. Sandin et al. (2014) analyze three assumptions regarding future technology of end-of-life treatments for glue-laminated wooden beams and steel frames. Research that highlights the multiple scenarios that a circular versus a linear building element can undergo throughout their lifespan and that puts the environmental impact into perspective based on these future scenarios is lacking.

1.3 Research objectives

Current research has not yet done an in-depth analysis on how the methodological framework of EN 15804/15978 can be used to set up LCA studies that can objectively determine the environmental impact of circular versus linear building elements. The research objectives of this paper are twofold. First, it is clarified how the methodological framework of EN 15804/15978 considers different circular principles; what are its possibilities and limitations. There is a particular focus on how the concept of multi-cycling can be included. Furthermore, the usefulness and limitations of module D are discussed. Second, and as the main research objective of this paper, it is analyzed which scenarios throughout the lifespan of a building element should be considered to obtain sufficient insight into its possible environmental impact. Transformation scenarios during the lifespan are incorporated to take into account multiple use cycles and the end-of-life approach is improved by using alternative scenarios. The focus lies on combining characteristic transformation and end-of-life scenarios into characteristic life cycles scenarios. This is illustrated by an LCA study of a linear and circular facade system. A key question is whether using characteristic life cycle scenarios provides sufficient information to answer the question: in which situations does the circular building element have a lower environmental impact than the linear solution? Is this dependent on the specific end-of-life scenario or on the fact that transformations takes place? Additionally, when representing the results of the LCA study it is examined how the inclusion of module D changes the results. This paper aims to provide LCA practitioners a framework to execute more robust LCA studies for circular versus linear building elements based on the standards EN 15804/15978.

2 Methods

2.1 Research steps

In section two ‘Methods’, important circular principles throughout the life cycle of a building element are determined and it is elaborated if and how these can be accounted for by the methodological framework of EN 15804/15978. In section three ‘Results’, an LCA study is executed for two facade systems: ETICS, a non-circular solution, and a ventilated facade, a circular solution. Characteristic life cycle scenarios are drawn up and it is analyzed if these provide sufficient insight into the possible environmental impact of the facade systems. Section four ‘Discussion’, contains a critical discussion on the use of characteristic scenarios, taking into account multiple use cycles and module D. The paper ends with concluding remarks in section five 'Conclusion'.

2.2 Methodological framework EN 15804/15978

For the building sector the standards EN 15804 and EN 15978 provide a methodological framework for LCA studies of building products and buildings, respectively. There is no specific standard on building element level, which is the scope of this paper, but the framework on product and building level can be translated to element level. **Figure 1** illustrates the relationship between product, building element and building level. EN 15804 has been updated in 2019, while EN 15978 is currently in the process of being updated. Since EN 15804 has a more recent version and is more extensive, this standard is referred to further in this research. However, the information in the following sections is also in line with EN 15978 since this standard follows the same structure and principles as EN 15804.

2.2.1 Modules of a life cycle

According to EN 15804 the life cycle of a building element is divided into modules (see **Figure 2**). Following the modularity principle of the standard, all environmental aspects and impacts are declared in the life cycle stage where they appear. The choice for EN 15804 automatically defines the considered allocation methods which in turn influence how certain circular principles are accounted for (Eberhardt el al. 2020a; Lei at al. 2021). Modules A to C follow the cut-off allocation approach (100:0). Module D is calculated by system expansion and provides additional information on the net environmental benefits and loads resulting from reuse, recycling and energy recovery beyond the system boundary.

Module D is calculated from when the material has reached its end-of-waste (EOW) status to the point of functional equivalence where the secondary material, fuel or exported energy substitutes primary production. Equation (1) shows the formula for module D provided by EN 15804. A study by Delem et al. (2019) tackles the methodological aspects of calculating module D.

$$Module\ D = (RR - RC) * (E_{recycling} - E_{virgin} * Q) \quad (1)$$

With:

RR — *recycling rate: amount of material exiting the system that will be recycled in a subsequent product system (determined at EOW point) [kg]*

RC — *recycled content: amount of input material to the product system that has been recycled from a previous system (determined at system boundary) [kg]*

$E_{recycling}$ — *emissions and consumed-resources arising from recycling processes at the end of life [impact/kg]*

E_{virgin} — *emissions and consumed-resources arising from acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials at the end of life [impact/kg]*

Q — *quality ratio between outgoing recycled material and the substituted material*

2.3 Circular principles

To avoid focusing on one single aspect of circularity and to prevent unwanted trade-offs, an LCA study should be able to evaluate circular principles that relate to different moments of the life cycle of a building element. The most important circular principles are listed in **Table 1**. Inspiration for the principles was drawn from a study by Allacker et al. (2014). In the following paragraphs it is examined how each of these circular principles are taken into account by the standard. Since the circular principles relate to different moments of the life cycle of a building element they will relate to the different modules of a life cycle as defined by EN 15804.

2.3.1 New versus secondary materials

Following the cut-off allocation approach, secondary materials (recycled or reused) that are used as input to the production stage (module A) do not carry the impact from primary material production since this is attributed to the previous life cycle (Delem et al. 2019). Only the loads from the end-of-waste until the secondary material is ready for use are stated in module A. This means the difference in 'production' impact between existing materials or materials with a recycled content and their equivalent primary version is shown in module A. Differences in remaining lifespan, maintenance requirements or end-of-life treatments between new and secondary materials are not considered here.

2.3.2 Increase of the recycled content

The circular principle 'account for the increase of the recycled content' relates to the same aspects as the circular principle 'differentiate between new and secondary materials'. According to the cut-off allocation approach the higher the recycled content of a material, the less impact from primary material production must be accounted for in module A. The increase of the recycled content of a material becomes clear through the impact declared in module A. It is possible however that the use of a secondary material leads to a higher environmental impact than the use of primary materials.

2.3.3 Multiple cycles

Circularity aims to keep materials, building elements and buildings cycled at their highest utility and value for as long as possible through value retention processes (VRPs) such as reuse and recycling. Therefore, there is a clear notion in literature that circularity can only be correctly assessed through LCA when we evolve from modelling one cycle to modelling multiple cycles (Eberhardt et al. 2019b, 2020a; van Stijn et al. 2021).

Existing research focusses on determining the impact of each cycle. In this case the following question becomes important: how should the benefits and burdens of components and materials be allocated between the cycles that share them? Different allocation approaches are possible. PAS 2050 (2008), a methodology for the carbon footprinting of goods and services, handles reusable products by equally dividing their production and end-of-life (EOL) impact by the expected number of times the product will be reused. Although PAS 2050 is not developed for the building sector, its approach has been used by papers researching the environmental impact related to the reuse of building components (Eberhardt et al. 2019b, Tingley et al. 2012).

Another possible method is the linearly digressive (LD) approach. Instead of equally sharing the impact of reuse between the predicted cycles, the LD approach allocates the largest share of initial production and disposal impact to the cycle where they occur. The share of impact allocated to following or previous cycles reduces linearly. The impact of the VRPs is divided evenly between cycles (Eberhardt et al. 2020a). Apart from reuse, this approach is also intended for other VRPs such as recycling (Allacker et al. 2017). Although predicting the amount of recycling or reuse cycles for a material remains difficult due to future uncertainty, to a certain extent the LD approach takes this uncertainty into account by allocating the largest share of the impact to the cycle where it effectively occurs.

Accounting for multiple cycles through EN 15804

Eberhardt el al. (2020a) state that EN 15804 can only look one life cycle ahead through module D. The authors of this paper chose to take a different approach within the framework of EN 15804 to consider multi-cycling: the multiple cycles are not considered different life cycles, but rather different use cycles within one life cycle.

