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Analysis of lifetimes of building elements in the literature and in renovation practices and sensitivity analyses on building LCA & LCC

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Abstract

In this study, the service lives of the building elements, an important parameter in renovations and LCA/LCC calculations, are analyzed, based on a comprehensive literature review and a survey of Swiss households. The literature review showed that there is no consensus about the service lives, among the different countries, while the results of the survey on the renovation timing of the building elements, showed on average an agreement between the element's effective lifetime and the average from the literature data. In addition, based on the literature data, lognormal distributions were defined for the service life of the building elements and then the probabilistic LCA & LCC were calculated. The results showed that the uncertainty of 6 building elements' service lives can significantly influence the reliability of the results. For the practitioners, the study confirms that the current practice of using service life data of the SIA 2032 technical books, for building LCA and LCC, constitutes a relative good estimation of the most probable value of the probabilistic LCA.

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1. Scope

The lifetime of building elements influence both the life cycle costs (LCC) and environmental impacts (LCA) of new constructions, during their planning stages and also the renovation of existing buildings. So far, it is not clear to which extent the lifetime values vary, i.e. values found in literature and observed in renovation practices. This potential variability may generate a lack of consistency, especially in the life cycle related studies (i.e. LCA, LCC). In that context, the DUREE project proposes a three steps approach to reduce the current knowledge gap and deal with this variability, as presented in Figure 1.

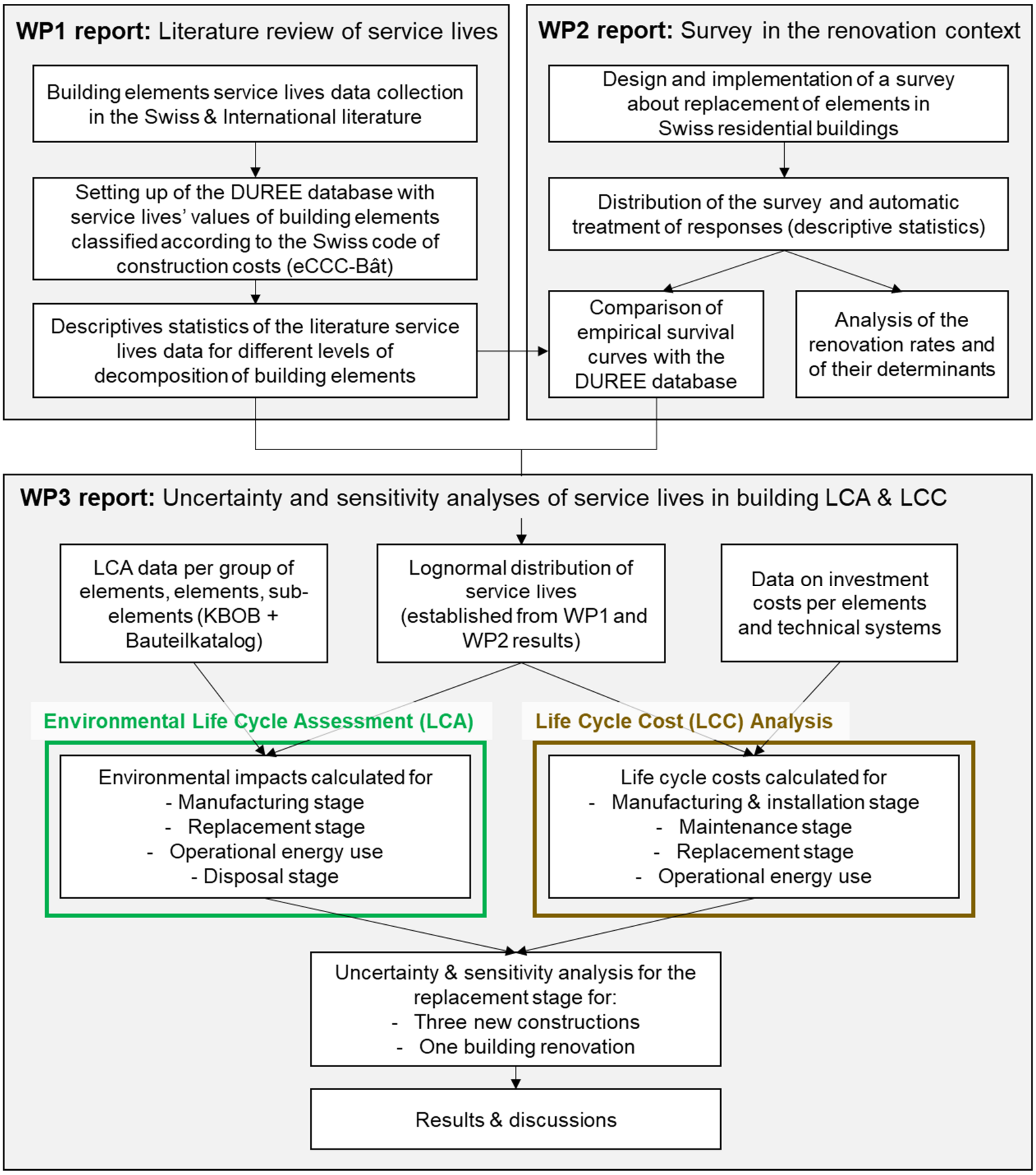

Figure 1 Three steps approach of the DUREE project

The three steps approach includes:

- First, a **state of the art** gathering the data of the building elements service life, from the Swiss and international literature (WP1);

- Second, the evaluation of what is being done in practice, through a **survey** for building owners, in order to determine the effective lifetimes of the building elements that derive from their replacement during renovations (WP2);
- Third, the analysis of the **influence of the variability** of service lives in the life cycle assessment (LCA) and life cycle cost (LCC) analysis for residential buildings (WP3);

Finally, recommendations are provided for policy makers and for the LCA/LCC community (both experts commitees and practitionners), in order to better handle the variability of the service lives of the building elements and technical systems in buildings.

