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DUREE Project

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

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Foreword

The lifetimes of building elements influence both the life cycle costs and environmental impacts of new constructions, during the planning stages and also in the renovation of existing buildings. Currently, it is not clear to what extent the lifetime values of the building elements 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 (LCA, LCC). In that context, the DUREE project proposes a three steps approach to reduce the current knowledge gap and deal with this variability:

- First by providing a state of the art gathering the data of the building elements service life, from the Swiss and international literature;
- Second, by examining 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;
- Third by analysing the influence of the service life of building elements in the life cycle assessment (LCA) and life cycle cost (LCC) analysis for residential buildings;

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.

Avant-propos

La durée de vie des éléments de construction influence à la fois les coûts du cycle de vie et les impacts environnementaux des nouvelles constructions, tant au stade de la planification que dans la rénovation des bâtiments existants. Actuellement, il n'est pas clair dans quelle mesure les valeurs de durée de vie des éléments de construction varient, c'est-à-dire les valeurs trouvées dans la littérature et observées dans les pratiques de rénovation. Cette variabilité potentielle peut générer un manque de cohérence, surtout dans les études liées au cycle de vie (LCA, LCC). Dans ce contexte, le projet DUREE propose une approche en trois étapes pour réduire l'écart actuel des connaissances et faire face à cette variabilité :

- D’abord, en fournissant un état de l'art en rassemblant les données de la durée de vie des éléments de construction, à partir de la littérature suisse et internationale ;
- Puis, en examinant ce qui se fait dans la pratique, par le biais d'un sondage auprès des propriétaires d'immeubles, afin de déterminer la durée de vie utile des éléments de construction qui découlent de leur remplacement lors de rénovations ;

- Enfin, en analysant l'influence de la durée de vie utile des éléments de construction dans l'analyse du cycle de vie (ACV) et l'analyse du coût du cycle de vie (CCV) des bâtiments résidentiels ;

Enfin, des recommandations sont formulées à l'intention des décideurs et de la communauté LCA/LCC (comités d'experts et praticiens), afin de mieux gérer la variabilité de la durée de vie des éléments de construction et systèmes techniques du bâtiment.

Vorwort

Die Lebensdauer von Bauteilen beeinflusst nicht nur die Lebenszykluskosten, sondern auch die Umweltauswirkungen von Neubauten, sowohl in der Planungsphase als auch bei der Renovierung bestehender Gebäude. Derzeit ist nicht klar, inwieweit die Lebensdauerwerte der Bauteile variieren, wie zum Bespiel Werte, die aus der Literatur und der Renovierungspraxis stammen. Diese potenzielle Variabilität kann zu einem Mangel an Konsistenz führen, insbesondere in den lebenszyklusbezogenen Studien (LCA, LCC). In diesem Zusammenhang schlägt das DUREE-Projekt einen dreistufigen Ansatz vor, um die derzeitige Wissenslücke zu verringern und mit dieser Variabilität umzugehen:

- Zunächst durch einen Überblick zum Stand der Technik, bezüglich der Daten zur Lebensdauer der Bauteile aus der schweizerischen und internationalen Literatur;
- Zweitens, durch die Untersuchung, der Praxis einer Umfrage der Bauherren, um die effektive Lebensdauer der Bauteile zu ermitteln, die sich durch deren Austausch bei Renovierungen ergibt;
- Drittens durch die Analyse des Einflusses der Lebensdauer von Bauteile auf die Ökobilanz (LCA) und die Lebenszykluskostenanalyse (LCC) für Wohngebäude;

Schließlich werden Empfehlungen für politische Entscheidungsträger und für die LCA/LCC-Gemeinschaft (sowohl Expertenkomitees als auch Praktiker) angeboten, um die Variabilität der Lebensdauer der Bauteile besser zu handhaben.

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Management summary

The DUREE project presents an analysis of both literature and empirical lifespans[1] of building elements, from the Swiss and international literature. Finally, the importance of their variability is identified on the LCA and LCC analyses of building case studies. Figure 1 shows the relationship between the three workpackages of the DUREE project.