A circular building element distinguishes itself from a linear element by the fact that its components can be reused with a required transformation while for a linear element the existing element must be demolished and a new element constructed. An essential question is 'how many transformations (i.e. use cycles/times reuse) must take place before a circular solution has a lower environmental impact than a linear one'. While existing research focusses on determining the impact of each cycle, in this case the total impact of all cycles becomes important.

Instead of considering each change to a building element for which reuse takes place a new life cycle, it is considered a transformation within the life cycle of a building element, as illustrated by **Figure 3**. Examples of transformations of a building element can be: repositioning an internal wall, increasing the insulation of a facade or updating the finishing layer of an element to give the space a new look. While a replacement happens at a component's end-of-life to bring the building element back to its initial condition, a transformation can happen at any moment during the life cycle of the components and aims to make the building element meet new requirements.

Considering multi-cycling through transformations within a life cycle means the production and end-of-life impact of a component are not allocated over its multiple life cycles and are always fully accounted for, avoiding the need to find an appropriate allocation factor and the danger of pushing current impacts to the future. This is in line with the modularity principle of EN 15804. The traditional life cycle of a building element is calculated from modules A to D. Multiple transformations can take place during this life cycle just as multiple replacements can occur. Following this logic, transformations should be a module themselves, just as replacements are module B4.

The original module B5 Refurbishment aligns most closely with the concept of transformations. The definition of module B5 is not 100 % clear, neither in EN 15804 nor in EN 15978. The technical expert support from the CEN TC 350 working groups who drafted the standards confirm that module B5 is suited to report future transformations of building elements if these are foreseen at the time the LCA is performed. It is difficult to predict the amount of transformations that will take place and although this is not handled within this research, it is important to deal with this uncertainty. According to the authors of this paper, the most appropriate way to do so is by considering the number of transformations a variable parameter.

It is difficult to define refurbishment/transformation scenarios on product level since this often depends on how the product is integrated in the construction. It is easier to define them on building level. When defining transformations on building element level, which is the scope of this paper, the type of building of which the element is part must be taken into account (e.g. offices require different and more frequent transformations than apartments). The authors consider four types of general transformations to be covered by module B5 Refurbishment: upgrade, expansion/addition, relocation, contraction/ removal (Fawcett 2011; Galle 2016).

Module B5 takes into account reuse during the study period while module D considers reuse at the end of the study period. When comparing linear and circular building solutions it is important to consider the same amount and type of transformations since each transformation means a change in requirement and thus in functional unit (FU). When considering transformations, the functional unit is no longer static over the defined study period but must incorporate the changes due to transformations. In this paper, the functional unit is defined as ‘1 m² building element that meets the changing requirements during the study period’. The concept of multi-cycling through transformations is further illustrated by the LCA study for the two facade systems.

2.3.4 Long use/lifespan of materials

A long use or lifespan of a material leads to less replacements (visible in module B4). This means there is a lower demand of new materials, which is environmentally beneficial. However, certain materials may not have reached their full lifespan at the end of the study period (i.e. period over which the characteristics of the building element are analyzed) and their residual lifespan must be acknowledged to truly stimulate the circular principle ‘long use/lifespan of materials’. For example, in **Figure 4** the fiber cement cladding has a lifespan of forty-five years. At the end of the study period it has a remaining lifespan of thirty years due to the second lifespan ending at ninety years. If the fiber cement can be recovered without damage it can be reused in a next life cycle and this benefit can be accounted for in module D (taking into account reuse at the end of life is more elaborately discussed in the next section). However, the study period is an important parameter of the LCA study which can significantly influence the results. Just as the number of transformations, the study period can be considered a variable parameter to put the results of the LCA study more in perspective. However, this is outside the scope of this paper.

2.3.5 Recycling and reuse

With the amendment of the standard in 2019, the calculation of modules C and D has become mandatory and EN 15804 states that module D recognizes the “design for reuse, recycling and recovery” concept for buildings by looking at their consequences beyond the building’s life cycle.

The benefits of recycling and reuse are already partly apparent when only modules A to C are considered since no impacts after the EOW have to be taken into account. However, in this case only the benefits of avoided waste processing are shown whereas it has already become clear that the largest benefit of recycling and reuse is related to the avoided production in the next cycle, which is stated in module D (FCRBE 2022). However, module D is considered outside the system boundary and its result may not be added to the results of modules A to C. Although this might seem conflicting with the idea of circularity where the end-of-life is considered an inherent part of the life cycle, stating module D separately has multiple motivations.

Firstly, given the long lifespan of a building, the uncertainty concerning the potentially avoided impact is very high (e.g. recycling technologies will evolve) (Delem et al. 2019). Speculative benefits should not greenwash the results and the focus should be on reducing current emissions (Rasmussen 2019). Secondly, adding the results of module D to the results of modules A to C can erase certain nuances as illustrated by **Figure 5**. The net impact of the two bars is the same while the impact in modules A to C differs significantly between the new and existing material. When considering reuse at the end of life, the impact of module D might (almost) fully counter the impact of modules A to C. Although module D has the potential to capture the benefits of recycling and reuse, it is important to handle this module in the appropriate way to ensure no information gets lost. This is further elaborated in the next paragraphs.

2.3.6 Open-loop versus closed-loop recycling

The formula for module D provided by EN 15804 (Equation (1)) avoids double counting by only reporting the net impacts from recovery (recycling or reuse). The secondary material on the input side (RC) must be subtracted from the secondary material on the output side (RR) if they have an identical physical form. The formula seems to favor open-loop over closed-loop recycling while closed-loop recycling is assumed to be better for the environment (Delem et al. 2019). **Figure 6** shows the difference between open-loop and closed-loop recycling: with open-loop recycling, the recycling process at the end of life is a different process than with the recycled content ($E_{recycling,EOL} \neq E_{recycled}$ and $E_{virgin} \neq E_{*virgin}$) (Mirzaie et al. 2020). The amount of secondary materials used as input (RC) cannot be subtracted from the materials for recycling at the output (RR) , as the nature of these secondary materials at the input and output side are often considerably different. By contrast, with closed-loop recycling RR is reduced by RC, resulting in a lower benefit in module D.

This net impact also means that for closed-loop recycling an increase of the recycled content on the input side (module A) is nullified by a lower net impact in module D (RR-RC). When evaluating the circular principle 'increase of the recycled content' it is thus important to consider this separately from module D and only take into account modules A to C.

The concept of module D has some defects regarding open-loop and closed-loop recycling. Nevertheless, it has the potential to stimulate recycling and reuse at the end of life. When evaluating circular principles related to the end of life, the authors of this paper recommend to calculate the results with and without module D, in order to analyze if the same tendencies can be observed and conclusions be drawn. Taking into account multiple possible end-of-life scenarios also helps to put the end-of-life impact and thus the impact of module D into perspective. This is further elaborated when discussing the results of the LCA study for the two facade systems.

2.3.7 Representing the results of an LCA study

The circular principles relate to different modules of the life cycle of the building element (see **Table 2**). Therefore, when executing an LCA study it is important to calculate modules A to D. In the results section of this paper, depending on what is analyzed, the results are displayed per module or as a total score (modules A to C added). For each, the impact per module is always stated and the influence of module D on the results is shown separately. According to the EN 15804, which was developed for EPD's, only the submodules A1, A2 and A3 may be aggregated. However, the authors believe that for certain research purposes the representation of the environmental impact as a total score (modules A to C) and per modules can lead to more clear conclusions.