2. WP1: Literature review of service lives in Switzerland and abroad

The first step of the project included a literature review of service life data for different building elements. The term 'service life' (or lifetime) can be differently defined, depending on the scope of the final user e.g. building designer, owner, LCA or LCC expert [1]. Thiebat [2], made a distinction among the physical, functional or economic service life of a building. The physical service life corresponds to the lifetime allowed by physical degradation procedures, while the functional one additionally takes into consideration the 'performance/requirements ratio'. The economic service life corresponds to the residual economic value. Moreover, the international standard ISO 15686 [3], presents a variety of definitions, as for example the service life, the reference service life, the estimated service life, the predicted service life and the service life during the design. In Switzerland, the Swiss Society of Architects and Engineers (SIA) differentiates the technical service life (SIA 2047, 2015 [4]; SIA 480, 2016 [5]), from the useful life (SIA 2047, 2015; SIA 260, 2003 [6]; SIA 480, 2016) or the amortization period (SIA 2032, 2010 [7]), used for LCA calculations.

2.2. Methods

The literature search of service life data was performed in English, French and German via Google, Google Scholar and Science Direct, for all the different aforementioned terms. The identified sources (67 in total) were energy standards, LCA and LCC standards, scientific reports, documents from the public sector, private associations, banks, building management and insurance companies. The search was focused on data for the structural system, the technical installations, the façade elements and coatings, the roof elements, as well as for the interior layout. Moreover, the partners of the IEA EBC Annex 72 contributed to this research and they provided additional service life data through a survey, conducted on national LCA methodologies, in the beginning of 2019 [8]. The service life data were grouped in a database and formed the DUREE Database in an Excel spreadsheet, according to the SN506511 [9] that it is appropriate for different Level of Details - LOD calculations, in BIM-based LCA and LCC analyses. From this functional nomenclature, five main groups of building elements were extracted, which include the structural work (main group C), the technical installations (main group D), the façade elements and coatings (main group E), the roof elements (main group F) and interior layout (main group G), see Figure 2. Based on the SN 506511 nomenclature, these five main groups were additionally decomposed into two sub-categories, (i.e. the intermediate element level and the detailed element level, e.g. D.1 and D1.2a, respectively in Figure 2). Finally, five additional sub-categories were inserted to this decomposition, in order to cover lower levels for more detailed elements. In total, the database includes approximately 7'000 service lives data, for more than 2000 building elements. From these data, approximately 79% came from LCA and LCC sources. In addition, approximately 28% came from Switzerland and the rest were international data, mostly from European countries. The majority of Switzerland's data came from the management sector, while the majority of the international data belonged to the LCA domain.

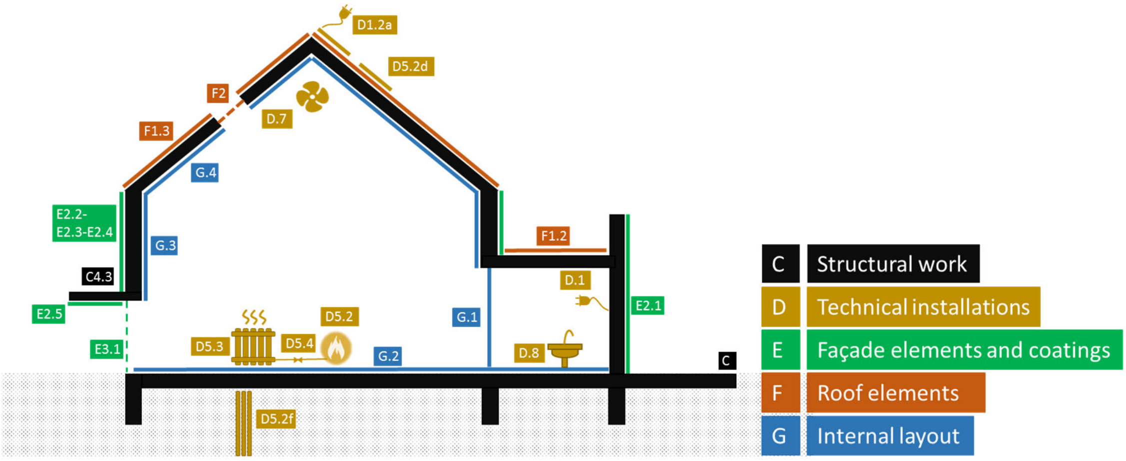

Figure 2 *Main groups and intermediate element levels from the eBKP-H - SN 506511 nomenclature, for the 24 building elements, according to SIA 2032.*

2.3. Results

The different data were analyzed, using descriptive statistics, for the different samples and levels of details, i.e. statistics were derived for the different countries (Switzerland or International data) or the different scopes (LCA, LCC and Management sources). Figure 3 presents the descriptive statistics for the global, LCA, LCC and Management samples and for a selection of eight building elements, included in the LCA calculation in Switzerland, according to the SIA 2032 and SIA 2040 technical books. The results are presented using boxplots, which represent 50% of the data in the box (interquartile interval) and 80% of the data between the upper and lower whiskers. In addition, the median is represented by the horizontal black line within the box. For example, as far as the heat distribution is concerned, 50%, of the global sample, are between 18 and 35 years, while 80% are between 16 to 60 years, the median value being equal to 27 years. For all the building components, there is a high variability in the global sample, as well as within the different samples (LCA, LCC, management). Similar findings were observed for the other samples (Swiss and International), as well. Although the variability is often substantial, for some components, median values or interquartile ranges are relatively comparable between the three sub-samples (e.g. heat production, compact façade, sloping roof). The results in Figure 3 show that there is no identified clear tendency of a specific sample, providing consistently higher or lower lifespans for the different building elements.

