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Abstract. With a growing building stock and initiatives such as the European "renovation wave" which aims to double the annual energy renovation rates in the next ten years, environmental assessment of building refurbishment becomes still more important. Using standardized environmental assessment methods such as life cycle assessment (LCA) on renovation projects is important to keep impacts low, and avoid burden shifting. However, a specific methodological challenge in refurbishment projects is how to include the existing building materials in the assessment. The aim of this study is therefore to present and characterise different existing allocation approaches for LCA in refurbishments. Furthermore, the study highlights advantages and disadvantages of the analysed approaches from an LCA practitioner's view. A literature review was conducted to find studies that illustrate the different allocation approaches and modelling of the existing materials in refurbishment projects. The approaches characterised in the study include allocation using 50:50, avoided burden, product environmental footprint (PEF), burden-free (and semi-burden-free), residual value or depreciation, and adjusting for past production of existing materials. The implications for LCA-practitioners were evaluated based on the work burden required for application. Here, the main cons relate to the large workload connected to modelling the existing building.

Keywords: building, refurbishment, life cycle assessment, allocation, renovation

1. Introduction

Refurbishment projects play an important role in the fulfillment of climate targets. In the EU, 85-95 % of the building stock will still be standing in 2050 [1] and many of these buildings need upgrades due to e.g. bad energy performance or inefficient use. For refurbishment projects as well as new construction, it is important to consider the environmental impact of materials along with energy use to avoid shifting environmental burdens from operational energy to building materials. A method for determining the resource use and environmental impacts from refurbishment is the common and standardized method; life cycle assessment (LCA). In LCA, environmental impact potentials from both materials and operational energy use are included across the building life cycle. In this paper, we focus on impacts embodied in building materials.

A specific methodological challenge in refurbishment projects, however, is how to include the *existing* building materials in the assessment. This includes the question *if* the existing building materials should be included at all, and if so, *how much* of the existing building materials should be included, and finally *how* exactly it should be accounted for. The European standard EN 15978 [2] defines refurbishments as a part of the use stage in the life cycle of buildings. Further, in refurbishment projects without a previous LCA, the standard allocates refurbishment impacts to the initial product stage, dividing the building life cycle into two life cycles: one before refurbishment and a new one after refurbishment, as illustrated in **Figure 1**. This raises the question of how to allocate material impacts between the two consecutive life cycles. Methodological choices for the second life cycle are key, because they provide the foundation for deciding if the building should be demolished and replaced by a new one, or which interventions should be made in the refurbishment.

Previous literature reviews on refurbishment-LCA exist [3–5] but lack a focus on allocation approaches and modelling used for the existing building materials. The aim of this study is therefore to present and characterise different existing allocation approaches for LCA in refurbishments. Furthermore, the study highlights advantages and disadvantages of the analysed approaches from an LCA practitioner's view.

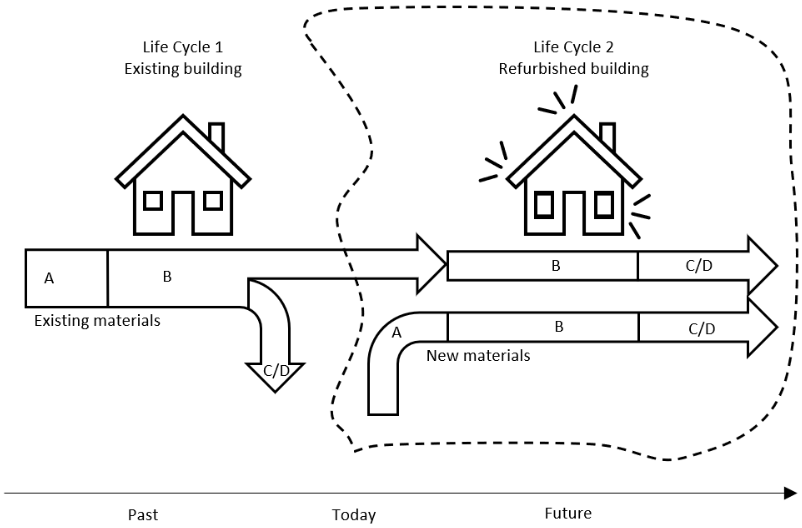

Figure 1. System boundaries for refurbishment (life cycle 2) can vary, and are relevant in terms of work load, building design, and benchmarking. The letters refer to the life cycle stages of a building defined in EN 15978 [2]: product and construction process (A), Use (B) end-of-life (C), and benefits and loads beyond the system boundary (D).

