Investigation of maintenance and replacement of materials in building LCA

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Abstract. Recent life cycle assessments (LCAs) of buildings highlight the importance of global warming potential from construction materials, in particular in energy-efficient buildings. It is therefore important to address the influence of methodological choices related to materials on LCA results. This paper focuses on scenarios for the maintenance and replacement of building elements.

Methods: A literature review is carried out to summarize the state of the art regarding scenarios for maintenance and replacement in building LCA, their influence on LCA results and related methodological issues. Additionally, a case study is carried out to investigate whether assumptions about service lives in LCA could significantly influence the recommended design for a building’s roof, using a Monte Carlo analysis considering service lives as stochastic variables.

Results: The literature review reveals a broad range of impacts from maintenance and replacement in case studies. There is therefore no consensus about the relative impact of these processes. These differences can be partly explained by differences in scope (e.g. what elements are considered to be replaced and what kinds of processes are included), in methods for service life estimation and in future scenarios for the production and recycling of materials. Relative impacts from maintenance and replacement seem to be highest for energy efficient buildings with a long service life, and for elements such as carpets, paint, insulation, doors and windows. The case study of roofing materials exemplifies a case where assumptions about service lives could influence design decisions. Both the ranking of alternatives and the relative significance of maintenance and replacement processes depend on assumptions about service lives. An asphalt roof cover is preferred when considering only initial installation, but a clay tile roof cover is preferred over asphalt in roughly two thirds of the cases when considering maintenance and replacement. Metal roofs almost always had a poorer environmental performance under the assumptions considered.

Conclusions: Results from the case study are compared with previous studies of maintenance and replacement processes, and methodological issues deserving further consideration are highlighted. In particular, the case study is used to discuss the issue of whether a modelling based on independent service lives for various building elements accurately reflects industrial practices. Moreover, the relevance of including maintenance and replacement in regulations and climate declarations for buildings is discussed.

Grant support: This work is part of the research programme “E2B2 – Research and innovation for energy-efficient construction and housing”, funded by the Swedish Energy Agency.
1. Introduction

1.1. Background – Maintenance and replacement in building LCA
Buildings are responsible for about 32 to 35% of global final energy use, and 19 to 40% of global energy-related greenhouse gases emissions [1,2]. Mitigating global warming potential (GWP) caused by buildings is therefore important to meet the climate target of the Paris Agreement [3]. Mitigation strategies require knowledge about the environmental impact of buildings, e.g. to identify hotspots or compare alternative building designs. Life cycle assessment (LCA) has been used for this purpose since the 1980s, and the assessment of buildings has been partially standardized since the 1990s [4]. Recent case studies indicate a rising importance of the relative contribution of construction materials in GWP compared to operational energy use, due e.g. to an increase in building energy performance and a decarbonation of the energy supply [5–9].

Despite ongoing efforts towards standardization and a growing body of case studies, a number of methodological questions about building LCA remain. One such question is the importance of assumptions about the future maintenance and replacement of building materials. If maintenance and replacement processes throughout a building’s life cycle are responsible for a large share of GWP, then it is important to make sure that appropriate assumptions are taken about the frequency and extent of these processes. If there are cases where such processes contribute a negligible amount of environmental impact, then the possibility to simplify assessments by ignoring these processes should be considered.

1.2. Aim and research questions
The overall objective of the present paper is to investigate the importance of assumptions about maintenance and replacement in the LCA of building elements. In particular, the following research questions are investigated:
- Do maintenance and replacement processes contribute to a significant share of GWP over the life cycle of a building or building element?
- Can assumptions regarding the replacement and maintenance of non-structural building elements significantly influence which design alternative is considered to have the lowest GWP?

First, a literature review is used to present the state of research about maintenance and replacement in LCA. Second, a case study of roofing materials is used to exemplify the importance of assumptions about the service lives of buildings and building elements when comparing design alternatives.