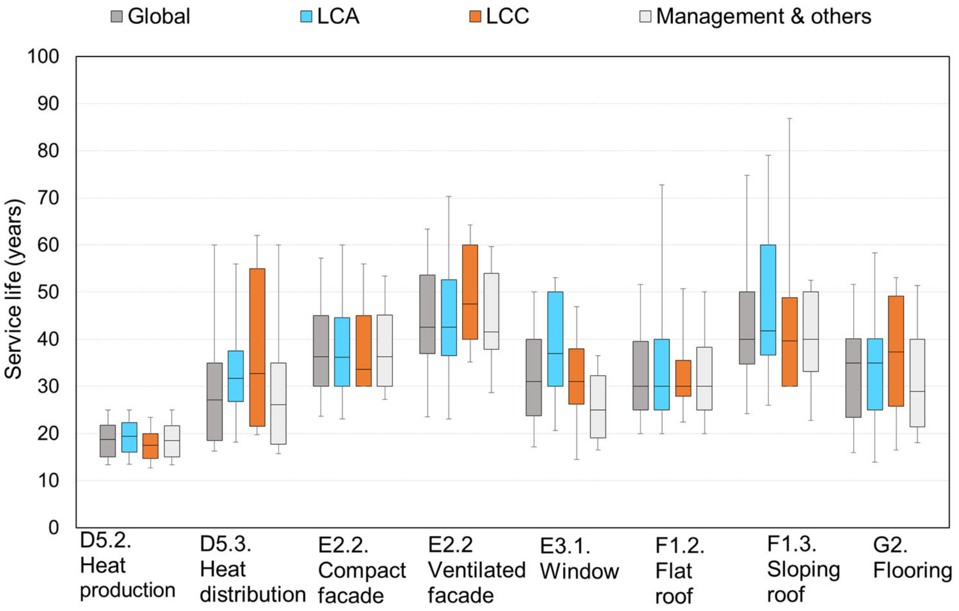

Figure 3 *Boxplots of the service lives for eight building elements, included in the system boundary of the SIA 2032 technical book, for the LCA calculation in Switzerland.*

In addition, Table 1 presents a comparison of the median Swiss and global DUREE samples with the SIA 2032 and the CRB (mean) values of the 16 building elements, used in building LCA & LCC (WP3 study). From this table, we notice that the service lives proposed by the SIA 2032 technical book correspond relatively well to the collected Swiss data. On the contrary, the CRB mean values are not always in accordance with the median from the Swiss and global samples, the highest deviations being for the technical systems (heat distribution and diffusion, ventilation and electrical systems).

	Operational standards		DUREE Database Switzerland	*Differences with standards*		DUREE Database Global	*Differences with standards*	
Values in years	SIA 2032	CRB (mean)	median	*SIA 2032*	*CRB (mean)*	median	*SIA 2032*	*CRB (mean)*
D1 Electrical installations	30	45	30	*0%*	*-33%*	30	*0%*	*-33%*
D5.2 Heat production	20	20	20	*0%*	*0%*	19	*-5%*	*-5%*
Solar collectors	20	-	21	*5%*	*-*	20	*0%*	*-*
D5.3 Heat distribution	30	60	30	*0%*	*-50%*	27	*-10%*	*-55%*
D5.4 Heat emission	30	60	30	*0%*	*-50%*	25	*-17%*	*-58%*
D7. Ventilation system	30	40	25	*-17%*	*-38%*	21	*-30%*	*-48%*
Sanitary equipment	30	-	30	*0%*	*-*	30	*0%*	*-*
E 2.2 Compact facade	30	35	30	*0%*	*-14%*	38	*27%*	*9%*
E2.3 Ventilated facade	40	40	40	*0%*	*0%*	43	*8%*	*8%*
E3.1 Windows	30	35	29	*-3%*	*-17%*	30	*0%*	*-14%*
F1.2 Flat roof	30	25	30	*0%*	*20%*	30	*0%*	*20%*
F1.2 Sloping roof	40	40	40	*0%*	*0%*	40	*0%*	*0%*
G1 Internal partitions	30	35	30	*0%*	*-14%*	42	*40%*	*20%*
G2 Floor coverings	30	35	26	*-13%*	*-26%*	33	*10%*	*-6%*
G3 Wall coverings	30	30	27	*-10%*	*-10%*	38	*27%*	*27%*
G4 Ceiling coverings	30	30	30	*0%*	*0%*	38	*27%*	*27%*

Table 1 *Comparison of the median data for the Swiss and global samples of the DUREE database (DB), the average values reported in the SIA 2032 and CRB documentations.*

3. WP2: Survey on renovation practices

The second step of the study was focused on the analysis of empirical lifespans of the main building elements and technical systems in owner-occupied and tenant-occupied residential buildings in Switzerland. The empirical lifespans were gathered from two annual surveys in Switzerland. The main purpose of this step is to identify to what extent the actual replacement rates follow the lifetime values reported in the WP1 study. It provides information on how replacement rates evolve as elements age - information captured in the form of “survival curves” of building elements. Here, “survival” of an element represents the continuation of the element’s lifetime before replacement that is, the element’s “effective service life”. In other words, the concept of survival curves is expressed as the conditional probability that an element remains in place (not renovated), as a function of its lifespan. In the survival analysis, it is considered that any observed replacement or major renovation is the end of the element’s service life. Thus, the observed or “empirical” survival curves are compared to the norm-based and “technical” survival curve and the lifetime values reported in the first step study.