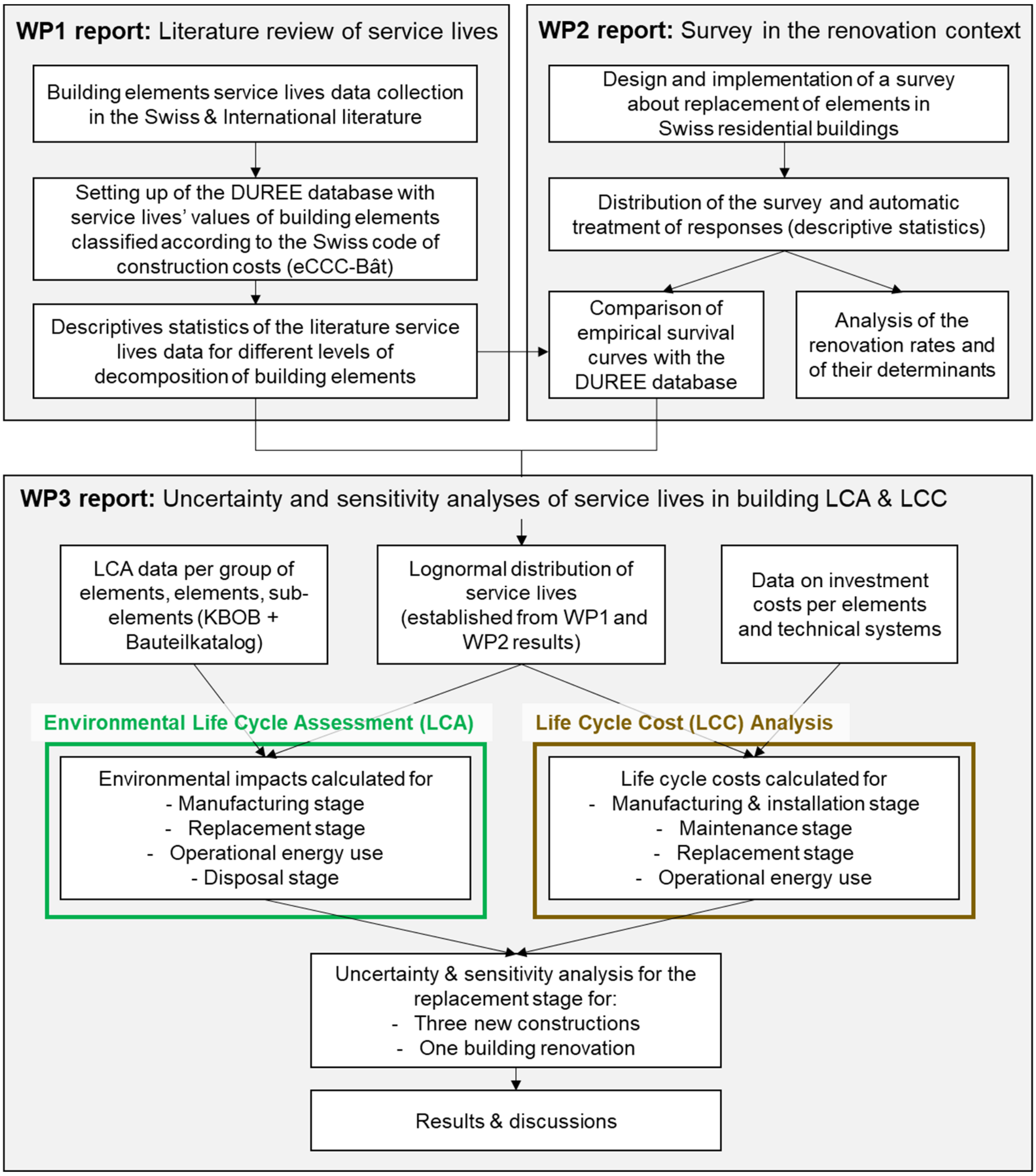

Figure 1: Approach developed in the DUREE project

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[1] In the DUREE project, the terms "lifespan", "lifetime", "service life" of building elements are considered to be equivalent. They correspond to the number of years between the installation of a building element and its future replacement.

WP1: Literature review of service lives (Switzerland and International)

A literature review was conducted and approximately 100 sources were collected. A significant diversity of definitions for the service life was found, as for example “life span", “lifetime” or “service life”. Different values exist among the countries, including Switzerland and the different domains (e.g., guidance documents or standards for energy and environmental life cycle assessment (LCA), life cycle cost analysis (LCC) or building stock management).

In this study, all the identified literature sources were grouped in an Excel database, according to the eCCC-Bât classification from the Centre for Building Rationalisation (CRB), responsible for providing the construction costs. This database helped in the organisation of the literature sources. To that purpose, different levels of details for the building decomposition were defined. The DUREE database (DB) comprises the four eCCC-Bât levels (i.e., the main groups, the groups of elements, the elements and sub-elements), while additional components and systems were defined at lower levels of details. The service lives data were sorted according to the geographical area: Switzerland and International (Europe and the rest of the world). In addition, they were grouped, according to three different domains: energy and environmental life cycle assessment (LCA), life cycle cost analysis (LCC) and building management.

The different data were analysed using descriptive statistics for all the aforementioned samples and the different levels of details. Figure 2 presents the descriptive statistics for the global, Swiss and International 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 data are between 18 and 35 years, while 80% are between 16 to 60 years, the median value being equal to 30 years. For all the building components, there is a high variability in the global sample as well as within the different samples (Swiss and International). Similar findings were observed for the other samples (LCA, LCC, management), as well. Even though the variability is often substantial, for some components, median values or interquartile ranges are relatively comparable between the three samples per geographical zone (e.g., heat production, windows, sloping roof). The results in Figure 1 show that there is no identified clear tendency of a specific sample, providing consistently higher or lower lifespans for the different building elements. In addition, Table 1 presents the comparison of the median Swiss and global DUREE DB samples with the SIA 2032 and the CRB (mean) values of the 16 building elements, used in building LCA & LCC (WP3 study).

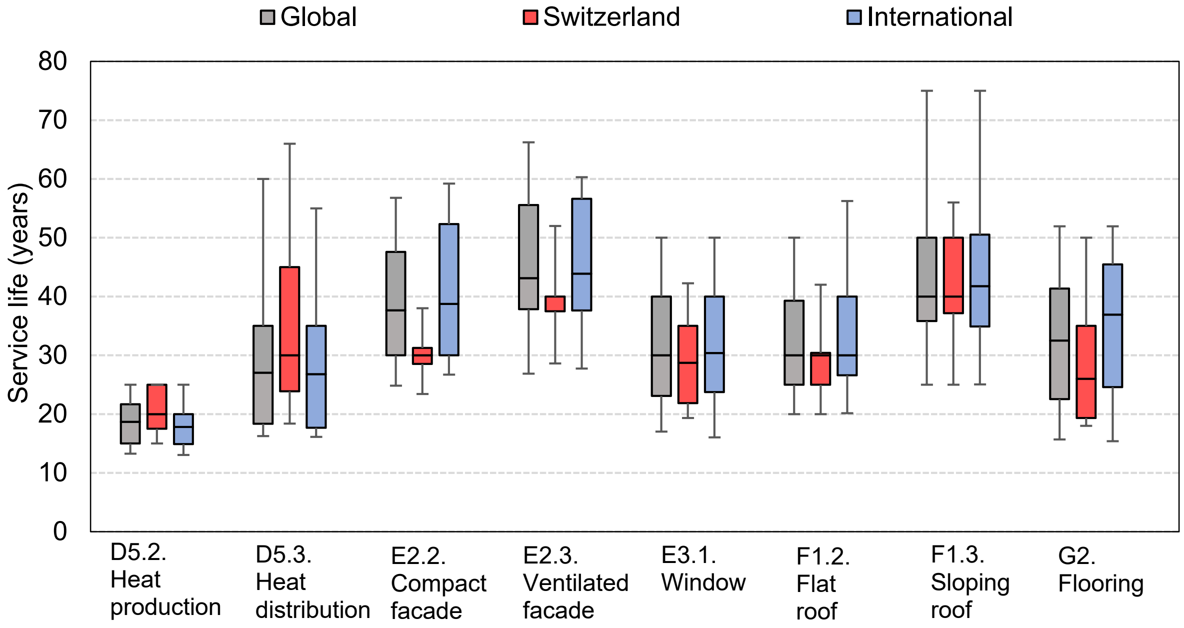


Figure 2: Boxplots of the service lives for eight building elements, included in the system boundary of the SIA 2032 technical book, for the LCA calculation in Switzerland

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

	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%*

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).