2.4 LCA study facade systems

An LCA study is conducted for two facade systems: ETICS and a ventilated facade. ETICS does not qualify as a circular building solution due to the mortar fixation of the insulation and the plaster finishing. The ventilated facade is a circular solution, constructed according to the circular design principles independent layers and reversible connections. The bearing structure of both facade systems is assumed identical and therefore neglected in this study. Appendix A provides additional information on both systems: drawings and thickness, weight and lifespan of the materials. The lifespans considered in this research are chosen to facilitate certain scenarios, they should not be interpreted as exact values.

The life cycle phases taken into account are modules A1-5, B2, B4, B5, C1-4 and D. The functional unit is 1 m² facade that can fulfill the changing requirements over a study period of sixty years. The specific scenarios throughout the lifespan of the facade systems and thus the changing requirements are discussed and illustrated in the next paragraphs. The modelling assumptions per life cycle phase are included in section one of the **Supplementary Material**. The LCA study is conducted using the life cycle software SimaPro with the Ecoinvent 3.7 database. The Ecoinvent processes are transformed to the Belgian context based on data used by the Belgian LCA tool TOTEM. The impact method used is the EN 15804 +A2 method with PEF normalization and weighting factors. Because the main objectives of this paper relate to methodological aspects the environmental impact is expressed as a single score, i.e. in millipoints (mPt), rather than focusing on a specific impact category.

2.4.1 Scenario modelling: transformation and end-of-life scenarios

Circular building elements can have a higher initial environmental impact than linear elements and it is important to determine which future scenarios must take place for the initial investment to pay off. Scenario modelling is necessary to deal with the uncertainty of which future scenarios will take place. This research focusses on transformation scenarios (i.e. module B5 as discussed in 2.3.3) and end-of-life scenarios (modules C1-4 and D).

Instead of taking into account every possible scenario throughout the lifespan of a building element, it is researched if sufficient insight can be gained by modelling a set of characteristic life cycles that determine the result range of the environmental impact. To draw up characteristic life cycles the appropriate transformation and end-of-life scenarios must be combined.

The possible transformations of a building element are endless and therefore it is necessary to define a set of characteristic transformations to get a well-founded idea of their influence on the environmental impact, e.g. how many or which transformations should take place before the circular building element has a lower environmental impact than the linear element? The possible transformation scenarios are defined by the type of building element and building typology.

The possible end-of-life scenarios are finite. They are dependent on the construction method of the building element and its constituting materials. At its end of life a building element can either be demolished or deconstructed. Next, the obtained materials are either sorted on-site or off-site, meaning they are deposited in a mono or mixed stream container, respectively. Four end-of-life treatments are considered within this research: landfill, incineration with energy recovery (simply referred to as incineration further in this research), recycling and reuse. It is assumed that with demolition reuse of materials is not possible, but recycling is. When materials are sorted off-site it is expected that the materials are too contaminated for reuse.

2.4.2 Scenarios for the facade systems

In this paper, a transformation scenario refers to the set of transformations that can occur during the lifespan of a building element. Four characteristic transformation scenarios are considered for both facade systems: no transformations, (1) the increase of the insulation from U = 0.24 W/m²K to U = 0.15 W/m²K at year thirty, (2) updating the finishing layer at year forty and (3) both the increase of the insulation at year thirty and the updating of the finishing layer at year forty. A graphical representation of each life cycle with a characteristic transformation scenario set on a timeline is visible in **Figure 7**. The FU for each characteristic life cycle is stated in the figure.

Since ETICS is not circular, no adaptions can take place and for each transformation the existing system must be demolished and a new system constructed. The ventilated facade can be deconstructed and certain materials reused. To evaluate if materials can effectively be reused, either with a transformation or at the end-of-life of a building, it is necessary to look at their remaining lifespan: a component can only be reused if its remaining lifespan is larger than or equal to the fraction qt (time quotient) of its estimated lifespan (Galle 2016). In this research a time quotient of three is defined. For example, fiber cement has a lifespan of forty-five years. When a transformation happens at year thirty, its remaining lifespan is fifteen years. This is equal to one third of its initial lifespan (45/3 = 15) and fiber cement can be reused with this transformation. For the increase of the insulation, the ventilated facade is deconstructed up to the insulation layer, additional insulation is added and the facade reconstructed. It is assumed that the rain screen cannot be reused and also the distance screws are too short for reuse, both go to their 'business as usual' end-of-life treatment. When updating the finishing layer of the system, ETICS with plaster is replaced by ETICS with stone strips and the fiber cement cladding of the ventilated facade is switched out for wood cladding while the rest of the system remains untouched. Appendix A displays which new materials must be added with the transformation scenarios of both systems.

Figure 8 shows the possible end-of-life scenarios during the life cycle of a facade system. While the linearity of ETICS hinders certain end-of-life practices such as deconstruction, recycling and reuse, the ventilated facade can undergo all end-of-life scenarios due to its separable construction. It can be demolished or deconstructed and per constituting material each end-of-life treatment is feasible, based on what current practice allows. The end-of-life scenarios for ETICS are underlined in **Figure 8**. **Table 3** gives an overview of the feasible end-of-life treatments for each material of ETICS and the ventilated facade, including for both possible finishing layers (option a and b) of each system. Only current recycling possibilities are taken into account since future technologies cannot be modelled. Materials that are currently not reused (on a larger scale), but have a theoretical potential for reuse in the future are marked with a grey X. The current standard Belgian end-of-life treatments as defined by the Product Category Rules (NBN 2017), further referred to as 'business as usual end-of-life treatments', are underlined in **Table 3**. In section two of the **Supplementary Material** for each characteristic life cycle scenario of the facade systems a material timeline is displayed indicating the changes that happen with a transformation and the possible end-of-life treatments of the materials.

Linear building elements such as ETICS only have a limited amount of possible end-of-life scenarios which can be easily calculated. On the other hand, circular building elements such as the ventilated facade have a range of possible end-of-life scenarios which are time-consuming to model and analyze. For this LCA study, first the environmental impact of all possible end-of-life scenarios of the ventilated facade is calculated through programming in R. Based on the results, characteristic end-of-life scenarios are determined. Furthermore, it is analyzed if and how the results and conclusions change with and without the inclusion of module D.

3 Results

3.1.1 Graphical representation

The following paragraph gives a short explanation on which and how the results of the LCA study will be presented. First, the environmental impact considering all possible end-of-life scenarios of the facade systems is calculated. Based on this, it is analyzed if characteristic end-of-life scenarios can be deduced. The environmental impact is represented by a total score (modules A to C) which is displayed on an axis. ETICS only has one possible end-of-life scenario and per life cycle with a characteristic transformation scenario its environmental impact is represented by a single point on the axis. The ventilated facade has many possible end-of-life scenarios and for each life cycle with a characteristic transformation scenario its environmental impact is presented as a range.

After guidelines for the characteristic end-of-life scenarios have been determined, the environmental impact is calculated using only characteristic life cycles, i.e. combining characteristic transformation and end-of-life scenarios. For each characteristic life cycle scenario, the environmental impact is represented on a bar plot, showing the impact per module and the net impact. This allows to zoom in on the different circular principles and highlight the influence of module D on the results. It is analyzed if considering characteristic end-of-life scenarios gives the same degree of information as when all possible end-of-life scenarios were modelled.

3.1.2 Results modelling all end-of-life scenarios

The environmental impact of ETICS and the ventilated facade when all end-of-life scenarios are modelled is shown in **Figure 9** for modules A tot C added to a total score. The same calculations are performed with the inclusion of module D. These results are not displayed but will be discussed briefly.

Each result range of the ventilated facade exhibits a gap, which is marked by a grey dotted line. It is analyzed which scenarios correspond to the maximum and minimum of the result range and what the gaps are caused by. This is done by analyzing the results of the life cycle without transformations (NT) in detail and relating these conclusions to the life cycles with transformations.