3.1. Methods

The analysis was conducted on data extracted from two annual surveys (2017 and 2018) of the Swiss Households Energy Demand Survey (SHEDS), i.e. an online survey of approx. 5’000 households per year, in the German and French speaking parts of Switzerland. Lifespans were derived from information on the renovation history of the household’s current residence for four categories of building elements: windows, heating system (heat production and distribution), façade (compact and ventilated) and roof (flat and inclined). Compared to WP1, this study provides a limited scope in terms of building elements, but has much higher data representativeness, using 5000 observations. The survey retains only individuals, who are at least partially responsible for the household decisions. The dependent variables used in this study are the survival times (life spans) in years of all four building elements. In order to use the data efficiently, for each element, one observation is used per household, focusing on the most recent reported replacement or major renovation. To obtain the age of a building element at the time of the last renovation, the following procedure was applied. For each element the respondent reports a replacement (or a major renovation) and whether this has been the only replacement throughout the building's lifetime. In that case the element's age is obtained by the difference between the replacement year and the building's construction year. When the respondent reports more than one major renovation, he is asked to indicate the renovated element's age at the time of renovation. The respondents, which do not know the specific year, have the opportunity of selecting among several 5-year intervals so that they can report a range. This applies to the renovation year, as well as the building's construction year.

The estimates of the survival time are calculated from the survival probability that is, the probability of an element not to be replaced for t years. This probability can be specified by the Kaplan Meier's formula [10], as the product of the probabilities of not being replaced over all the previous years hence:

$$\hat{S}(t) = \prod_{\substack{i=1 \\ t_{(i)} \leq t}}^{100} \frac{n_i - r_i}{n_i} \qquad (1)$$

where $\hat{S}(t)$ denotes the estimate of the element's survival probability, $t_{(i)}$ is the survival time with i ranging from 1 to 100 years, n_i is the number of cases in which the element is not replaced at the beginning of year i and r_i is the number of cases where the element is replaced in that year.

In addition to the calculation of the survival curves and the comparison to the literature lifetime data, an analysis using the SHEDS data was conducted to provide a more comprehensive understanding of the factors related to delaying renovations, beyond the differences across elements identified in the preceding results. It is based on the semiparametric proportional hazards model, introduced by Cox [11]. These analyses are helpful for identifying potential barriers for renovation and thus provide important information for the political debate and the empirical evaluation of competing policy measures.

3.2. Results

Figure 3**,** plots the elements over their lifespans for the SHEDS owner-occupied households and the WP1 data. These latter data are plotted using the global sample of WP1 data and the CRB data, i.e. "CRB-RSL" (Reference Service Life) and "CRB-ELS" (Estimated Service Life). This figure provides information on the shape of survival curves of the building elements i.e. the evolution of the renovation probability with increasing element age. A new building element has a high survival probability at the outset, hence a low probability of replacement. This probability rises with the element's age. As the element's service life approaches its end, the survival probability approaches zero with the greatest likelihood of replacement. Results show that in both samples and across all building elements, replacement probabilities seem to follow a more or less similar pattern. They are very low for an initial period of 10-20 years. Replacement rates then accelerate over the ensuing survival time such that replacement rates in the period between 20 and 30 years after installation are between 3.3 times (roof) and 6.4 times (windows) higher than during the first 10 years. For the elements experiencing rapid acceleration of replacement probabilities (windows, heating systems), an abatement in replacement probabilities is observed over the lifetime's final decades. Comparing literature-based curves (WP1 study) with empirical survival curves (WP2 study), we find that renovation timing relatively coincides in their median values. That is, across all elements the period after which 50% of elements in SHEDS are replaced, is approximately the same as the corresponding period predicted based on the literature lifetimes. This is particularly valid for elements of the building envelope, such as the windows, the façade and the roof. With the exception of heating systems, a greater similarity in central tendency is found, when we use service lives provided by the CRB for

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Switzerland, than the global sample of WP1 database. It is found that CRB-based survival curves for the heating system overestimate the year of empirical heating system replacement. This may be related to the fact that a large majority of reported replacements in the SHEDS refer to boilers or furnaces, rather than to the heat distribution.