2. Method

A literature study was conducted to find studies that use and describe the allocation approach and modelling used for refurbishment. The goal was not to quantify how common the approaches are, but to identify studies that can illustrate the range of different allocation approaches and modelling of the existing materials in refurbishment projects. Literature was found using the following search string in Scopus: building AND renovation OR refurbishment OR retrofit AND "life-cycle assessment" OR lca OR "life cycle assessment" OR "ghg". The snowball approach was used to find additional relevant papers. Other papers known to the authors to be of relevance were included. This paper focusses on the two life cycles (before and after refurbishment).

The practical implications for LCA-practitioners were evaluated for each approach identified in literature. The evaluation includes considerations on work burden in relation to data collection and specific competences needed that may not be typical for an LCA-practitioner in the building industry who do not have environmental expert knowledge.

3. Results and discussion

In **Table 1** the different approaches are listed along with examples of literature using them. The first approaches are directly related to the allocation between the two life cycles, while the last approach relates to the modelling approach. The approaches are described in sections 3.1. to 3.4. Pros and cons from an LCA-practitioners point of view qualitatively estimated based on the authors expertise in the field are listed in the table and discussed in section 3.6.

Table 1. Allocation and modelling approaches for existing materials in refurbishment projects and evaluated pros and cons for the LCA-practitioner in relation to the methods.

Approaches	**Examples of approaches in literature**	**LCA-practitioner** + **Pros** − **Cons**
Allocation using 50:50, avoided burden, PEF	Obrecht et al. [6]	+ Shows the value of existing materials − Additional workload in mapping data from the existing building, and performing the allocation approach
Burden-free (and semi-burden-free)	Wijnants et al. [7] Hasik et al. [8] Rasmussen and Birgisdottir [9] Zimmermann et al. [10]	+ If end-of-life (EoL) of existing materials is included, it shows *all* impacts that happen from today and onwards + Correlates with CEN-standards, thus easier to implement in e.g. regulation + Less workload when EoL of existing materials is not included − Additional workload when EoL of existing materials is included − Challenges in biogenic accounting for global warming potential
Residual value or Depreciation	Wijnants et al. [7] Rasmussen and Birgisdottir [9] Obrecht et al. [11]	+ Shows the value of existing materials − Requires service life evaluation − Additional workload in mapping data from existing building
Adjusting for past production of existing materials	Bin and Parker [12] Potrč Obrecht et al [13]	− Requires advanced knowledge about previous production − Additional workload in mapping data from existing building and gathering historical data

3.1. Allocation using 50:50, avoided burden and PEF

As described in the introduction and illustrated in **Figure 1**, refurbishments can be considered a new building life cycle. However, this requires allocation between the impacts from the two consecutive life cycles if we want to assess the life cycles separately. Approaches for allocation from reuse and recycling of building materials have been investigated previously in literature [14–16], focusing mainly on product level. The common conclusion is that allocation approaches are not objective, and all have advantages and disadvantages. Allocation approaches deal with the distribution of impacts from production and EoL stage of reused and recycled materials [14]. The use stage is not included; thus, the service life of building products is not a part of these allocation approaches. Building products typically have the largest impact during production [17], making the allocation of the product stage the most influential impact to allocate [14–16].