The difference between the environmental impact of demolition and deconstruction is negligible (module C1), as is the difference between off and on-site sorting (module C3 or included in C4). It is the specific end-of-life treatment that is determining for the environmental impact of the end-of-life scenario. In **Figure 9**, the result range of each life cycle with a different transformation scenario is determined by the combinations of end-of-life treatments of the materials. The columns on module C in **Table 4** show the impact of the possible end-of-life treatments for the materials of the ventilated facade for the life cycle with no transformations. The worst end-of-life treatment of a material is underlined twice while its best treatment is underlined once. The maximum and minimum environmental impact of the ventilated facade for the life cycle with no transformations align with the combination of all the worst and best end-of-life treatments, respectively.

The gaps in the result range are related to the choice of end-of-life treatment for PIR, which is either incinerated or reused. **Table 4** (columns on module C) shows that the difference in environmental impact for PIR between reuse and incineration is significant. There are two clear zones in the result range relating to whether PIR is reused or not. The incineration of PIR has a higher environmental impact (module C = 0.28 mPt/m²) than when all other materials have their worst end-of-life treatment (module C = 0.17 mPt/m²). In other words: it is better to reuse PIR and have the worst end-of-life treatment of all other materials than to incinerate PIR and have the best end-of-life treatment of all other materials. In the life cycle with no transformations and with transformation scenario (2) there is no increase of the insulation and the gap in the result range is more narrow than with transformation scenario (1) and (3). The tables for the life cycles with transformation scenarios (1), (2) and (3) can be found in section three of the **Supplementary Material**.

If the same calculations are done with module D included in the total score, the choice of end-of-life treatment of PIR remains influential, i.e. creates a gap. However, for the life cycle with no transformations and for the life cycle with transformation (1) there are two additional gaps within the result range of the ventilated facade. These are due to the choice of end-of-life treatment of fiber cement. **Table 4** shows that fiber cement is either reused or landfilled and when module D is included the difference between these two options is significant. For the life cycles with transformation scenario (2) and (3) there is no gap relating to the end-of-life treatment of fiber cement. During the transformation relating to the finishing layer, the fiber cement cladding is replaced by wood cladding and is landfilled (reuse is not possible since the residual lifespan of the fiber cement is too low). The wood cladding has no influential end-of-life treatment and does not create a gap.

For the ventilated facade, the environmental impact of the end-of-life scenarios is most influenced by the choice of end-of-life treatment for PIR, also when module D is included in the total score. However, PIR is currently not systematically reused and the results in the zone 'reuse of PIR' in **Figure 9** are hypothetical future scenarios. For other building elements the combination of end-of-life treatments of certain materials may be determining instead of the end-of-life treatment of one material being dominant.

3.1.3 Guidelines for characteristic end-of-life scenarios

Figure 9 shows that per life cycle with a characteristic transformation scenario the environmental impact of a circular building element can be presented as a range. Based on the information derived from **Figure 9**, general guidelines are drawn up for defining characteristic end-of-life scenarios that determine this result range.

The authors recommend to draw up tables such as **Table 4**. This provides insight into the impact of the end-of-life treatment of the constituting materials and allows to easily make different combinations relating to different end-of-life scenario's. Within the recycling and reuse scenario there are still multiple options based on the replaced material or product. In order to keep the study comprehensible, it was chosen to consider only one recycling and reuse scenario, i.e. the most common (Belgian) recycling option and reuse in the same application. The modelling assumptions for recycling and reuse are mentioned in section one of the **Supplementary Material**.

A first important characteristic end-of-life scenario is a scenario on the (1) 'business as usual end-of-life treatment', showing the current state of affairs. If module D is not included in the total score this scenario will align with the maximum environmental impact. If module D is included this is not necessarily the case. **Table 4** shows that if module D is taken into account the business as usual end-of-life treatment of wood, i.e. incineration, has a better environmental impact than recycling (wood is downcycled into wood chips for particle boards which gives a limited environmental benefit compared to the energy recovery with the incineration of wood). A second important characteristic end-of-life scenario is a scenario on (2) 'maximal reuse'. This means all materials with the potential for reuse are reused and the best end-of-life treatment is considered for the other materials. This scenario corresponds to the minimum environmental impact.

Characteristic end-of-life scenarios should indicate the difference between current possibilities and future potential. The (2) 'maximal reuse' scenario relates to all materials with potential for reuse. A scenario taking into account only (3) the materials that are currently reused must be defined. Additionally, a scenario indicating (4) current recycling possibilities must be modelled. Determining a scenario relating to future recycling is more difficult since it requires making a prediction about future technologies. A possible approach could be to increase the recycling rate and change the energy mix to a more sustainable alternative. This is out of scope for this research.

Depending on the building element, the choice of end-of-life treatment for one material or the combination of end-of-life treatments of various materials has a significant influence on the results. Therefore, defining general guidelines for characteristic scenarios relating to materials with an influential end-of-life treatment is complex. **Table 4** shows for which materials the difference in end-of-life treatment is significant (i.e. materials that have the potential for recycling or reuse and for landfill or incineration) and if their end-of-life treatment has a significant impact compared to that of the other materials. After plotting the environmental impact of a circular building element considering the four mentioned characteristic end-of-life scenarios, it can be decided if it is necessary or relevant to add (5) characteristic end-of-life scenarios indicating materials for which the choice in end-of-life treatment is influential. This will be a balance between the level of detail required and the available time and effort for calculations.

3.1.4 Results based on characteristic life cycle scenarios

While for **Figure 9** all possible end-of-life scenarios were modelled, for **Figure 10** the environmental impact of both facade systems is determined using characteristic life cycles, i.e. combining characteristic transformation and end-of-life scenarios. **Figure 10** shows the impact per module for each characteristic life cycle of ETICS and the ventilated facade. The figure provides information on three levels. First, it shows the influence of transformation scenarios (multi-cycling) on the environmental impact of a building element. Next, for a life cycle with a characteristic transformation scenario it shows how the choice of end-of-life scenario impacts the result. Finally, it allows to compare building elements and choose the solution with the lowest environmental impact based on the expected transformation scenario. Only the life cycle scenarios with the same characteristic transformation scenario have the same functional unit.

The following five characteristic end-of-life scenarios are considered (the numbers align with the numbers of the guidelines in 3.1.3): (1) 'Bau': business as usual end-of-life treatment for each material; (4) 'Rec': maximal recycling of all materials, materials that cannot be recycled are incinerated or landfilled; (3) 'Reu': reuse of materials that can currently be reused; (5) 'Reu\PIR': reuse of all materials that have potential for reuse apart from PIR; (2) 'MReu': maximal reuse of materials with potential for reuse. Scenario (2) 'MReu' and (5) 'Reu\PIR' are hypothetical future scenarios.

The following paragraphs focus on whether using characteristic life cycle scenarios provides sufficient information to answer the question: in which situations does the circular building element have a lower environmental impact than the linear solution? Is this dependent on the specific end-of-life scenario or on the fact that transformations takes place?

The initial impact of the ventilated facade is significantly higher than that of ETICS. This initial impact can be countered by transformations taking place over the life cycle. Each transformation more than doubles the environmental impact of ETICS; the existing system must be demolished and a new system with additional insulation and/or a new finishing constructed. The impact of the transformation on the ventilated facade is smaller since a majority of the materials can be reused. The specific end-of-life scenario also plays a role but is less determining; when no transformations take place the ventilated facade cannot have a lower impact even though it has the best end-of-life scenario. Without module D the difference between the different end-of-life scenarios is very limited. Only with scenario (2) 'maximal reuse' there is a visible difference. By also displaying the net impact it becomes obvious that for certain end-of-life scenarios module D significantly influences the result. The end-of-life scenarios relating to reuse clearly benefit from the inclusion of module D. This is because the largest benefit is related to the avoided primary production and not the avoided waste processing.