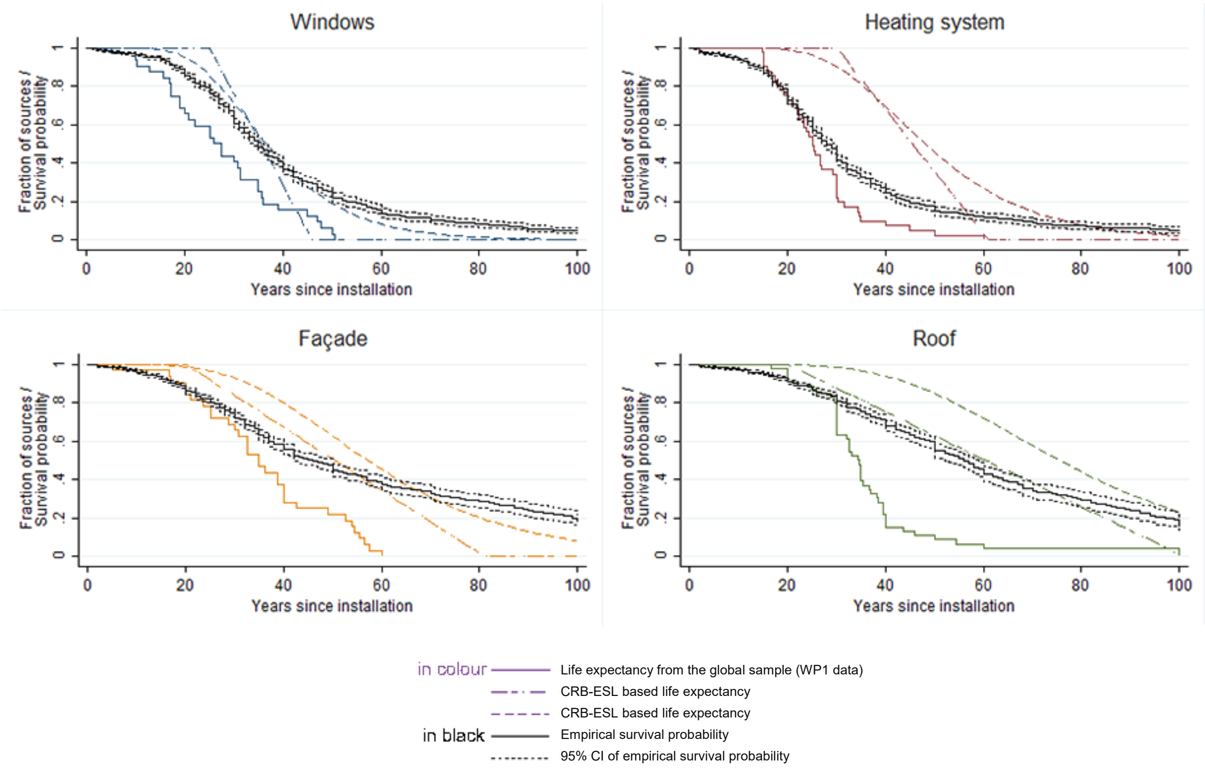


Figure 3 *Survival curves for the four building elements for the heating system using SHEDS 2017 and 2018 in comparison with the global statistics in the WP1 study and CRB data.*

Independently of the lifetimes' sources, the gap between the empirical replacement timing and that predicted from WP1 data widens when moving away from the mid-point of the survival distribution. That is, lifetime values from the WP1 study, systematically underestimate replacement rates among younger building elements, and over-estimate replacement rates among older ones. This is largely independent of the assumption underlying the construction of technical survival curves. That is, there is a significant number of elements that are replaced well before literature data from WP1 would predict such a behaviour. At the same time, there is a substantial proportion of elements that remain in the initial state long after literature data from WP1 would predict a replacement. Thus, assuming constant replacement rates independent of the element's age may be overly simplistic when aiming to predict (energy-related) changes in the building stock. Much like assuming a linear function for survival curves, assuming constant rates is likely to lead to an over-estimation of replacement behaviour in buildings with a majority of recently installed or very old elements, while it is likely to underestimate renovation behaviour in a building stock where elements are between 30 and 50 years old. Taking account of the age-structure of the element stock would therefore help to improve the predictions.

The SHEDS results also showed a non-negligible number of respondents reporting several renovated elements at the same time, i.e. a combined renovation operation. The combinations of elements from the building envelope (window, façade, roof) are more frequent than combinations of the envelope with the heating system. It seems that the thermal insulation of the building envelope appears to be considered somehow as a global approach but not related to the technical installation modifications. This observation could lead however to suboptimal renovation scenarios since the old technical installations could be oversized and could not properly account for the new building heating demand.

Finally, the results of the analysis of the derived econometric models revealed that the building type is strongly related with the length of element survival, with elements installed in multi-family buildings are replaced sooner than elements in single-family houses. This finding holds independent of the ownership status of the building. Moreover, there is robust evidence that dwellings situated in rural areas and the agglomeration tend to have significantly and substantially higher replacement rates than otherwise comparable buildings located in city centres. However, less robust evidence is found that replacement timing occurs earlier among wealthier households (measured using the size of the living space and monthly household gross income), suggesting that financial reasons are still among the most important barriers to (energy-efficient) renovation. Consequently, financial incentives are likely to play an important role in encouraging replacement decisions. In general, elements belonging to a more recent age cohort (installed after 1990) are replaced more frequently than elements belonging to an older cohort. This result suggests that replacement cycles have become shorter in recent decades. This is in line with much of the previous research indicating that replacement rates in Switzerland have risen over time [12, 13]. Finally, we obtain contradicting tendencies for the effects of dwelling cohort on replacement hazards. While not statistically significant across different specifications, elements installed in newer buildings tend to show lower replacement rates.

4. WP3: Uncertainty and sensitivity analyses of service lives in building LCA&LCC

The third step of the project presents a systematic way to deal with the literature (WP1) and empirical (WP2) service life uncertainty of the building elements, in the building LCA and LCC calculations, within a probabilistic framework. Grant [14] has already summarized different studies, mentioning that the service life calculation is driven by high uncertainty. This is explained by the fact that the service life is influenced by a variety of uncertain factors, not necessarily technical, which cannot be defined objectively. Cooper [15] summarizes different studies that identified parameters, such as *'the design, the technological change, the cost of repair and the availability of parts, the household affluence, the residual and resale values, the aesthetic and the functional quality, fashion, advertising and social pressure',* among the ones that influence the service life. Hence, by taking into account the uncertainty of the service lives in the building LCA and LCC calculations the confidence in the LCA result can be increased, as already mentioned in the international literature.

4.1. Methods

The general probabilistic framework, followed in the current study, has been already proposed by Padey [16] and Cucurachi [17]. It consists of the following four steps: (1) definition of the LCA/LCC models, (2) determination of the probability density function (PDF) of the building elements' service life, (3) uncertainty analysis and (4) sensitivity analysis. The building LCA model was defined, taking into account the manufacturing, replacement, disposal and operational energy stages. Following that, the service life data, collected in WP1 (DUREE literature database), were used to define probability density functions, with a consistent way and calculate, thus, stochastically the replacement rates for each building element, by dividing each service life with the reference study period (RSP), equivalent to the building lifetime, in the DUREE project. Monte Carlo simulations were computed, in order to, probabilistically, take into account the replacement of the building elements. Like that, the Probability density functions (PDF) of the LCA and LCC outputs were defined. Finally, a global sensitivity analysis was conducted and the Sobol' Sensitivity Indices [18] were calculated, in order to determine the impact of the service lives' variability on the LCA/LCC uncertainty, for the different building elements. The first order index that represents the main effect, i.e. the influence of individual parameters was calculated, as well as the total index effect, which takes additionally into account possible interactions among the input parameters. This methodology is applied to four residential multifamily building case studies, including three new constructions and one renovation project. Here, the results of the new constructions are presented. Three LCA indicators (greenhouse gas emissions (GHGe), primary non-renewable energy (NRE), total ecopoints using the ecological scarcity method 2013 (UBP), as well as the life cycle cost (LCC) were evaluated. In addition, two scenario analyses were performed, considering different RSPs – Reference Study Periods and different calculation modes of the replacement rate, fractional, rounded up and rounded, 20%, (the replacement rate is rounded up, in case that it is higher than 20% of its integer value, otherwise it is rounded down).