WP1 Findings & Recommendations:

The WP1 study provide some insights for expert committees and practitioners interested by the definition of service lives values for building elements.

 # 1: A substantial variability is found in the literature service lives values gathered in the DUREE database (DB), no matter the level of details of the building decomposition. 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.

 # 2: 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., a sample systematically providing higher or lower lifespans for the different building elements.

 # 3: 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).

 # 4: For probabilistic building LCA & LCC studies, the global sample of the DUREE DB is recommended for deriving robust statistical distributions of service lives.

WP2: Survey to determine the effective building elements' service lives in the renovation context

The WP2 presents an analysis of empirical lifespans of the main building elements and technical systems in owner-occupied and tenant-occupied residential buildings in Switzerland. Its main purpose 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 - an 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". The WP2 contributes to the current state-of-the-art in two ways. First, unlike most previous research, the analysis covers a large geographical scope, including all of the French- and German-speaking regions. Second, instead of eliciting replacement rates over pre-defined time intervals, the survey aims at eliciting the renovation history of buildings. This allows tracing replacement rates by the age of the element, rather than the age of the entire building, hence to construct detailed life-tables and survival curves for the building elements of interest. The analysis is conducted on data extracted from two annual waves (2017 and 2018) of the Swiss Households Energy Demand Survey (SHEDS), an online survey of roughly 5’000 households per year in the German and French speaking parts of Switzerland. Lifespans are 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 a much higher data representativeness using 5000 observations.

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 “CRB-RSL” and “CRB-ESL”). This figure provides information on the shape of survival curves of building elements i.e., the evolution of 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.

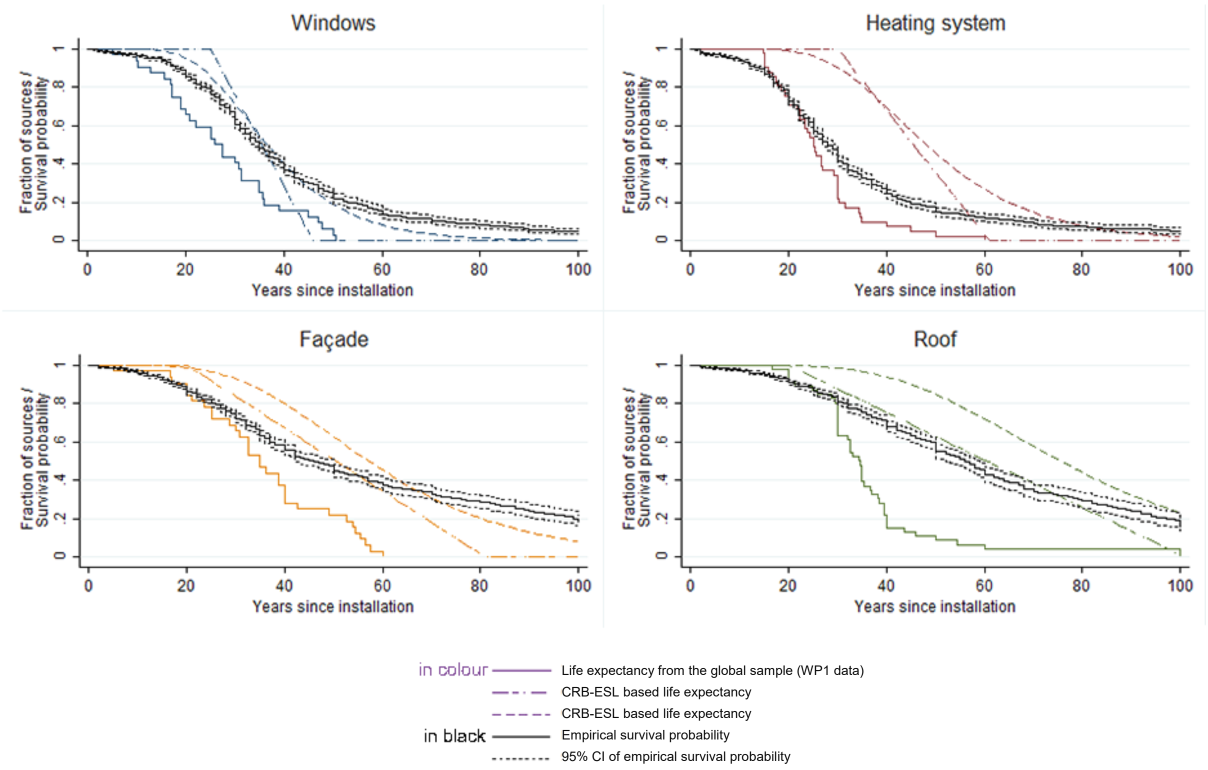


Figure 3: Survival curves for the four building elements for the heating system using SHEDS 2017 and 2018 in comparison with the global statistics in the WP1 study and CRB data

Comparing literature-based curves (WP1 study) with empirical survival curves (WP2 study), we find that renovation timing generally coincides in their median values (see Figure 3). 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's 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 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. To analyse in more details, Figure 4 shows the results for the heat production and distribution sub-elements. For heat production, the CRB-based survival curves are now very close to the all WP1 data. The SEHDS slightly over-estimate the year of the median replacement. Conversely, all WP1 data, and to a less extent the CRB, under-estimate the heat distribution replacement compared to the SHEDS.