How the environmental impact of ETICS and the ventilated facade relate to each other depends on the transformation scenario, the end-of-life scenario and whether module D is included. **Table 5** provides an overview of these results. In certain cases the difference in environmental impact between ETICS and the ventilated facade is limited. Since there is always some uncertainty on the input data for the calculations the difference must be significant to make fixed conclusions.

4 Discussion

4.1.1 Module B5 and module D

Although the methodological concept of module D is not 100% accurate, it is perceived as an important module to stimulate recycling and reuse at the end of life. In general, module D can provide insight in the future reuse potential (and thus "circularity potential") of virgin products, but module D is difficult to interpret and even misleading for reuse products (Douguet et al. 2022). By considering multiple use cycles under the form of transformations in module B5, reuse during the lifespan of a building element can be taken into account. It seems feasible to define well-thought-out transformation scenarios for building elements. For example, it is known that every few years offices require a new lay-out because of changing tenants or it is expected that certain building elements will require additional insulation because energy regulations will become more strict. It could be argued that there is more uncertainty about reuse taking place in a different building at the end of the study period (considered in module D) than reuse during the study period within the same building (considered in module B5). Furthermore, what is the certainty that an element that has already been reused during the study period will be reused again at the end-of-life? Therefore, the authors question if for a building element with multiple use cycles module D should get the same value as module B5 in a building LCA study.

Whether conclusions must be based on the results with or without module D has no straight answer. Representing the results as in **Figure 10**, which shows the impact per module and the net impact provides a lot of information on the influence of both modules B5 and D. The standards EN 15804/15978 could be improved by clarifying how the difference between open-loop and closed-loop recycling should be dealt with in module D. Additionally, the concept and use of module B5 Refurbishment should also be further elaborated.

4.1.2 Characteristic transformation and end-of-life scenarios

It is not possible to predict what will happen over the long lifespan of a building element and assuming that all materials will be reused just because the building element is designed in a circular way is not realistic. The aim of the research on characteristic end-of-life scenarios is to obtain a more robust and detailed understanding in the possible environmental impact of a building element by modelling only a limited amount of scenarios. Modelling all possible end-of-life scenarios (as done in **Figure 9**) shows the gaps in the result range of the environmental impact. This adds some information on top of the characteristic end-of-life scenarios but it requires more modelling effort and is not necessarily relevant. The characteristic transformation and end-of-life scenarios provide a more practical understanding in which scenarios need to take place (and which systems need to be in place) for the circular building element to have a lower environmental impact than the linear element.

The research question how many transformations should take place before the circular solution has a lower environmental impact than the linear one was already partly answered in this paper; from the moment two transformations take place the ventilated facade has a lower environmental impact than ETICS. However, other building elements, such as an internal wall in an office building, probably will have more potential for a large amount of transformations.

When an LCA practitioner provides the environmental impact in the context of multiple characteristic life cycle scenarios it can be a driver for the 'owner/user' of the building element to make certain decisions at the beginning of the lifespan (which building element seems the most logical choice in the context of the building, taking into account anticipated scenarios), during the lifespan (which transformations can take place and how should they take place) and at the end of the lifespan (which materials should go to which end-of-life treatment). In addition, it can be an incentive for a manufacturer or architect to design the product or element in such a way that it facilitates certain scenarios.

5 Conclusion

The goal of this research was to research how an LCA study should be set up that can determine the environmental impact of a circular versus a linear building element within the methodological framework of EN 15804/15978. To take into account the concept of 'multi-cycling' the authors propose to consider multiple transformations (use cycles) within one life cycle instead of considering several life cycles where the impact of the reused component must be allocated. Recycling and reuse at the end-of-life are mainly stimulated by module D. However, the concept of module D must be handled with the necessary care to provide correct information.

An LCA study is executed for ETICS, a linear solution, and a ventilated facade, a circular solution. Within this research an essential question is: in which situations does the circular building element have a lower environmental impact than the linear element? Is this dependent on the specific end-of-life scenario or on the fact that transformations take place? To answer this question it is necessary to model characteristic life cycles by combining well-defined characteristic transformation and end-of-life scenarios.

Based on the type of building element and building typology a number of characteristic transformation scenarios are determined. Characteristic end-of-life scenarios must indicate the difference between current possibilities and future potential. Following characteristic end-of-life scenarios are defined (1) 'business as usual end-of-life treatment' as the current state of affairs, (2) 'maximal reuse' as the minimum environmental impact, a (3) scenario on current reuse and a (4) scenario on current recycling. When necessary and relevant characteristic scenarios (5) indicating materials for which the choice of end-of-life treatment is influential are to be added.

The application of characteristic life cycle scenarios on the case study of the two facade systems shows that while each considered transformation more than doubles the environmental impact of ETICS, the impact of the transformations on the ventilated facade is smaller since a majority of the materials can be reused. The specific end-of-life scenario is less determining for the environmental impact; when no transformations take place the ventilated facade cannot have a lower impact even though it has the best end-of-life scenario. Without module D the difference between the different end-of-life scenarios is very limited. The inclusion of module D mostly favors the reuse scenarios.

The standards EN 15804/15978 are well established within the building sector. Developing LCA studies within their methodological framework that can account for important circular principles and consider characteristic life cycle scenarios are important first steps to determine the environmental impact of circular versus linear building elements in a more robust way. In future research, the influential parameters such as the transformation frequency, the study period and lifespan of the materials must be considered variable instead of fixed to fully grasp the dynamism and complexity of a building element.

Supplementary information The online version contains supplementary material available at…

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Data availability statement The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

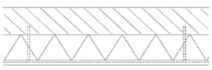
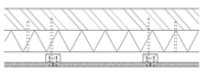
Conflict of interest The authors have no competing interests to declare.

Appendix A

Table A.1 *Information on the material layers of the facade systems.*

T= transformation scenario; indicates materials that are added with a transformation.

T1/T3a = increase of insulation; T2 = update finishing layer; T3b = update finishing layer after T3a

		Original		**T1/T3a**	**T2**	**T3b**	
	Material	**t (cm)**	**w (kg/m²)**	**t (cm)**	**t (cm)**	**t (cm)**	**Lifespan (years)**
ETICS	Mortar	-	3	-	-	-	60
	Plugs	19	0.08	28	19	28	60
	EPS	15	2.25	24	15	24	60
	Base plaster	1	7	1	1	1	60
	Glass fiber	-	0.21	-	-	-	60
	Cover plaster	1	3	1			30
	Mortar				-	-	60
	Stone strips				2	2	60
Ventilated	Plugs	14	0.06	21			60
	PIR	10	3.40	7			90
	Rain screen	-	0.21	-			60
	Distance screws	20	0.49	27			100
	Wooden battens	4	3.30				90

Fiber cement cladding	1	12				45
Wood cladding				1.8	1.8	40
Screws cladding	-	0.11				100

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Tables

Table 1 *Important circular principles throughout the life cycle of a building element*

	Circular principle
Beginning	Differentiate between new and secondary material
	Account for increase of the recycled content
During	Take multiple use/life cycles into account
	Stimulate long use/lifespan of materials
End	Stimulate recycling and reuse
	Differentiate between open-loop and closed-loop recycling

Table 2 *Overview of how circular principles relate to different modules of the life cycle of a building element*

	Circular principle	Module where principle is visible
Beginning	Differentiate between new and secondary material	Module A
	Account for increase of the recycled content	Module A
During	Take multiple cycles into account	Module B5: multiple use cycles under the form of transformations
	Stimulate long use/lifespan of materials	Fewer replacements: module B4 Lifespan exceeding study period: can be taken into account in module D but study period remains important parameter
End	Stimulate recycling and reuse	Partly apparent in module C but largest stimulus through module D
	Differentiate between open-loop and closed-loop recycling	Module D seems to favor open-loop over closed-loop recycling.