2. Literature review

2.1. Importance of maintenance and replacement processes
The significance of maintenance and replacement processes in life cycle GWP or energy assessments varies greatly between studies. A number of case studies indicate a relative contribution of maintenance and replacement of around or less than 1% of building life cycle GWP or energy use [10–16]. Other studies indicate contributions of up to 39% [17] 37-54% [18], or 59% [19]. The highest results seem to be reached for studies of low/net zero energy buildings, or studies assuming a long building service life. Blengini & Di Carlo [7] conclude that the construction of the building frame remains the main contributor of environmental impact for low energy buildings, but that maintenance processes can play a considerable role in several impact categories. They also point out the need for more reliable service life data to reduce uncertainty on the impact of maintenance. Studies focusing on embodied emissions indicate a share of embodied emissions due to maintenance and replacement of up to 45% [20] or even 75% in a study with a 300 years time horizon [21]. However, maintenance and replacement processes are often overlooked: Pomponi & Moncaster [22] highlight that they are ignored in 85-88% of studies of embodied carbon mitigation strategies. Regarding industrial practices, De Wolf, Pomponi & Moncaster [23] mention that practitioners often omit use phase embodied carbon in their assessments due to uncertainty, lack of data and potentially a lack of understanding of the importance of the impact.
A closer look indicates that the significance of maintenance and replacement processes depends on the impact category and the materials considered. Lavagna et al. [15] and Allacker et al. [16] both indicate a small contribution to GWP but a contribution to resource depletion of around 18%. A case study of building refurbishment by Colli et al. [24] reported small contributions to GWP but higher contributions to human toxicity (25%) and resource depletion (34%). Blengini & Di Carlo [25] report a 35% contribution to photochemical ozone formation for a low energy house. Junnila, Horvath, & Guggemos [26] indicate a contribution to particulate matter emission of up to 22.5%. Building elements highlighted as having a significant impact due to maintenance and replacement include carpets [26–30], paint [11,27,31–33], insulation materials [19,26,31], doors and windows [19,24,33].

There is therefore a great variability in the significance of maintenance and replacement processes between various studies, as highlighted in previous studies [34,35]. Vilches, Garcia-Martinez & Sanchez-Montañes [36] offer arguments to explain this difference. They point out the influence of including the impact of transport, construction and deconstruction processes and the end of life impact of substituted materials, as well as use scenarios and scenarios for future energy supply and materials production. Dixit [35] mentions the importance of replacement that is driven not by the end of service life, but by changes in ownership, technological or aesthetic trends. Dixit also mentions the influence of maintenance policies on the service life of building elements, as well as the importance of synchronizing replacements of elements with the service life of the building in order to avoid rare but major replacements.

2.2. Ambiguity and differences in scope

One significant issue that can also explain the range of differences between the case studies mentioned is ambiguity in terms of the scope of maintenance and replacement processes. The European Norm EN15804 distinguishes between four closely related modules [37]: B2 maintenance, B3 repair, B4 replacement and B5 refurbishment. However, the interpretation of what exactly is included under each of these labels differs between different studies and standards. These differences in scope and interpretation of boundaries hinder comparability. Vilches, Garcia-Martinez & Sanchez-Montañes [36] point out that different LCAs of building refurbishment use different scopes for module B5, and that some confuse module B5 with modules B2, 3 and 4. Chastas et. al. [8] reviewed 95 case studies and described a lack of clear definitions of the scope of modules B1-5. Dixit [35] highlights that differences are partly explained by differences in scope regarding what processes were considered (minor/major maintenance, replacement, major retrofit) and what building elements were assumed to be replaced (only envelope and finishes or also furniture, electricity, plumbing, etc.). Dixit mentioned that many studies only include replacement activities, some include maintenance and repairs, and many are not clear about what module they include. In a review of building rehabilitation case studies, Thibodeau, Bataille & Sié [38] mention that 83% of the studies reviewed included module B4, 20% included B2 and none included B3. De Wolf, Pomponi & Moncaster [23] mention that modules B1, B2, B3 and B5 are often omitted in industrial practice. Therefore, differences in the significance of maintenance and replacement processes in LCA can partially be explained by differences in scope. Different studies might group different processes under each module, and they might cover all or only some of the building elements.