Three commonly used allocation approaches are: 1) the 50:50 approach in which burdens from reuse/recycling are allocated equally between the first and second cycle in which the material is used, 2) the avoided burden approach in which burdens from reuse/recycling are allocated to the cycle reusing/recycling the material, and 3) the circular footprint formula (CFF) approach from the product environmental footprint (PEF) in which a factor-based distribution reflecting supply and demand between systems is applied. The application of the different approaches have shown to yield significantly different results[14–16].

These allocation approaches have been used to consider the reuse and recycling of materials, specifically in terms of design for disassembly, and other reuse in the future. However, Obrecht et al. [11] have recently considered them in the light of refurbished building components, where some materials are preserved in the refurbishment. The different allocation approaches for the reused or recycled content showed a significant difference in results in the second life cycle. The study also argues that the allocation approach should be chosen based on the goal and scope of the project, as they promote different incentives for decision-making. Some buildings may also undergo several refurbishments, influencing the allocation approach, and the results of the study. The allocation of a component between life cycles can be seen in **Figure 2**.

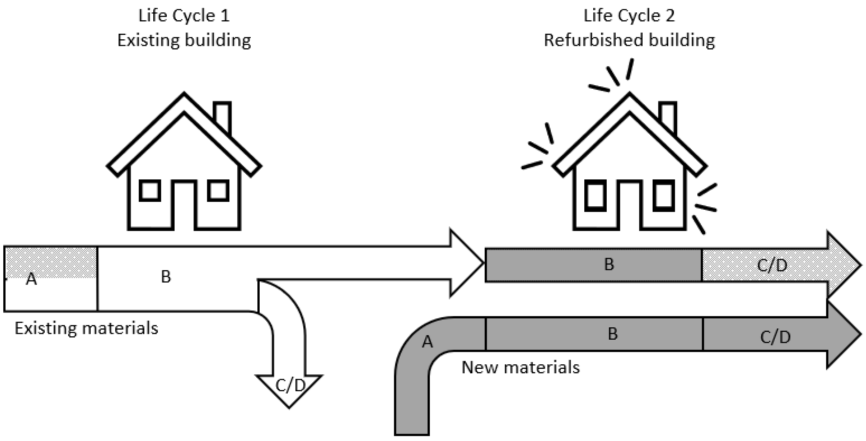

Figure 2. Existing materials that are reused or recycled and re-installed in the building, can be allocated between the first and second life cycle (light grey) using different methods. New materials and the use stage (B) of reused materials are in principle always included in life cycle 2 (dark grey).

3.2. *Burden-free (and semi-burden-free) approach*

The burden-free approach follows some of the principles given in the European standard EN 15804 [18]. Some variation in the method exists, but a common denominator is that the production of the existing material is always allocated to the first life cycle. As mentioned, allocation of reuse and recycling between life cycles can be done for production and end-of-life (EoL), but not for the use-stage, as this belongs to the life cycles where they occur [14]. Thus the use stage in the second life cycle (stage B) has to be accounted for even in a burden-free scenario [8]. However, this is not always done as it entails additional work by the LCA-practitioner, e.g., due to replacements of the reused materials which requires the estimation of quantities and impacts associated with the products. The use stage for existing materials is for instance not included in the case study by Rasmussen and Birgisdottir [9]. Hasik et al. [8] included the use stage in their case study as the only impacts from existing materials. Here the preserved elements were mainly structural, thus the impacts from the use stage (though not shown explicitly) are likely minimal.

Wijnants et al. [7] included both a scenario with EoL from the first life cycle and a scenario only with impacts from new materials. They found that environmental and financial impact of EoL from the existing materials were insignificant, accounting for 2% for refurbishment, and 3.5% for demolition with new construction. In Zimmermann et al. [10] all grey and hatched stages illustrated in Figure 3 have been included. EoL in the refurbishment scenario was insignificant, however, for the demolition and new construction scenario, it accounted for 12% of climate impact.

Which stages from the standard (A-D) the impacts belong to can also be discussed: For instance, EoL of materials that are not kept in the building are illustrated as C/D of the life cycle 1, but can also be considered as part of the refurbishment process, which belongs to stage A in the refurbished project (life cycle 2).