Table 3 *Possible EOL treatments for each material of the facade systems (the current standard Belgian EOL treatments are underlined (= business as usual scenario); grey X = potential for future reuse)*

	Material	**Landfill**	**Incineration**	**Recycling**	**Reuse**
ETICS	Mortar, plugs, EPS		X		
	a) Plaster, glass fiber		X		
	b) Plaster, glass fiber, mortar, stone strips	X			
Ventilated facade	Plugs		X	X	
	PIR		X		X
	Rain screen		X		
	Distance screws			X	X
	Wooden battens		X	X	X
	a) Fiber cement cladding	X			X
	b) Wood cladding		X	X	X
	Screws cladding			X	X

Table 4 *Impact of modules C and D for the EOL treatments of the materials of the ventilated facade for the life cycle with no transformations (NT). Worst EOL treatment is underlined twice, best EOL treatment is underlined once. Materials for which the choice of end-of-life treatment is influential are highlighted in grey*

Material	**Environmental impact (mPt/m²) modules C and D**							
	Landfill		***Incineration***		***Recycling***		***Reuse***	
	C	D	**C**	D	**C**	D	**C**	D
Plugs	NA		**0.01**	0.00	**0.00**	-0.01	NA	
PIR	NA		**0.28**	-0.16	NA		**0.03**	-2.81
Rain screen	NA		**0.01**	-0.01	NA		NA	
Distance screws	NA		NA		**0.00**	-0.05	**0.00**	-0.11
Wooden battens	NA		**0.13**	-0.07	**0.11**	-0.02	**0.11**	-0.16
Fiber cement cladding	**0.02**	0.00	NA		NA		**0.00**	-1.07
Screws cladding	NA		NA		**0.00**	-0.01	**0.00**	-0.03

Total impact modules A1-5: 4.89 mPt/m²

Total impact modules B2, B4 and B5: 1.29 mPt/m²

Table 5 *Comparison environmental impact ETICS and ventilated facade based on the transformation scenario, the EOL scenario and inclusion of module D*

	With module D	**Without module D**
No transf.	Ventilated facade has a higher impact independent from the EOL scenario	Ventilated facade has a higher impact independent from the EOL scenario
Transf. (1)	Ventilated facade can only have a lower impact in future scenarios	Ventilated facade has a higher impact independent from the EOL scenario
Transf. (2)	Ventilated facade can have a lower impact based on current EOL possibilities	Ventilated facade can only have a lower impact in future scenarios
Transf. (3)	Ventilated facade can have a lower impact based on current EOL possibilities	Ventilated facade has a lower impact based on current EOL possibilities (the business as usual scenario is already sufficient)

Figures + Figure captions

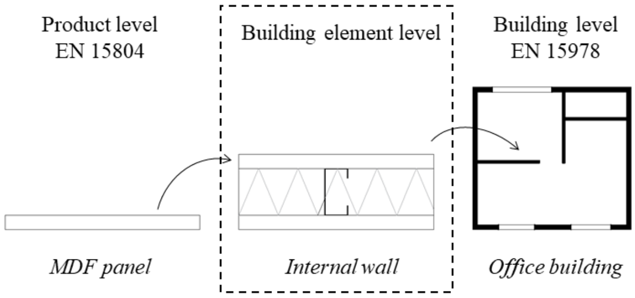

Fig. 1 *Relationship between product, building element and building level. The scope of this paper is on building element level*

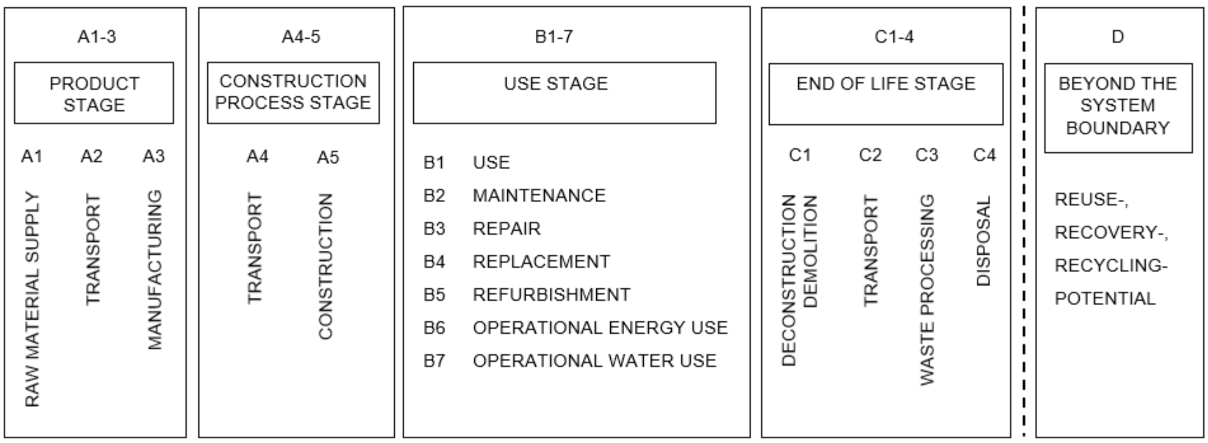

Fig. 2 *Modules of the life cycle of a building element according to EN 15804*

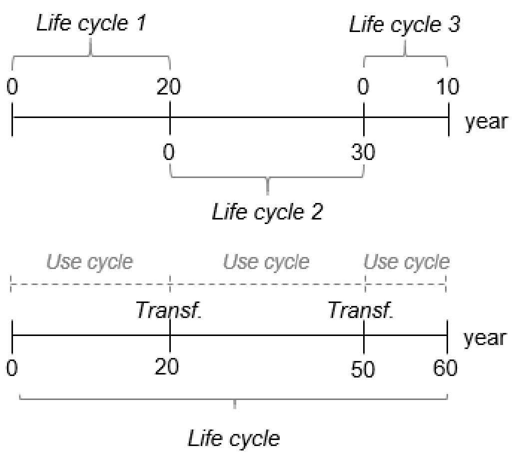

Fig. 3 *Taking into account multi-cycling in LCA. Above: by considering different life cycles (existing research). Below: by considering transformations (i.e. use cycles) during one life cycle (this research)*

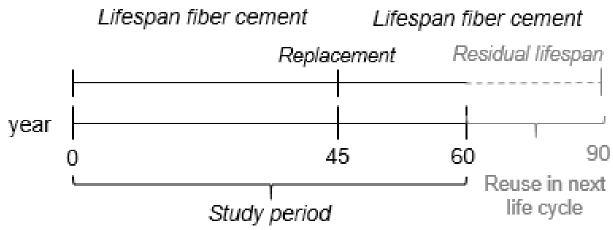

Fig. 4 *Taking into account the residual lifespan with the example of fiber cement*