2.3. Service life prediction

Another core issue when calculating environmental impacts from maintenance and replacement is estimating the service life of building elements. Different databases might include different values for the reference service life (RSL) of a product. Moreover, actual service lives might differ from the RSL due to differences in use and exposure conditions. Therefore, various methods exist to calculate an estimated service life (ESL). Grant et. al. and Silvestre et. al. [39,40] offer a classification of such methods. Deterministic methods based on structural engineering calculate a service life value based on the physical properties of materials and use conditions (e.g. load and exposure). Stochastic approaches are based on empirical analyses of the degradation of components in a large number of real use cases, in order to determine a probability distribution of service lives depending on certain parameters.
The norm ISO 15686-1 recommends using a method called the factor method. The ESL is then calculated by multiplying the RSL by 7 different case-specific correction factors to represent the influence of quality of materials, design and execution, exposure to indoor and outdoor environment, in-use conditions and maintenance procedures on the actual service life of building elements.

Therefore, we can distinguish between 4 broad types of service life data used in most case studies: reference service lives, service lives estimated through analysis of physical properties, service lives estimated through statistical analysis of real cases, and service lives estimated with the factor method. Additionally, Aktas & Bilec [41] propose a hybrid method. First, an average service life is determined by statistical analysis of real cases. Then, this average service life is adjusted it to specific conditions of the case study building using the factor method. It is argued that this method adequately considers the influence of social factors on service life, and relies on fewer assumptions and a narrower range for the various factors, thus limiting uncertainties.

Many of the papers reviewed did not clearly specify the source of the service life data they used. Of those who did, the majority uses RSLs and references service life values from previous reports or handbooks. Several papers use the term “estimated service life” [42,43], but only one of the papers reviewed directly and transparently applies the factor method for service life estimation [44]. Hereafter, a case study is used to investigate more in detail the influence of service life assumptions in LCA

3. Case study
3.1. Method
A case study was carried out to investigate whether the choice of service life values for roofing materials could influence which alternative is considered preferable. The case study building is a multi-family residence with a roof surface of 518 m² and a roof pitch of 20°. The alternatives considered for roofing materials are asphalt paper, steel, aluminum and clay tiles. It is assumed that the choice of roofing materials does not lead to any significant change in the building structure or its thermal properties.

A Monte Carlo analysis (10000 iterations) was performed to calculate the embodied GWP of roofing materials, treating service life values for the building and roofing materials as stochastic variables. The calculation encompasses GWP from initial production, maintenance, repair and replacement (modules A1-3 and B2-4), excluding emissions from on-site processes and the end of life of replaced materials.

Dixit and Hoxha et. al. [35,45] both provide reviews of service life values for various building elements and materials. For the Swedish context, Erlandsson & Holm [46] provide maintenance and replacement periods, depending on whether the material is particularly exposed, protected or used under average conditions. In the present study, these values were used as minimum, maximum and mean service life values for each material respectively. The probability distribution was assumed to be normal within these boundaries. The standard deviation was obtained by adjusting standard deviations from Dixit and Hoxha et. al. [35,45] to keep a similar ratio between mean and standard deviation. The probability distribution for building service life is an arbitrary assumption. Emission factors are taken from the BM software database [47]. All parameters are summarized in Table 1.

It is assumed that roof underlayment for the asphalt and metal alternatives is only ever replaced when the cover is replaced. The period for other maintenance procedures for these roofs is “reset” when cover replacement occurs. For instance, if the periods for cover replacement and painting are 30 and 20 years respectively, the cover will be painted at year 20, replaced at year 30, and painted again at year 50. For the clay tile roof, the cover and underlayment can be replaced independently (one can replace the tiles and keep the underlayment, or replace the underlayment and put the tiles back afterwards). Therefore, the replacements of cover and underlayment are assumed to be independent for the clay tile roof. When the underlayment is replaced, it is assumed that 15% of the tiles are damaged and replaced as well.
Table 1. Parameters used in the case study