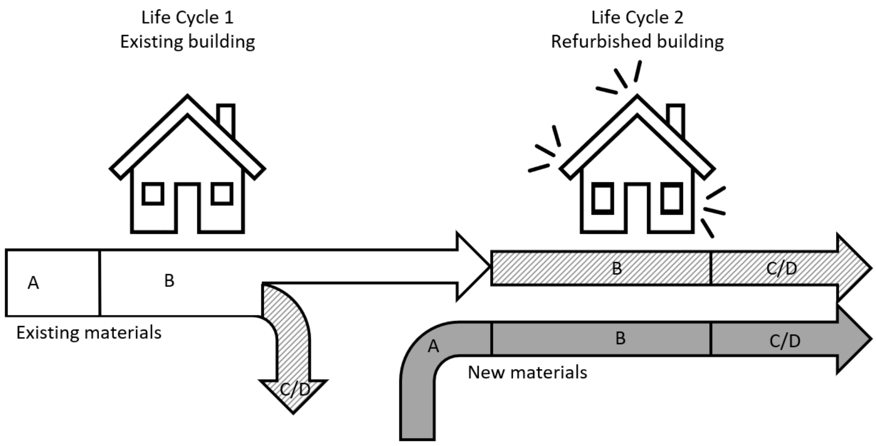

Figure 3. Burden-free approaches sometimes still include impacts from the existing structure. The hatched stages are occasionally included in burden-free approaches.

3.3. Residual value or depreciation

Residual value, also called the depreciation approach [7], can be used for allocation between the first and second life cycles. Residual value means the unamortized value of a product at a specific time – for instance at the time of refurbishment. In the context of LCA, it refers to the impact from production and EoL, which is ratioed between the remaining life span and predicted life span, also called reference service life, RSL. The method for determining residual values is the depreciation of impacts over time. This is commonly achieved by linear distribution.

Either all materials with residual value can be allocated to the second life cycle, or only the residual value from materials, that are reused in the building, see Figure 4. Rasmussen and Birgisdottir [9] used the latter approach to determine the environmental impacts of a refurbishment project (energy retrofit). Impacts were equally distributed across the RSL of the products and remaining unamortized impacts at the time of refurbishment are allocated to the second life cycle. This allocation resulted in larger impacts from the refurbishment than the traditional “burden-free” approach, however, greenhouse gas emissions were still well below those of new construction. A similar allocation approach was used by Wijnants et al. [7]. Here different refurbishment scenarios are compared, along with demolition and new construction scenario, and a scenario where nothing is done to the building. With the depreciation approach, the authors note that in their case study, the environmental cost of the existing components is only a minor part of the costs in the second life cycle. However, it still makes up more than 20% of the demolition and new construction scenario. Results also show that allocation with depreciation and the “burden-free” approach provided the same conclusions as to which scenario performed best. This could be because the residual value is the same in all scenarios. But the lifespan of the second building life cycle has a significant influence on the results, because of the balance between materials and energy impacts.

Obrecht et al. [11] consider the residual value *after* allocation between the two life cycles, as a way to consider the value of the element years into the first and second life cycle, and how different allocations approaches and time of refurbishment result in variation in this value.

Determining the residual value of elements that are reused or recycled within the refurbishment requires a time-consuming evaluation. Another important aspect pointed out by Obrecht et al. [11] is the significance of the RSL when determining the residual value of products. These values can vary greatly between RSL databases and have a significant influence on the results; thus, sensitivity analyses are often included in the assessments.