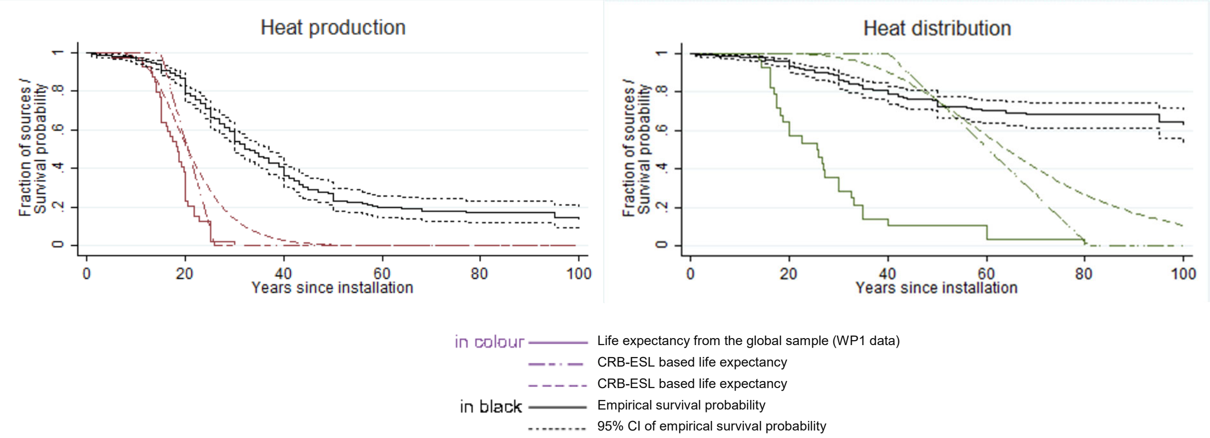


Figure 4: Survival curves for the sub-elements for the heating system using SHEDS 2017 and 2018 in comparison with the global statistics in the WP1 study and CRB data

Independent of the lifetimes' sources, we observe that 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 under-estimate 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.

From a policy perspective, there are two – somewhat contrasting – conclusions that can be drawn from the previous observation. Which one dominates depends on the primary function that literature-based lifetime values are supposed to fulfil in the building environment. If they are primarily there to describe the technically or environmentally optimal timing of renovations, then the observed discrepancy between the literature and empirical element survival suggests that a significant number of renovations are sub-optimal. Therefore, shifting renovation timing among this group would yield comparatively large economic and environmental benefits. On the other hand, if the main function of the WP1 data is to provide guidelines for the prediction and planning of replacement cycles, then the observed differences indicate that they are likely to gain in predictive accuracy by accounting for these differences. One way to improve the predictive power of existing literature service lives, is to analyse the age-specific replacement probabilities.

The SHEDS results also show 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.

A final 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 econometric models that are introduced in chapter 5 of the WP2 report. 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. While there is some variation in the relationship across the different elements, the following patterns emerge across all elements:

- 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.
- 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.
- 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 [3], [10]. 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.

Additional results in the form of survival curves for tenant-occupied households and also survival patterns of sub-elements are further described in the WP2 report. Other in-depth analyses comparing renovation rates derived from the SEHDS with those reported in previous studies, are documented in the WP2 report (chapter 3). Finally, there are some limitations to the present research. In particular, relying on self-reported retrospective replacements makes our estimates vulnerable to potentially systematic errors of recall. Moreover, reported renovations generally refer to major retrofits, but may potentially include minor upgrades and repairs, as well. In future work, a more detailed analysis restricting the sample to major energy-efficiency renovations would be a valuable addition to the present results, and would allow to judge to what extend smaller element refurbishments drive current findings. As the SHEDS is an ongoing survey, more data will become available in the near future, and will therefore lend itself to such analyses.

WP2 Findings & Recommendations:

The WP2 study provide some insights for policy makers regarding the promotion of energy efficient renovations.

 # 1: Renovation cycles vary considerably across elements. The renovations tend to occur at different points of each element’s effective lifetime. While 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.

 # 2: Comparing literature survival curves (global WP1 and the Swiss CRB) with empirical survival curves (WP2), we find that, in central tendency, predicted renovation timing generally coincides except for some elements (e.g., heating distribution and roofs) calling for a focused policy attention.

 # 3: 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.

 # 4: The comparison of observed renovation patterns with those recommended by the different literature sources (WP1 study) indicate 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.

 # 5: 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.

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.

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

The WP3 study presents a systematic way to deal with the literature (WP1) and empirical (WP2) service lives uncertainty of building elements when performing building LCA and LCC calculations. In the beginning, the uncertainty analysis is conducted. Service lives data, collected in WP1 (DUREE DB) and WP2, are used to calculate the replacement rates for each building element by dividing each service life with the reference study period (RSP), equivalent in the DUREE project to the building lifetime. Monte Carlo simulations are 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 are defined. Finally, the Sobol' Sensitivity Indices are calculated to determine the impact of the service lives' variability on the LCA uncertainty, for the different building elements. This methodology is applied to four residential building case studies, including three new constructions and one renovation project. 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) are evaluated.

Figure 5 (left) presents the uncertainty analysis of one new construction case study (B1), for the GHG emissions. 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 results show that the uncertainty of the replacement rate can significantly affect the LCA uncertainty. 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. The replacement stage in the probabilistic LCA, accounts for 14% to 36% of the GHG emissions for the B1 residential building (see Figure 5 - right). Similar results can be found in detail, in the WP3 report for the other indicators and building case studies.