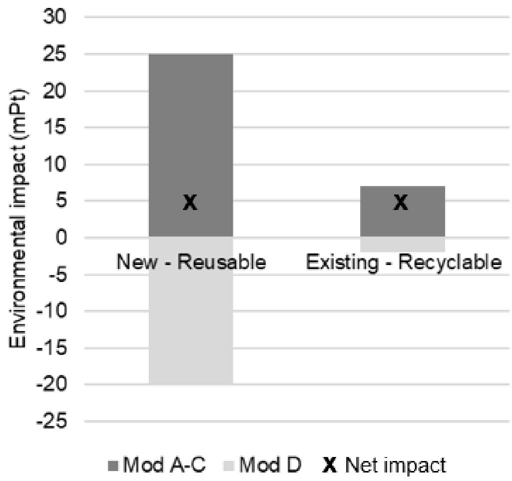

Fig. 5 *Influence of module D on the net environmental impact*

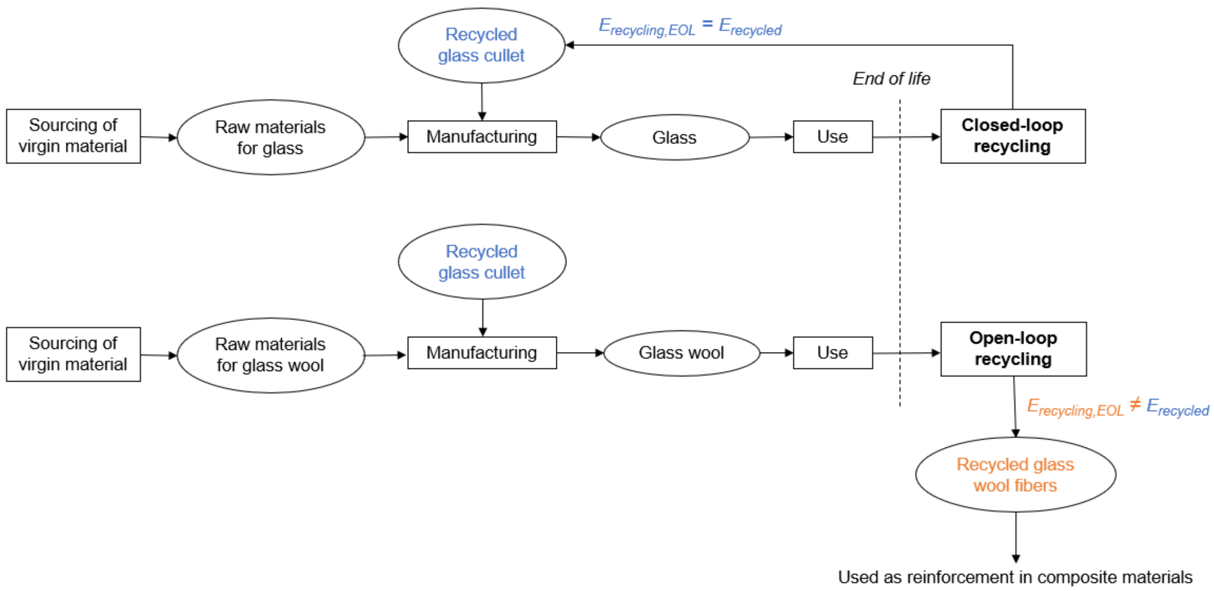

Fig. 6 *Concept of closed-loop and open-loop recycling with the example of glass cullet*

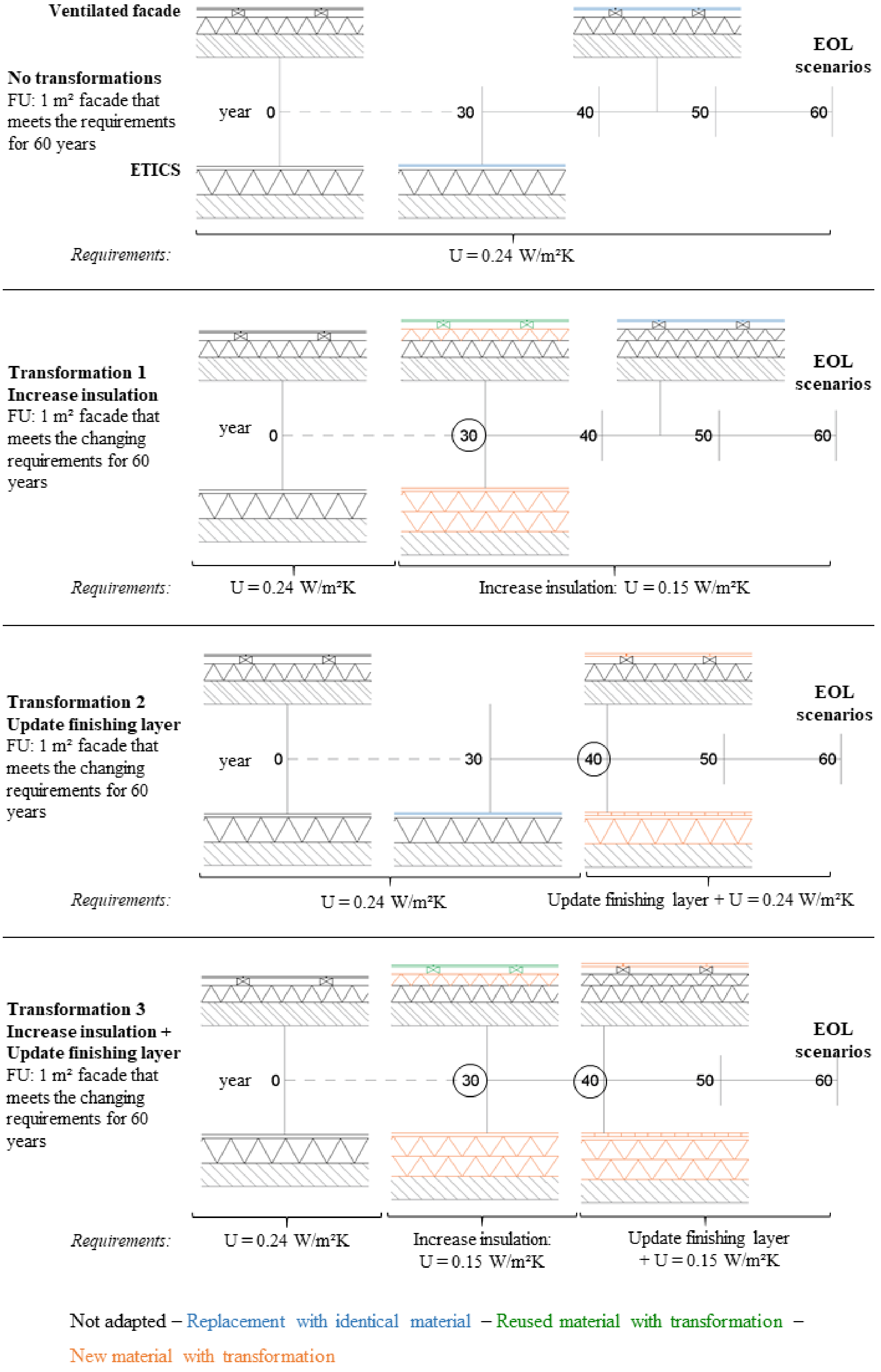

***Fig.** 7 Graphical timeline of the different life cycles with a characteristic transformation scenario*

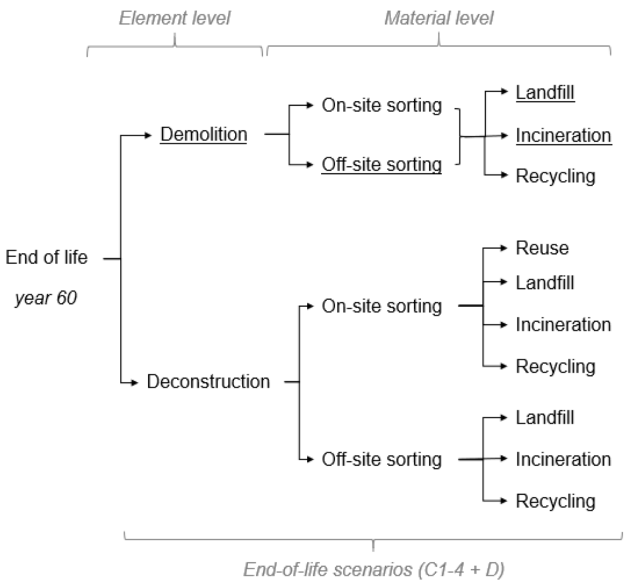

Fig. 8 *Possible EOL scenarios of a facade system (EOL scenarios for ETICS are underlined)*