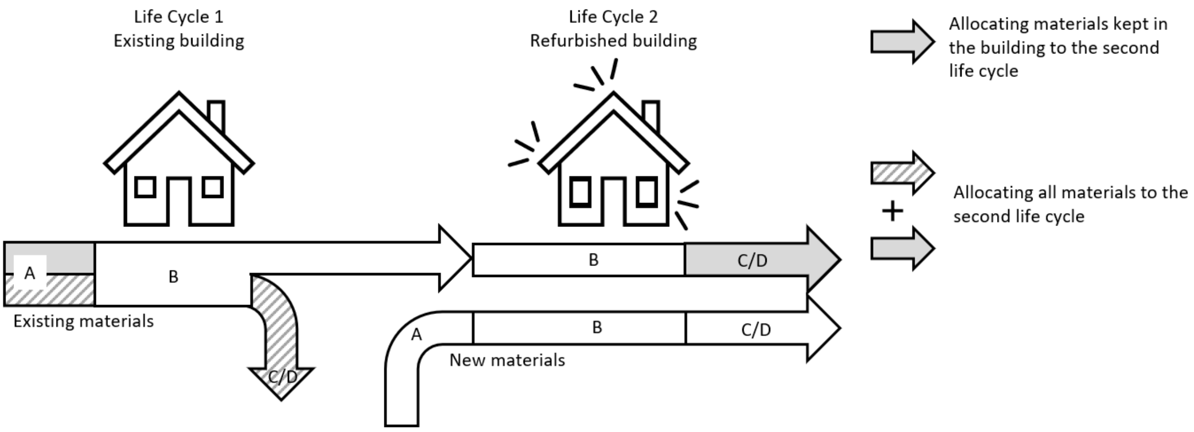

Figure 4. Allocation approaches in refurbishment can include only the reused materials (light grey), or all materials, that have residual value at refurbishment (both gray and hatched).

3.4. Adjusting for past production of existing materials

Impacts from material production were different in the past due to differences in manufacturing processes, transportation, and energy production. This can be accounted for in a refurbishment-LCA and links closely to the principles of dynamic LCA, where temporal inconsistencies are accounted for. While a dynamic approach to LCA is used for anticipating future changes, it may also be used for considering past impacts in refurbishment-LCA.

Bin and Parker [19] have estimated an existing building's impacts from the production one century ago, applying data from architectural historians, current manufacturers, and literature for determining energy and carbon emissions embodied in the materials. They conclude that impacts from the existing building are similar or lower than producing the materials today. However, Bin and Parker found that initial impacts were not as low as one might expect. This was due to the energy extensive brick production.

Potrč Obrecht et al. [20] assume that production processes have remained the same for materials. However, they have modified the electricity mix in current datasets, and adjusted the efficiency of electricity use. This was tested on materials in a case building from 1970 in Slovenia. The past electricity mix was remodeled based on the national mix at the time of construction, and there was assumed a 0.5% production efficiency increase per year. Results show a higher impact from the previous production of between 8.3% and 14.7% for the building components in the case building. Potrč Obrecht et al. highlight the importance of considering the electricity mix in all subprocesses to get a realistic result.

The two studies showed a higher and lower impact from adjusting for the previous production. It can be concluded that adjusting for past production may influence the results, though it may not be significant. Concerning implementation for an LCA-practitioner, these dynamic approaches will result in a high work load as data and tools to perform dynamic LCA is lacking.

3.5. Method considerations in studies

3.5.1. Suggested methods. Obrecht et al. [11], Hasik et al. [8] and Zimmermann et al. [10] all recommend and test different methods for refurbishment-LCA in their studies: Obrecht et al. [11] suggest a new methodology for calculating environmental impact and the residual value of refurbishment measures, to correctly assess components that are reused or recycled after refurbishment. Thus, they suggest including impacts from the existing building in the refurbishment projects, using allocation principles, and to consider the residual value of materials. They argue that by excluding the first life cycle, the benefits of refurbishment could be overestimated. The residual value shows how much damage is done to the environment if materials are removed prematurely. The decision of system boundaries in refurbishment projects influences the impacts that happen today. This includes decisions on the reuse and recycling of materials that leave the system during the refurbishment. If this is left out of the refurbishment-LCA scope, then the incentive to properly reuse or recycle materials that leave renovation projects is lacking and must be secured by other means such as waste regulation. Hasik et al. [8] do not include residual value or EoL of existing materials, but consider that environmentally preferable EoL processes should be chosen for the existing materials, thus their disposal could be assessed separately. The French building certification scheme HQE [21] try to encourage the reuse of elements that leave the system. Section 3.3. showed that the residual value of materials that are removed from the project can be allocated to the refurbishment project (acting as a "punishment" for not using the materials to their full extent / service life). However, in HQE this impact can be negated, if the materials are reused in a different building project, see Figure 5**Fehler! Verweisquelle konnte nicht gefunden werden.**. Similarly, the refurbishment project is ascribed with impact from the reuse of products from another project.