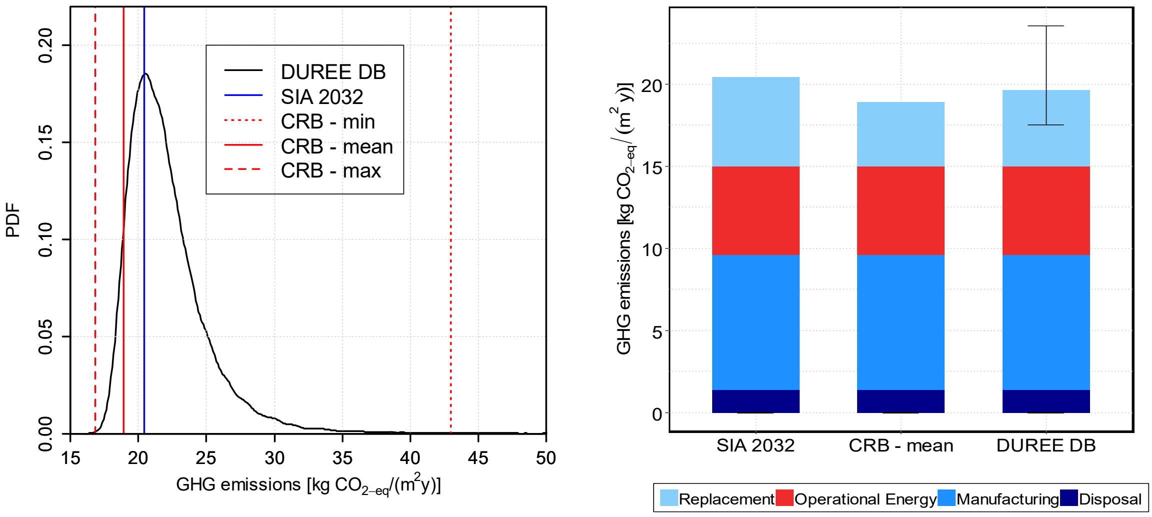


Figure 5: PDF of the probabilistic LCA for the B1 case study and comparison with the deterministic LCA, using the SIA 2032 and CRB service lives for the GHG emissions (left); contribution analyses for the probabilistic LCA and comparison with the deterministic LCA, using the SIA 2032 and CRB - mean service lives

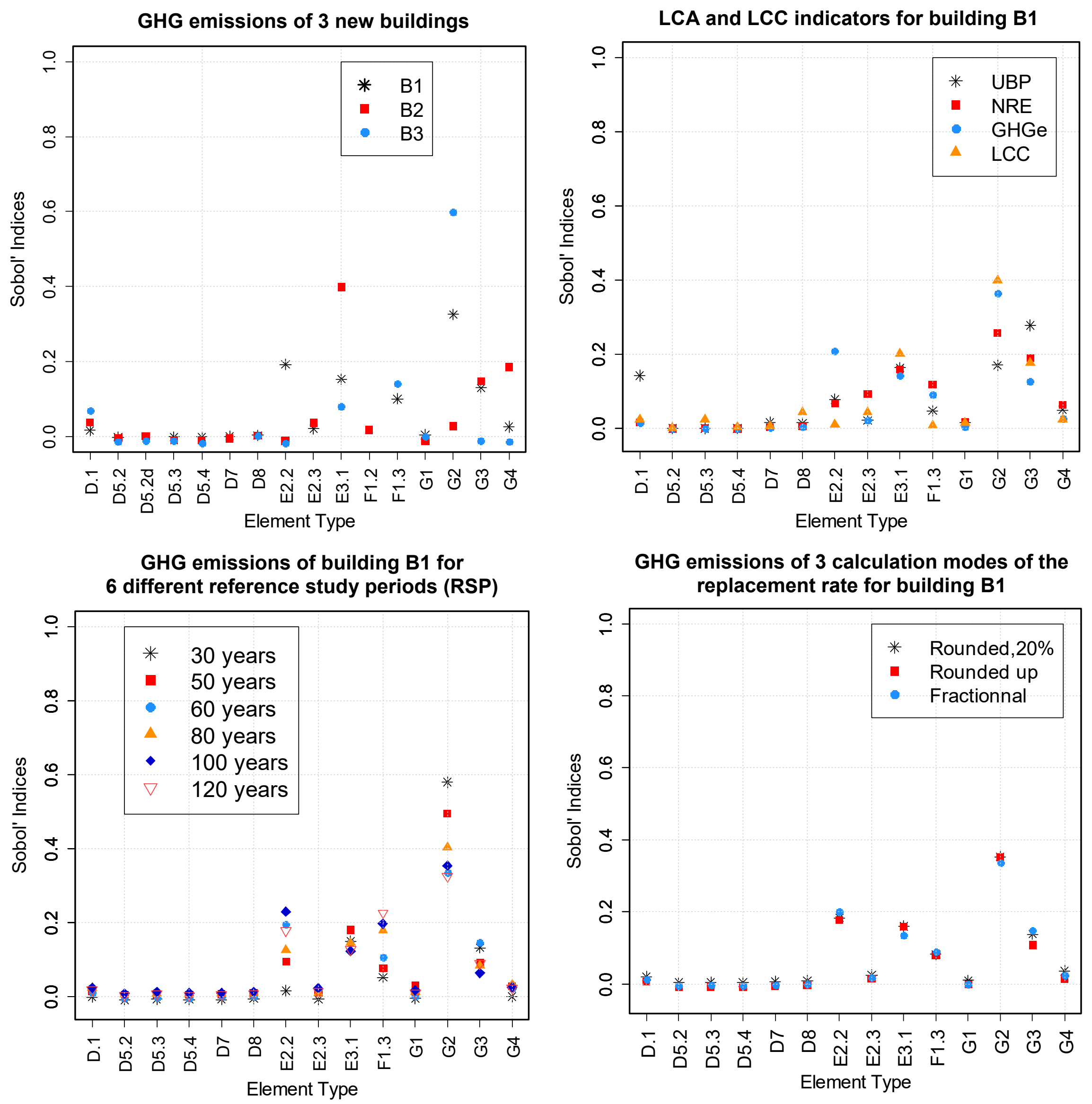
Figure 6 presents the synthesis of sensitivity analyses for the following configurations:

- the GHG emissions of three new residential buildings (B1, B2, B3),
- LCA and LCC indicators for the B1 case study;
- the GHG emissions of building B1 for six reference study periods;
- the GHG emissions of three calculation modes of the replacement rate for the B1 case study.

The outcomes of the WP3 study 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 (compact 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. In further probabilistic LCA analysis, the LCA model could be simplified and conventional deterministic values from the standards (SIA 2032, DRB) could be used for this building element, instead;
- 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. Hence, for the UBP indicator and the GHGe special attention should be given to the attribution of D1 and E2.3 service life, respectively;

- 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. Thus, the RSP is an influential parameter on the LCA and LCC uncertainty.
- The LCA uncertainty is 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. Hence, both modes could be used in further LCA and LCC analysis.