4.2. Results

The uncertainty analysis of one of the case studies, i.e. (B1, new construction), for the GHG emissions, is presented in Figure 4 (left). The probabilistic LCA [μ=22 kg $CO_{2\text{-eq}}$/(m^2y), $\sigma^2=3^2$], along with the deterministic LCA, from SIA 2032 [20.4 kg $CO_{2\text{-eq}}$/(m^2y)] and CRB [min=43kg $CO_{2\text{-eq}}$/(m^2y), mean=19 kg $CO_{2\text{-eq}}$/(m^2y), max=17 kg $CO_{2\text{-eq}}$/(m^2y)] are plotted. The variance of the LCA ($\sigma^2 = 3^2$) reveals that the LCA can be significantly spread away from the mean [μ = 22.0 kgCO2-eq/(m^2y)]. The most probable LCA value i.e. the mode of the distribution, is 21.6 kg CO2-eq/(m^2y). The LCA results, calculated using the deterministic approach (SIA 2032 and CRB – mean) can be found inside the PDF of the probabilistic LCA and they exhibit a relative good approximation of the PDF mode. Figure 4-right shows the contributions of the different LCA stages for the deterministic SIA 2032 and CRB - mean, as well as for the probabilistic LCA, expressed in GHG emissions of the B1 case study (labelled as “DUREE DB”). The replacement stage in the probabilistic LCA, accounts for 14% to 36% of the GHG emissions for the B1 residential building. The manufacturing stage presents the highest share on the total GHG emissions with values between 47% - 35%, followed by the operational energy use, i.e. 30% - 23%.

The sensitivity analysis followed and the results are presented in Figure 5 for the following configurations: a) the GHG emissions of three new residential buildings (B1, B2, B3), b) the LCA and LCC indicators of the B1 case study, c) the GHG emissions of building B1 for six reference study periods and d) the GHG emissions of three calculation modes of the replacement rate for the B1 case study.

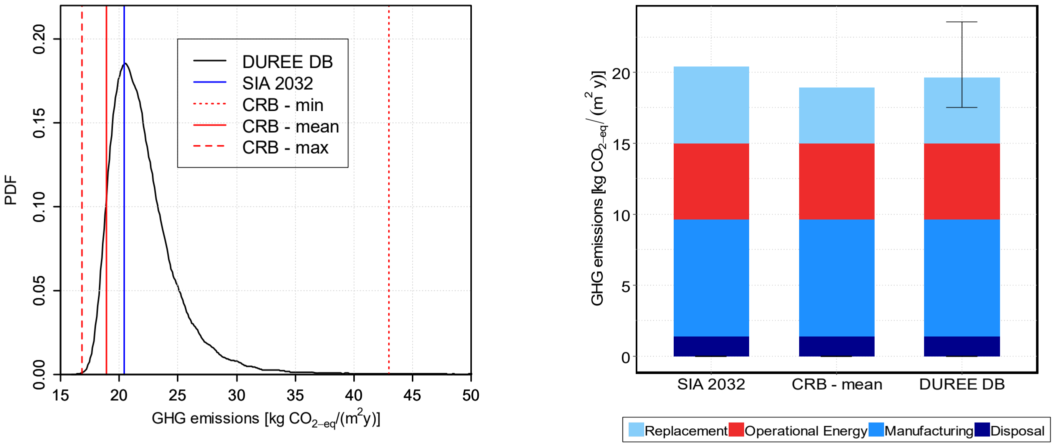
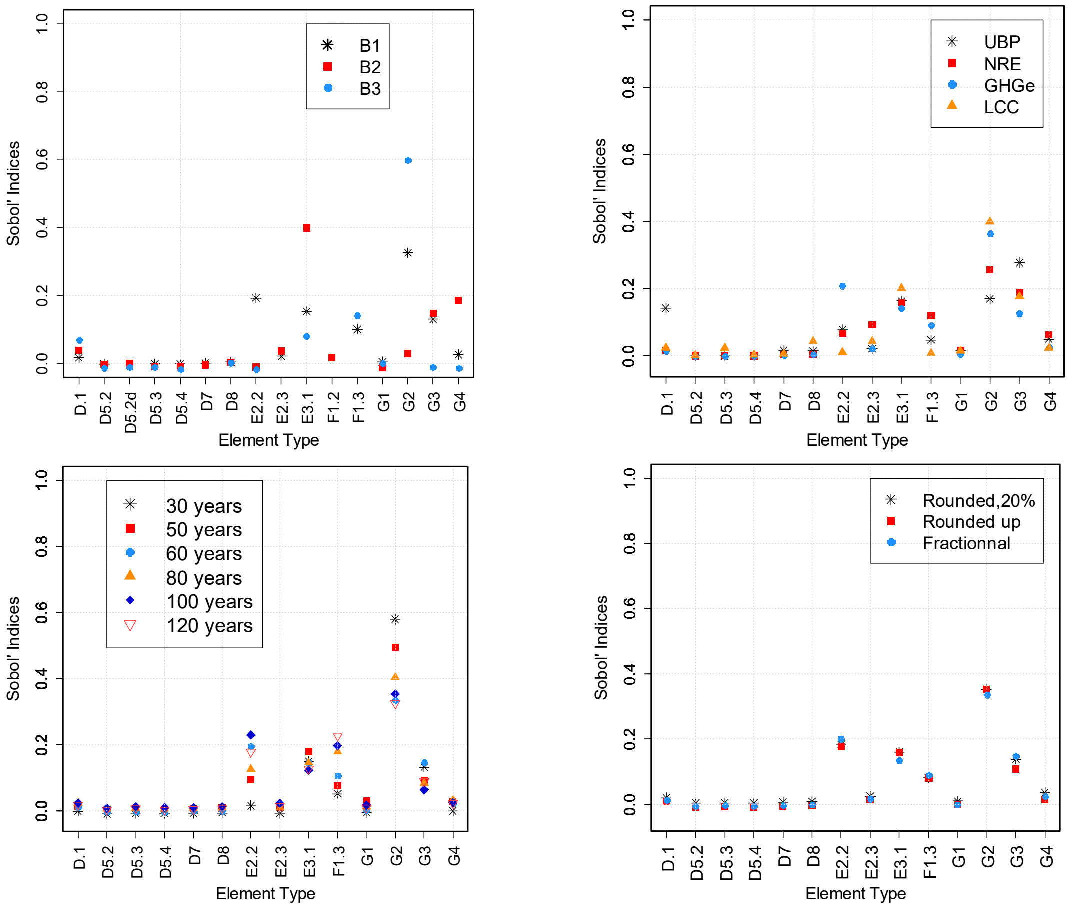