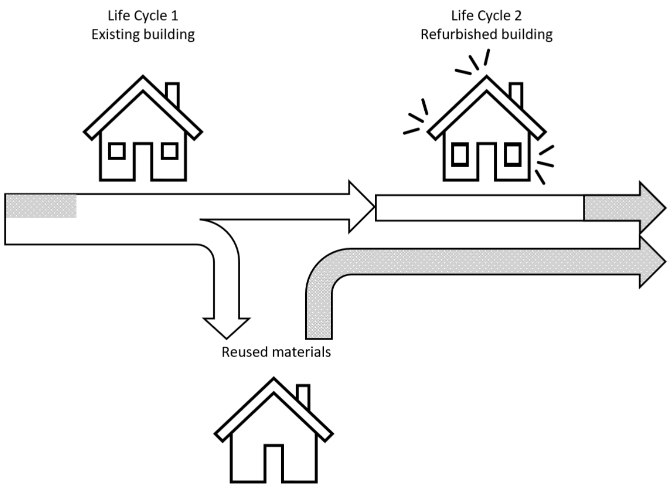

Figure 5. Allocating products that leave the system to the refurbishment project can be negated if products are reused in another system. This gives the incentive to make sure that materials are circulated in other projects. (Similarly reused products from other systems can be allocated to the refurbishment project).

Hasik et al. [8] present different methodological approaches to performing LCA on refurbishment projects. They suggest a method for comparative LCA for major renovations where only the use-stage of the existing building is included. They argue that this is more consistent with the scope of building-LCA for new construction, which does not typically include the EoL of the previous building on the lot – and possibly there was not even a building beforehand. Furthermore, they argue that renovation projects should not be penalized for decisions made for the existing building, which they have not been part of.

Zimmermann et al. [10] developed a framework for whole-building LCA when an existing building is the starting point. This includes impacts that happen from today and into the future building life cycle, but excludes impacts that have already happened. In this way, all future impacts are considered. They highlight that temporal perspective should be considered, such that demolition and new construction have a higher impact today, than preservation or renovation scenarios. While LCA is about considering impacts across the whole life cycle, mitigating impacts today should be of particularly high concern. This is both due to a higher uncertainty of impacts in future scenarios and because greenhouse gas emissions have to be cut rapidly to comply with the Paris agreement of limiting global warming to 1.5 degrees [22].

3.5.2. Influence of methodological choices. Wijnants et al. [7] and Rasmussen and Birgisdottir [9] tested whether the inclusion of existing materials had an impact on the results of their case studies: Wijnants et al. [7] wanted to focus on the methodological issue related to evaluating renovation interventions, such as the allocation of the existing materials between the life cycles before and after renovation. They found that this did not influence the overall decision related to renovation versus demolition and new construction. They also considered the role of estimating the building lifespan of the renovated project, which they found could affect the decision-making significantly. Rasmussen and Birgisdottir [9] tested the influence of the allocation approach in their study to consider methodological choices and its influence on their results. Although there was a difference in impact from allocating the initial impacts of existing materials to the second life cycle, the results were both lower than that of new construction, thus their overall conclusions remained the same.