GHG emissions of 3 new buildings

LCA and LCC indicators for building B1

GHG emissions of building B1 for 6 different reference study periods (RSP)

GHG emissions of 3 calculation modes of the replacement rate for building B1

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 6: 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).

WP3 Findings & Recommendations:

The WP3 study provide some recommendations for building LCA/LCC method & tool developers as well as for building LCA/LCC practitioners.

 # 1: 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 (i.e., greenhouse gas emissions (GHGe), primary non-renewable energy consumption (NRE), ecopoints (UBP), life cycle costs (LCC)).

 # 2: The uncertainty of the service lives of the technical systems (D) does not affect the LCA and LCC uncertainty, unless the 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).

 # 3: 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.

 # 4: 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.

 # 5: Either of the calculation modes for the replacement rate can be used in building LCA and LCC methodologies as no strong influence is noticed (i.e., fractional according to SIA 2032 & SIA 2040 technical books or rounded up according to SN EN 15978 standard).

Acknowledgments

The authors of the DUREE project warmly thank the international partners of the IEA-EBC Annex 72 project for their contribution to the additional data collection of service lives as part of the survey on national building LCA methodologies.

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International collaborations and disseminations

The outcomes of DUREE WP1 & WP3 studies have been used for the Swiss contribution to the IEA EBC Annex 72 project[2] "*Assessing Life Cycle Related Environmental Impacts Caused by Buildings*" under the Subtask 1 "Harmonised methodology guidelines". It concerns the following aspects:

- the provision of a template for reporting the service lives using the decomposition of building elements in different levels of details of the DUREE database based on the Swiss e-BKP nomenclature (see WP1 report);
- the writing of a technical note about the influence of service lives in the replacement stage of a building LCA;
- the preparation of a conference paper for a mini-symposium "Annex 72" during the IALCCE conference in October 2018.

Scientific and technical papers have also been prepared based on the DUREE project to disseminate the results to the scientific community:

- **WP1 Study:**

  K. Goulouti, M. Giorgi, D. Favre and S. Lasvaux, Development of a Service Life Database of Building Elements Based on an International Data Collection, in: Current Topics and Trends on Durability of Building Materials and Components, Serrat et al. (Eds). URL: https://www.scipedia.com/public/Goulouti_et_al_2020a

- **WP2 Study:**

  B. Volland, M. Farsi, S. Lasvaux, P. Padey (2019). Service life of building elements: An empirical investigation, *Working paper*, 2019. https://www.econstor.eu/bitstream/10419/213486/1/1687400857.pdf

- **WP3 Study:**

  K. Goulouti, P. Padey, A. Galimshina, G. Habert and S. Lasvaux (2020). Influence of building elements' service lives in LCA & LCC of buildings: what matters? *Building & Environment*, 183, 2020, doi: https://doi.org/10.1016/j.buildenv.2020.106904.

  K. Goulouti, P. Padey, A. Galimshina, G. Habert and S. Lasvaux (2020). Descriptive statistics from a literature review on service lives data of building elements and parameters of the fitted lognormal distribution, *Submitted to Data-in-Brief*, 2020.

  K. Goulouti, P. Padey, A. Galimshina, G. Habert and S. Lasvaux, Uncertainty and Sensitivity Analyses for Evaluating the Building Element's Replacement in Building LCA, in: Current Topics and Trends on Durability of Building Materials and Components, Serrat et al. (Eds). URL https://www.scipedia.com/public/Goulouti_et_al_2020b

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[2] http://annex72.iea-ebc.org/

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Département fédéral de l'environnement, des transports,
de l'énergie et de la communication DETEC

Office fédéral de l'énergie OFEN

Projet DUREE

WP 1 : Analyse bibliographique des durées de vie de la littérature (Suisse et international)

Rapport final

Auteurs :

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(HES-SO | HEIG-VD | IGT-LESBAT)

Summary

The lifespan of a building element can vary according to the sources of information, which generates a lack of consistency in some analyses (economic, ecological, etc.). The aim of this project is to synthesize the values found in Swiss and foreign literature, examine what is being done in practice and analyse the effect of this variability on case studies in order to possibly propose more consistent values.

The objective of the DUREE WP1 report is to present an analysis of the lifetime values currently available in the literature for different geographical areas (Switzerland and International) and source types (use for life cycle assessment calculations, cost analysis or building management). Around hundred sources of lifetime data have been identified. After grouping some of them in a database structured according to the Swiss Construction Cost Code, descriptive statistics are presented by type of sources and geographical area. Although the data sample remains statistically limited, it provides a trend of current literature values. The results show that whatever the component, the dispersion of values remains significant. The results do not show systematic trends in lifetime values by geographical area or type of source. The global statistics can then be used to assess the lifetime sensitivity of elements on building case studies in the DUREE WP3 study.

Résumé

La durée de vie d'un élément de construction peut varier selon les sources d'information, ce qui génère un manque de consistance lors de certaines analyses (économique, écologique, etc.). Ce projet a pour but de faire une synthèse des valeurs trouvées dans la littérature suisse et étrangère, d'examiner ce qui se fait dans la pratique et d'analyser l'effet de cette variabilité sur des cas d'étude pour proposer éventuellement des valeurs plus consistantes.

L'objectif du rapport DUREE WP1 est de présenter une analyse de valeurs de durées de vie actuellement disponibles dans la litérature pour différentes zones géographiques (Suisse et International) et types de sources (utilisation pour des calculs d'écobilan, d'analyse de coûts ou pour gérer un bâtiment). Environ une centaine de sources de données de durées de vie ont été identifées. Après un regroupement d'une partie d'entre elles dans une base de données structurée selon le code des coûts de la construction suisse (eCCC-Bât), des statistiques descriptives sont présentées par type de sources et zone géographique. Même si l'échantillon de données reste limité d'un point de vue statistique, il fournit une tendance des valeurs actuelles de la littérature. Les résultats montrent que quel que soit le composant, la dispersion des valeurs reste importante. Les résultats ne montrent pas de tendances systématiques sur les valeurs de durées de vie selon la zone géographique ou le type de sources. Les statistiques peuvent alors être utilisées de manière globale pour évaluer la sensibilité des durées de vie d'éléments sur des études de cas de bâtiments dans l'étude DUREE WP3.