Figure 4 *PDF of the probabilistic LCA for the B1 case study and comparison with the deterministic LCA, using the SIA 2032 and CRB service lives for the GHG emissions (left); contribution analyses for the probabilistic LCA and comparison with the deterministic LCA, using the SIA 2032 and CRB - mean service lives .*

The outcomes of the sensitivity analysis are the following :

- If a threshold is defined at 0.10 for the sensitivity indices, only six element types out of 16 are the most influential on the LCA uncertainty, i.e. E2.2/E2.3 (compact & ventilated façade), the E3.1 (windows), the F1.3 (sloping roof), the G2 (flooring), G3 (internal finishing) and G4 (ceiling covering). This means that special attention should be given when defining the service lives for these element types in further LCA calculations. This result is valid independently of the building typology. The latter affects only the ranking of the 6 most influential building elements;
- The uncertainty of the technical systems service lives (D element type) present low impact on the LCA uncertainty for all the LCA indicators and the LCC.
- The same element types explain the uncertainty of all LCA and LCC indicators, apart from the D1 element type (electrical installation) for the UBP indicator and the E2.2 (compact façade) for the GHGe.

- Varying the reference study period (RSP) of the building from 30 to 120 years leads to a significant variation of the sensitivity indices of the most influential element types.
- The ranking of the elements, calculated with the Sobol' Indices, are not influenced by the calculation mode of the replacement rate, i.e. fractional according to SIA 2032 / SIA 2040 or rounded up according to SN EN 15978 standard.



Names of the building elements:

D1. Electrical installations
D5.2 Heat production
D5.2d Solar collector
D5.3 Heat distribution
D5.4 Heat distribution
D7. Ventilation
D8. Sanitary equipment
E2.2 Compact facade
E2.3 Ventilated facade
E3.1 Windows
F1. Flat or slanted roof
F1.3 Slanted roof
G1. Internal partitions
G2. Flooring
G3. Wall coverings
G4. Ceiling coverings

Figure 5 *Sobol' sensitivity Indices for different simulations: a) GHG emissions for 3 buildings (top-left), b) the three LCA and LCC indicators for building B1 (top-right), c) GHG emissions of building B1 for 6 different reference study periods (bottom-left) and d) the calculation mode of the replacement rate for building B1 (bottom right).*

5. Discussion

WP1: Literature review of service lives

A literature review was conducted for service life data of different building elements, in the Swiss and international literature. The data concerned service lives for structural elements, technical systems, façade elements and coatings and they were structured in a database, namely the DUREE Database. The descriptive statistics were calculated for different samples of the data, i.e. according to the country of their origin (Switzerland and International) and the scope of the sources (LCA, LCC and Management sources). The results showed that there is a relative important variability of the service lives. This is particularly valid for the building elements currently included in the LCA calculations according to the SIA 2032 & SIA 2040 technical books and the SN EN 15978 standard. Furthermore, there is no general agreement, concerning the service life data of the building elements, among the different sources. In addition, there is no significant difference, among the LCA-LCC-Management samples, in terms of variability. Finally, no clear tendency is found among the different sub-samples of service lives (global, Swiss, International, LCA uses, LCC uses, building management uses etc.) i.e. no sample systematically provides higher or lower lifespans for the different building elements. As far as the median values are concerned, two of the three sub-samples present similar values, but they are not systematically the same. Thus, the total sample can be used in further LCA analysis, for the service lives. The service lives proposed by the Swiss SIA 2032 technical book correspond relatively well to the median value of the Swiss sub-sample of the DUREE DB. For the LCC domain, the CRB mean values are not always close to the median value from the Swiss and global samples, the highest deviations being for the technical systems (heat distribution and diffusion, ventilation and electrical systems).

The DUREE database was structured, based on the CRB nomenclature, from which the five main groups were used, as well as two sub-categories. Moreover, five more sub-categories were added, in order to cover lower levels of details. This structure of the database, using a functional nomenclature, i.e. structural work, technical installations etc., offers the flexibility to the designer to attribute the service life data in different LODs, appropriate for BIM-based LCA analysis, e.g. screening LCA analysis (service lives from main groups), or more detailed LCA (service lives from sub-categories). Thus, the DUREE Database can be used for LCA calculations in the early design stages of a building, for which there is not detailed information about the components, or in the late design stages and more detailed LCA calculations.