|                      | Asphalt roof                  | Steel roof                    | Aluminum roof                  | Clay tile roof                  |
|----------------------|-------------------------------|-------------------------------|-------------------------------|---------------------------------|
| **Cover material**   | Asphalt roofing felt paper, 5.4 kg/m² | Painted steel sheets, 5.5 kg/m² | Painted aluminum sheets, 3.4 kg/m² | Clay tiles, 34 kg/m²            |
| **Amount (kg)**      | 2797                          | 2849                          | 1761                          | 17614                           |
| **Underlayment amount (kg)** |                               |                               |                               | 1223                            |
| **Replacement procedure** | Full replacement of cover material and bitumen underlayment at the end of cover service life. |                               |                               | Full replacement of clay tiles at the end of their service life. Full replacement of underlayment at the end of its service life. |
| **Cover service life (years)** | Min: 10, Max: 40, Mean: 25, SD: 13.3 | Min: 20, Max: 60, Mean: 40, SD: 15.9 | Min: 30, Max: 50, Mean: 40, SD: 12.6 | Min: 25, Max: 100, Mean: 65, SD: 25.1 |
| **Additional maintenance or repair procedure** | Asphalt compound addition | Repainting | Repainting | 15% of the tiles are damaged and replaced during the replacement of the underlayment. |
| **Additional maintenance period (years)** | Min: 5, Max: 12, Mean: 10, SD: 5.3 | Min: 10, Max: 50, Mean: 15, SD: 3.3 | Min: 10, Max: 20, Mean: 13.5, SD: 6.8 | Min: 20, Max: 30, Mean: 25, SD: 15.2 |
| **Building service life (years)** | Min: 30, Max: 70, Mean: 50, SD: 10. |                               |                               |                                 |

### 3.2. Results

Figures 1 illustrates the life cycle global warming potential (GWP) of the asphalt, steel, aluminum and clay tile roof alternatives. The asphalt roof alternative presents a lower initial climate impact but is replaced more often than the other alternatives. The impact of the other roofs presents a more stepwise distribution: since the impact of each replacement is higher but the number of replacements is lower, there is a noteworthy difference in impact between cases with 0, 1 and 2 cover replacements. The result is therefore sensitive to rare but major replacements, in particular for the metal roofs.

The impact of the clay tile roof is lowest in 63.1% of the model runs. The asphalt roof has the lowest impact in 35.6% of the model runs. The steel roof has the lowest impact in 1.3% of the cases and the aluminum roof in none of the cases. Therefore, the clay roof can be said to have the lowest impact under most maintenance and replacement scenarios, despite having a higher initial impact than asphalt. However, in more than a third of the cases, the asphalt alternative would be preferred. Service life assumptions can therefore introduce significant uncertainty as to which alternative would have the lowest environmental impact.
The average share of maintenance in embodied GWP over all alternatives was 9.5% and the average share of replacement 37%. The shares of maintenance and replacement in total embodied GWP ranged from 0% to 37% and 0% to 86% respectively, indicating a very broad range of possible values. The highest values were reached for the asphalt roof.

**Figure 1.** Life cycle GWP of the four roof alternatives in each run of the Monte Carlo analysis (ordered by total GWP for each alternative)
As indicated in figure 2, building service life significantly influences embodied emissions in all alternatives. Average building service life in cases where asphalt is optimal is 49.7 years, compared to 50.7 years when steel is optimal and 50.2 years when clay tiles are optimal. However, differences in the service lives of materials between these cases were much more significant. Unsurprisingly, cases where asphalt is the optimal solution had significantly longer service lives for asphalt, and similarly for steel and clay bricks. The few cases where steel was the optimal solution were also characterized by abnormally low service lives for both asphalt and clay bricks.

![Figure 2. Average life cycle GWP for each alternative, for each possible value of building service life](image)

**4. Discussion**

**4.1. Main outcomes and implications**

The case study exemplified how assumptions regarding maintenance and replacement can influence the results of an LCA, and potentially conclusions regarding which alternative would be preferable. First, it is noteworthy that the asphalt roof is the preferred alternative when considering only initial installation, but that clay tiles are preferred in most cases when including the impact of maintenance and replacement. This highlights the importance of including impacts from maintenance and replacement in the LCA of non-structural building elements. However, further work is needed to broaden the study and consider impacts at the building level. It should be kept in mind that, even though maintenance and replacement played a significant role in the embodied GWP of roofing materials, these materials might only account for a small share of the building’s GWP. It is therefore necessary to study the significance of maintenance and replacement at the building level.