Zusammenfassung

Die Lebensdauer desselben Bauteils kann je nach Informationsquelle variieren, was bei einigen Analysen (ökonomischen, ökologischen usw.) zu einer mangelnden Konsistenz führt. Ziel dieses Projekts ist es, die in der schweizerischen und ausländischen Literatur gefundenen Werte zu synthetisieren und zu untersuchen, was in der Praxis getan wird sowie die Auswirkungen dieser Variabilität auf Fallstudien zu analysieren, um möglicherweise konsistentere Werte vorzuschlagen.

Ziel des DUREE WP1-Berichts ist es, eine Analyse der in der Literatur derzeit verfügbaren Lebensdauerwerte für verschiedene geografische Gebiete (Schweiz und International) und Quellentypen (Verwendung für Ökobilanzrechnungen, Kostenanalyse oder Gebäudemanagement) darzustellen. Etwa hundert Quellen von Lebenszeitdaten wurden identifiziert. Nach einer Gruppierung

einiger davon in einer nach dem Schweizerischen Baukostengesetz (eBKP-H) erstellt. Obwohl die Datenprobe statistisch begrenzt bleibt, liefert sie einen Trend der aktuellen Literaturwerte. Die Ergebnisse zeigen, dass unabhängig von der Komponente die Streuung der Werte signifikant bleibt. Die Ergebnisse zeigen keine systematischen Trends der Lebensdauerwerte nach geografischen Gebieten oder Quellentypen. Die Statistiken können dann global verwendet werden, um die Empfindlichkeit von Elementen auf die Lebensdauer von Fallstudien in der DUREE WP3-Studie zu bewerten.

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Liste d’abréviations

ACHRU : Association canadienne d’habitation et de rénovation urbaine
ACV : Analyse de Cycle de Vie
ASLOCA : Association suisse des locataires
BDD : Base de données
BLP: Building Life Plans
BNB : Nutzungsdauern von Bauteilen
CATEF : Chambre tessinoise de l’économie foncière
CECB : Certificat Energétique Cantonal des Bâtiments
CRB : Centre suisse d'études pour la rationalisation de la construction
DUREE : Base de données de DUREEs de vie d’éléments de construction
DVR : Durée de vie de référence
eCCC-Bât : Code des Coûts de construction Bâtiment
eBKP-H : Baukostenplan Hochbau
EPFL: Ecole Polytechnique Fédérale de Lausanne
FMEA : Failure mode and effects analysis
IBGE: Institut Bruxellois pour la Gestion de l’Environnement
IEA-EBC: International Energy Agency Energy in Buildings and Communities Programme
ISO : International Standard Organisation
LBB : Lebensdauer von Bauteilen und Bauschichten
LCA: Life Cycle Assessment
LCC : Life Cycle Cost
LESBAT : Laboratoire d’Energétique Solaire et de Physique du Bâtiment
MERIP : méthode de diagnostic sommaire
ModEnHa : Modèle d'Encouragement Harmonisé des cantons
OFEN : Office Fédéral de l’Energie
SANETAP : Nachhaltige Gebäudeerneuerung in Etappen
SIA : Société Suisse des Ingénieurs et des Architectes
SVIT : Union suisse des fiduciaires immobilières
SVV : Association suisse d’assurance
TOTEM : Tool to Optimise the Total Environmental impact of Materials
UPSI : Union des Professionnels Suisse de l’Immobilier
VZI : Association des sociétés immobilières de Zürich

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1 Introduction

D'un point de vue technique, la durée de vie des éléments de construction est fonction de plusieurs paramètres de durabilité du matériau ou des matériaux constitutifs, et de ses conditions d'exposition et de dégradation à l'intérieur ou à l'extérieur du bâtiment. Selon le point de vue de l'acteur (gestionnaire de parc, planificateur de bâtiment, expert en écobilan, expert en calcul de coûts sur le cycle de vie), les définitions et les valeurs de durées de vie pourront différer. Il est alors important de faire un état des lieux des terminologies existantes et des notions rattachées au terme de « durée de vie ».

1.1 Terminologies existantes pour qualifier la durée de vie

La terminologie employée par les normes faisant mention de durée de vie diffère d'un document à un autre. Le Tableau 1 reporte ces différentes définitions.

Tableau 1: Exemples de terminologie existante dans la littérature pour qualifier la durée de vie d'un élément

	Terminologie existante	**Source**	**Définition** *(dans la langue de la référence)*
1	Durée de vie	ISO 15686-1 :2011 [1]	*« Période débutant avec la mise en service, durant laquelle une installation ou ses différentes parties atteignent ou dépassent les performances requises »*
		Dulling, 2006 [2]	*« The period after installation during which a building or its parts meet or exceeds the performance requirements »*
2	Durée de vie de référence	ISO 15686-1 :2011 [1]	*« Durée de vie connue d'un produit/composant/ensemble/système, prévue dans un ensemble particulier, c'est-à-dire un ensemble de référence, de conditions d'utilisation et pouvant servir de base pour l'estimation de la durée de vie dans d'autres conditions d'utilisations »*
		Dulling, 2006 [5]	*« Service life for a building or a building part for use as a basis for estimating service life »*
3	Durée de vie prédite	ISO 15686-1 :2011 [1]	*« Durée de vie prédite à partir de performances enregistrées dans le temps conformément au mode opératoire décrit dans l'ISO 15686-2 »*
		Dulling, 2006 [5]	*« Service life predicted from recorded performance over time as obtained, for instance, in ageing tests »*
4	Durée de vie estimée	ISO 15686-1 :2011 [1]	*« Durée de vie prévue ou attendue d'un bâtiment ou de ses différentes parties dans certaines conditions d'utilisation spécifiques, déterminée à partir des données relatives à la durée de vie de référence après avoir tenu compte des différences par rapport à la référence dans les conditions d'utilisation »*
5	Durée de vie prévue lors de la conception	ISO 15686-1 :2011 [1]	*« Durée de vie que le concepteur a indiquée au maître d'ouvrage pour étayer les décisions de spécification »*
6	Durée de vie technique	SIA 480:2004 [3] SIA 2047:2015 [4]	*« La durée de vie technique correspond à la période entre la mise en service d'un élément de construction et son remplacement consécutif à une diminution de fiabilité ou à une augmentation des coûts d'entretien et de remplacement de ses composants »*
7	Durée d'utilisation	SIA 480:2004 [3] SIA 2047:2015 [4]	*« Intervalle de temps prévu écoulé entre la mise en service et le remplacement d'un élément de construction ou d'installation. La durée d'utilisation est limitée soit par la durée de vie technique,*