Finally, the database includes 7000 data of service lives for different building elements and, thus, it offers the possibility to define statistical distributions, with a systematic way, for the service lives. Like that, the service lives can be taken into account using a probabilistic approach in the LCA, and thus, reliability issues in LCA, coming from the service lives uncertainty, could be mitigated.

WP2: Survey in renovation practices

The WP2 chapter concerns the investigation of the empirical lifespans of main building elements and technical systems. A survey was conducted for the renovation timing of the windows, the façade, the roof and the heating system. From this survey the empirical survival curves were calculated and the results were compared to the WP1 data. The survival curves showed that renovation cycles vary considerably across elements. The renovations tend to occur at different points of each element’s effective lifetime. Moreover, even though simultaneous renovations can bring more energy savings, the empirical patterns suggest that bundled renovations (e.g., wall, roof and windows altogether) are not the most frequent practice up to date, even if the SHEDS showed it is not unusual. In addition, the results showed that replacement rates are not constant but change systematically over the life-cycle of an element. In this sense, average annual replacement rates (as reported in previous studies) can provide some information on differences in replacement rates. Yet, given the general sigmoid form of the survival curves, they are likely to over-estimate actual replacement rates among recently installed and old elements, while underestimating actual replacement rates across the medium age range.

The comparison between empirical and literature survival curves showed that, in central tendency, predicted renovation timing generally coincides, except for some elements (e.g. heating distribution and roofs), which necessitates a focused policy attention. Moreover, WP1 literature data systematically under-estimate replacement rates among younger building elements, and over-estimate replacement rates among older ones. Assuming constant replacement rates independent of the element age may thus be overly simplistic when aiming to predict (energy-related) changes in the building stock. One way to improve the predictive power of existing literature service lives, is to analyse the age-specific replacement probabilities. Finally, this comparison indicated a general tendency for suboptimal renovation across all the considered elements especially over the second half-life. In other words, building elements (roof, façade, windows, and heating system) should be renovated earlier and more frequently. This finding confirms that there is room for improvements pointing to an energy-efficiency gap and highlights the importance of policies for promoting renovation of the building stock.

Last, but not least, the existing heterogeneity in norms and technical recommendations (in WP1) could create complexity for building owners who are interested in energy savings. Simplified norms and overall recommendations could be an important step in nudging toward renovation of old building elements.

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WP3: Uncertainty and sensitivity analyses of service lives in building LCA&LCC

The WP3 chapter was focused on the uncertainty and sensitivity analysis of the service lives of the building elements. Through the uncertainty analysis, the importance of the service lives' uncertainty on the LCA&LCC was calculated, while through the sensitivity analysis, the elements, whose service life uncertainty influence the most the LCA&LCC uncertainty, were identified. Based on three new building LCA and LCC studies according to the SIA 2032 system boundary, 6 element types out of 16 are sensitive i.e. the E2.2/E2.3 (compact and ventilated façades incl. the insulation), the E3.1 (windows), the F1.3 (roofing incl. the insulation), the G2 (flooring), the G3 (internal finishing) and G4 (ceiling coverings). The findings are valid whatever the building typology and the indicators are. In addition, the uncertainty of the service lives of the technical systems (D) does not affect the LCA and LCC uncertainty, unless the Ecological Scarcity (UBP) indicator is used and only for the electrical installations. This parameter could be treated deterministically, unless it is imposed by the scope of the study (e.g. in building renovation with only a few renovated elements). It is recommended that in daily practice, for the influential element types, the minimum, mean and maximum values from CRB can be used to approximate the LCA and LCC uncertainty, in order to avoid a probabilistic analysis. The deterministic SIA 2032 service lives values present a relatively good approximation of the LCA mode, i.e. the most probable value of the probabilistic LCA.

In addition, the building lifetime (RSP) is an influential parameter on the LCA and LCC uncertainty. The RSP should be treated probabilistically, in case that it is not surely known. Otherwise, scenario analysis, using conventional RSPs, is recommended. Finally, either of the calculation modes (fractional or rounded up) for the replacement rate can be used in building LCA and LCC methodologies noticed (i.e., fractional according to SIA 2032 & SIA 2040 technical books or rounded up according to SN EN 15978 standard).

6. Perspectives

The DUREE project was focused on the investigation of the service lives of the building elements, starting from a literature review on service life data, continuing with a survey on the empirical service lives and finishing with the uncertainty and sensitivity analyses. The research, reported in this article could be continued with the following activities:

a) The DUREE Database could be enriched, in order to include more service life data. Thus, the extracted PDFs for the service lives of the building elements could represent way the uncertainty of the existing service lives, nowadays.
b) As the SHEDS is an ongoing survey, more data will become available in the near future, and will therefore lend itself to such analyses. In general, there is still considerable potential in exploiting the SHEDS dataset to further improve our understanding of renovation decisions. For instance, an important future step would be to identify parametric functions that accurately describe the empirically observed survival and replacement curves. This information would be helpful to simplify predictions of expected service life, and may therefore directly inform life-cycle analyses or the definition of norms relying on service lives of building elements.
c) Additional case studies can be used for the uncertainty and sensitivity analyses, in order to secure the findings, concerning the LCA& LCC uncertainty, caused by the uncertainty of the service life data.
d) The probabilistic methodology of the current study can be applied in order to evaluate the uncertainty of other parameters, too, e.g. calculation of the heating demand, or other parameters of the LCA & LCC analyses (e.g. manufacturing impact uncertainty). Preliminary studies can be found in [19] and [20].

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