Second, it should be noted that uncertainty on service lives lead to significant considerable over the results. In particular, this influences which alternative would be preferable in terms of GWP: clay tiles were preferred in about two thirds of the cases, and asphalt in about one third. In the same vein, Silvestre, Silva & de Brito [39] showed that the modelling of replacement processes based on stochastic variables could lead to an inversion in terms of what alternative was preferred in a study of facades. In some cases, they considered the resulting uncertainty to be too high to draw conclusions. Grant & Ries [48] carry out a study of façade and roof solutions over a 500 years period, comparing the use of five different models predicting maintenance and replacement procedures. They find considerable variations between impacts estimated using different models. Uncertainty was highest for the impact of wood panels. The main reason is uncertainty on the frequency of major replacements, although maintenance processes played a role as well. Hoxha et. al. [45] identify different sources of uncertainty tied to construction materials (including uncertainties on emission factors, material amounts and service lives). Service lives are identified as the main source of uncertainty for some material categories. Similarly, Häfliger et al.
[19] highlight that variations in service lives of materials can cause uncertainties on GWP for the whole building of 10-20%.

The two remarks above raise an important issue. If maintenance and replacement processes can account for a large share of GWP, they should be included in climate declarations and LCAs for certification purposes. However, if service life data are fraught with uncertainty, and if this uncertainty can considerably influence LCA results, including such processes in assessments could decrease their precision and validity. If the purpose of such assessments is to encourage construction practices with a low GWP and if uncertainty overshadows the effect of potential green design decisions, an LCA including maintenance and replacement processes might become counterproductive. One potential solution to this issue could be to set mandatory generic values to be used for the service lives of various materials in certification schemes. However, this would prevent any benefit from design decisions aimed at increasing the service lives of materials. It would also misrepresent the fact that service lives depend not only on the type of material, but also on conditions of use, climate, exposure, maintenance and factors such as changes in ownership.

4.2. Further research directions

Further research is needed to improve the analysis, both in terms of its scope (e.g. assessing maintenance and replacement for all materials) and its validity. The LCA could for instance cover other impact categories, since the literature review highlighted that maintenance and replacement might contribute more to e.g. resource depletion, photochemical ozone formation or particulate matter formation. The modeling of probability distributions can also be improved. Aktas & Bilec [41] mention that actual service life data distributions are often skewed rather than symmetrical, making the use of a Weibull distribution more appropriate than a normal distribution. Moreover, it should be kept in mind that the values used represent the distribution of service life values in the literature, and not the real world distribution of service life values (i.e. values in the literature are not weighted based on how often they correspond to real world cases). There is therefore a clear need to use service life data based on large samples and that better represent physical reality. Finally, the number of runs in the Monte Carlo analysis also deserves consideration. Heijungs [49] cautions against using Monte Carlo analyzes based on a large number of runs when the initial sample size is small.

The analysis could also be further refined to better represent the complexity of real maintenance procedures. The present paper already introduced the idea that maintenance and replacement periods are not independent from each other (in that each replacement resets the time to next maintenance). This is an improvement from using independent service life values that overlook the timing and interdependence of replacement and maintenance procedures, but the model could be further improved. First, the frequency and extent of maintenance processes can influence the service lives of building elements by reducing wear and tear. Second, maintenance and replacement processes are often synchronized in practice. Replacements do not happen independently for different building elements: instead, several maintenance and replacement procedures are usually packaged together and executed at the same time. This is particularly relevant at the building level, but even when focusing on the roof it should be noted that it is unlikely for the cover to be replaced one year after undergoing maintenance, which the current model overlooks. Third, it should be kept in mind that the roof alternatives considered are not fully equivalent in terms of the function they provide. In particular, clay tiles are not an appropriate solution for flat roofs. Fourth, the risk of humidity damage has been overlooked. If an alternative would lead to higher risks of moisture-related damage, it should be reflected by introducing the replacement of roof sheathing and insulation. Fufa [50] previously showed that water damage can significantly influence the estimated impact of replacement. Finally, there is a need to integrate future scenarios in the background model of LCAs, to represent the fact that materials installed or recycled decades from now might use more efficient technology.
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