3.5.3. Evolution of construction technology, efficiency, and electricity mix. Bin and Parker [19] and Potrč Obrecht et al. [20] both investigate the initial construction impact, but with slightly different goals: Bin and Parker [19] chose to model impacts from the existing building, both embodied and operational energy use, to compare them to the refurbished building, and to contribute with information to construction-technology comparison and debates on refurbishment vs replacement. While their method for adjustment for past production (as described in section 3.4) showed that the embodied energy of the initial building was higher than expected, it was overshadowed by the energy use from the building, and the potential savings from deep renovation. This led to a general recommendation to enhance the energy performance of buildings through renovation due to the high energy savings. Potrč Obrecht et al.'s [20] study wanted to understand how past production of materials influences future refurbishment measures by considering their influence on the residual value of materials. The residual value can inform on the value at a given time and can be used for decisions about preservation, reuse, or discarding.

3.6. Practical barriers from including existing building

Barriers in terms of implementation and method can be expected when including the existing building in the assessment. Assessing the type and quantity of existing materials is not a regular part of refurbishment projects and will add to consultancy costs. Only few deep refurbishment projects include a complete mapping of the building geometry and registration of materials using conservatory methods or 3D scans, which would add to the bill of quantity necessary for the LCA. Furthermore, an assessment of the remaining component service life is neither a part of refurbishment projects nor common in building condition reports.

The magnitude of this extra workload depends on whether all or only a selection of existing materials is included e.g. the share of demolished or reused components. In principle, the impact from the use stage of existing materials should always be included, however, this requires modelling of e.g. replacements. Furthermore, allocation approaches deviating from the EN 15804 cut-off approach [18] will be a practical challenge to implement, since existing generic or environmental product declaration (EPD)-data for building products already use this method [16].

Methodological challenges can also appear, e.g. for biogenic materials. This specifically applies in the burden-free approach where EoL of existing materials is included. If EPD data is used, following the product category rules from in EN 16485 [23], the biogenic carbon will not be neutral within the system, if only EoL of the existing materials are included (because biogenic carbon is only neutral if both production and EoL is included). Using the standardized data from EPDs thus propose a challenge in this approach. The newest update to the EN 15804 standard [18] which is gradually being implemented in EPDs will make this easier due to the separate accounting for biogenic global warming potential.

3.7. Future work

Future research should investigate the magnitude of impacts from the existing structure in refurbishment-LCA, depending on modelling and allocation approach, and their influence on decision making for different types of refurbishment projects.

This study estimated a considerable extra workload when including existing building materials in the assessment. Future research should therefore investigate possibilities for making refurbishment-LCA more feasible to implement for the industry. Currently, approaches for aiding material quantification through parametric models are being developed for simplifying refurbishment LCA [24, 25], but it is still a topic that needs to be investigated in future studies.

4. **Conclusion**

This study has presented and characterized different allocation approach and modelling in refurbishment-LCA. These included allocation of materials between consecutive life cycles, how to allocate impacts that leave the system and adjusting data for historical production.

Refurbishments can be considered as a new building life cycle. This requires allocation of the impacts between the cycle before and after refurbishment if we want to assess the life cycles separately. The allocation approach 50:50, avoided burden and product environmental footprint deal with the allocation of production and end-of-life impacts of reused and recycled material. The approaches have shown a significant difference in results in the second life cycle, and they promote different incentives for decision-making. The burden-free approach is different, as it does not allocate the production stage of existing materials to the refurbishment life cycle. Since the production stage typically has the highest impact, this approach will result in limited impact from existing materials. The residual value approach shows the unamortized value of a product at a specific time and can be used as an allocation approach in itself, or in combination with other allocation approaches. In the two studies that tested residual-value allocation against the burden-free approach, it did not result in different design incentives. Adjustment for historical impacts from the existing materials can be done and influences the result, though the significance appears to be limited.

The study has described the pros and cons of the different approaches to the LCA-practitioner. The main cons relate to the large workload related to modelling the existing building. Future studies should investigate the influence on results from the existing materials in the refurbishment-LCA using the different allocation and modelling methods. Furthermore, future studies should investigate methods to ease the workload for LCA practitioners.

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