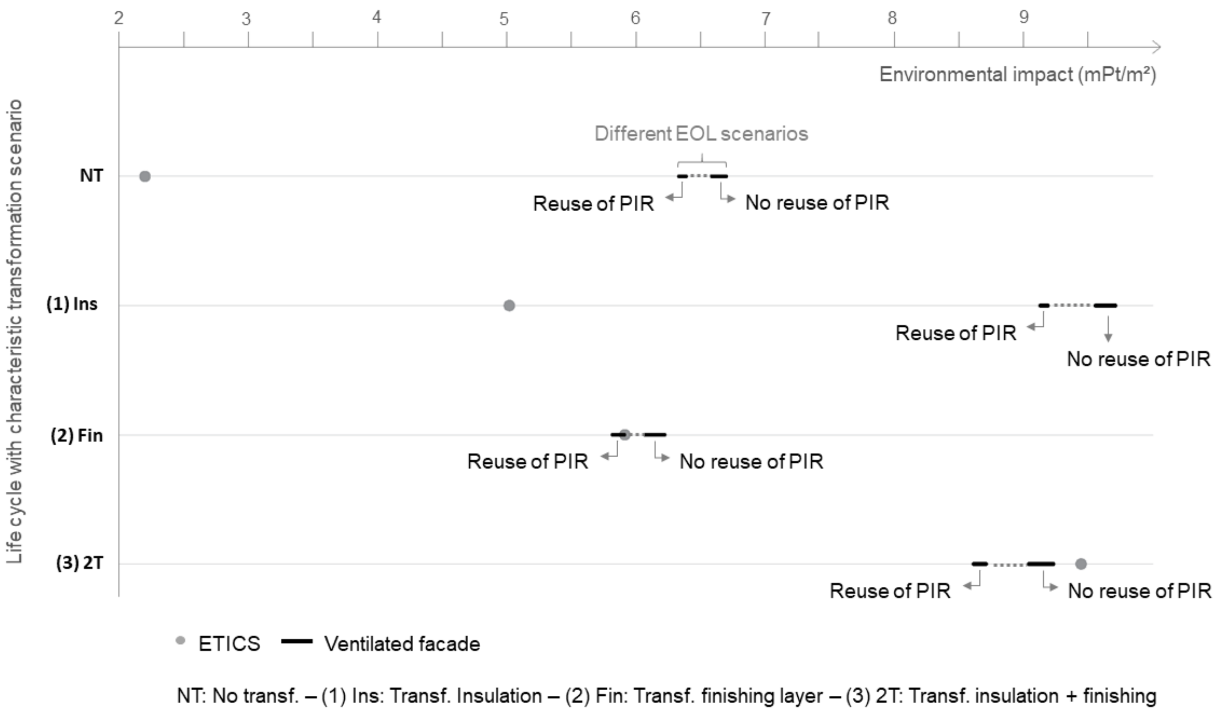

Fig. 9 *Environmental impact of the ventilated facade and ETICS for different transformation and all EOL scenarios (modules A to C are added to a total score). Grey dotted lines represent the gaps in the result range*

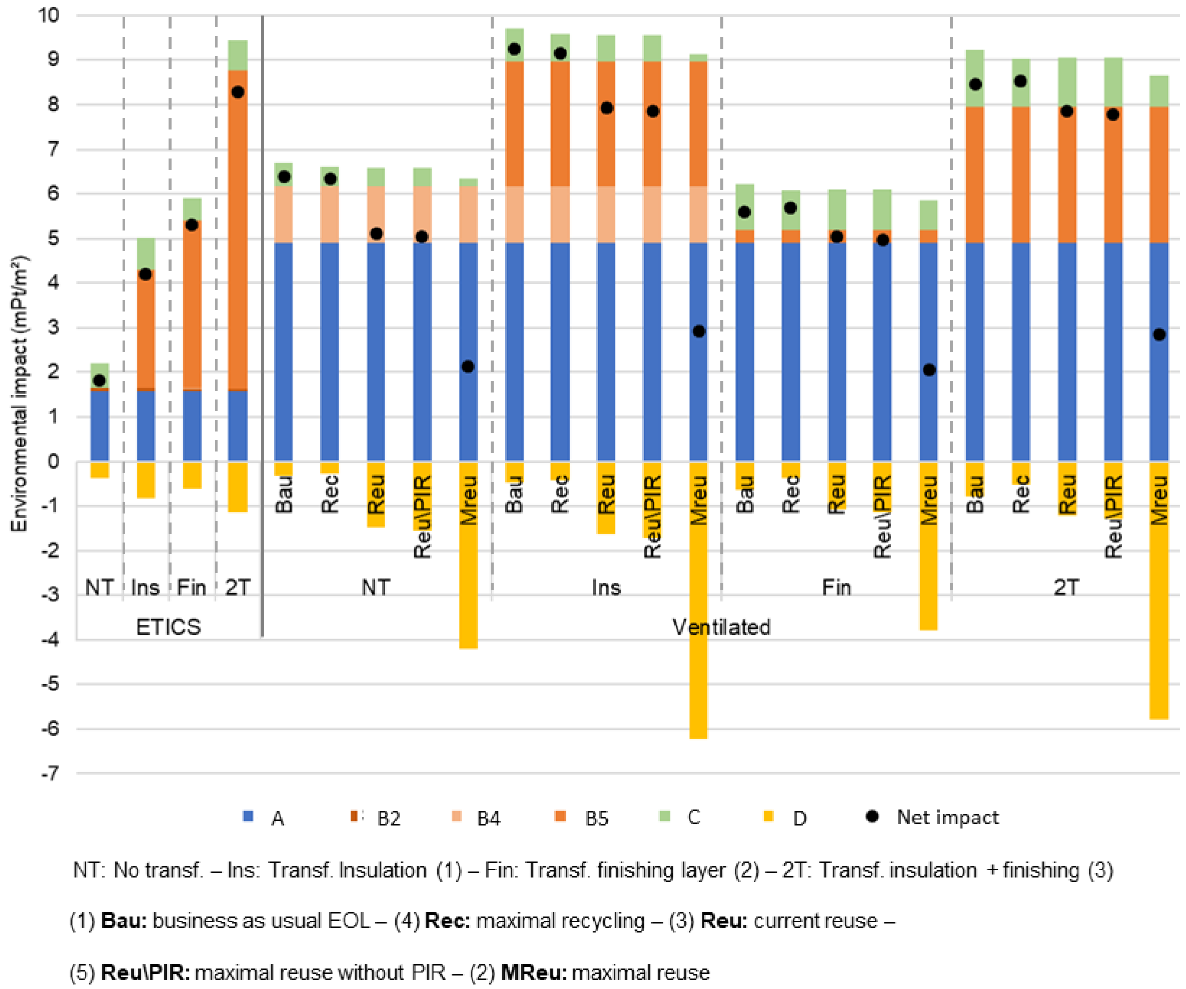

***Fig. 10** Environmental impact of ETICS and ventilated facade represented by characteristic life cycles. The impact of each module and the net impact is displayed*