	Terminologie existante	Source	**Définition** *(dans la langue de la référence)*
			soit par un remplacement éventuel visant à satisfaire de nouveaux besoins (confort, esthétique, nouvelle affectation, etc.) ou à améliorer les performances techniques (par ex. amélioration du bilan énergétique) »
8	Durée d'amortissement	SIA 2032 [5]	*« La durée d'amortissement est la période pendant laquelle l'énergie grise pour la construction et l'élimination est amortie.* *A l'exception de la fouille de fondation et la structure porteuse (groupes d'éléments B et C), la durée d'amortissement correspond à la durée d'utilisation.* *Pour la fouille de fondation et la structure porteuse, la durée d'amortissement fixée est inférieure à ce que serait la durée d'utilisation, de façon à ne pas charger les générations futures avec les amortissements correspondant aux investissements actuels en énergie grise»*

Le Tableau 1 montre que de nombreux termes ont été introduits via la norme internationale ISO 15686-1 [1] : durées de vie de référence, prédite, estimée, prévue lors de la conception. Cette norme forme un cadre de compréhension. La durée de vie de référence peut être modulée selon différentes conditions d'application pour arriver à une durée de vie estimée. De même, si des essais sont disponibles (p.ex. vieillissement accéléré), ils permettent de définir une durée de vie prédite. D'autres notions sont introduites pour les planificateurs de constructions neuves ou de rénovations. Le choix des durées de vie des éléments de construction se base actuellement sur des normes différentes selon le type de calcul à effectuer (analyse des coûts du cycle de vie ou écobilan). Pour la Suisse, il s'agit de la norme SIA 480:2016 "Calcul de rentabilité pour les investissements dans le bâtiment" [3] et du cahier technique SIA 2032:2010 "Calcul d'énergie grise des bâtiments" [5]. Selon ce dernier, la durée d'amortissement est la période pendant laquelle l'énergie grise pour la construction et l'élimination est amortie. Cette durée correspond, par convention, à la durée d'utilisation. La durée d'utilisation représente ensuite, selon la SIA 480 ou le cahier technique sur la rénovation énergétique SIA 2047 [4], l'intervalle de temps prévu/écoulé entre la mise en service et le remplacement d'un élément de construction. Elle est limitée soit par la durée de vie technique, soit par un remplacement visant à satisfaire de nouveaux besoins (confort, esthétique) ou à améliorer les performances techniques (p.ex. amélioration de la performance énergétique).

1.2 Facteurs d'influence et approches pour l'évaluation de la durée de vie

Des facteurs liés à la durabilité et à l'environnement

De nombreux facteurs influencent ou limitent la durée de vie d'un élément de construction. La Figure 1 offre une représentation de ces facteurs. En premier lieu, les facteurs de durabilité liés au niveau de conception, à la qualité des matériaux employés et de la mise en œuvre ainsi qu'au niveau de maintenance. Face à ces facteurs contribuant à augmenter la durée de vie d'un composant, il existe aussi des facteurs de dégradation liés au contexte dans lequel l'élément de construction est introduit : climat extérieur, climat intérieur et environnement opérationnel (niveau de sollicitation et d'utilisation de l'élément).

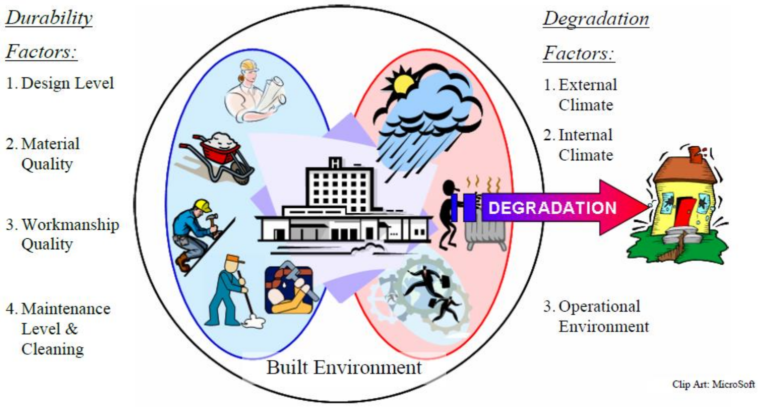

Figure 1: Facteurs de durabilité et de dégradation d'un élément de construction, tiré de Dulling 2006 [2]

Le rapport sur la méthode de diagnostic sommaire (MERIP), rédigé dans le cadre du projet PI BAT [6], classe quant à lui les types d'obsolescence en deux catégories : ceux propres au bâtiment lui-même et ceux liés à des facteurs externes. Les obsolescences intrinsèques au bâtiment sont définies comme étant les pertes de fonctionnalité, le manque ou un changement d'utilisation ou l'aspect esthétique. Les facteurs externes définis sont les nouvelles exigences légales, les effets de mode, les aspects écologiques pas ou mal considérés par le passé, et la rentabilité économique.

Pour tenir compte de ces facteurs de durabilité et de dégradation dans l'évaluation de la durée de vie, la norme ISO 15686-1 introduit la méthode dite des facteurs. Cette méthode part d'une durée de vie de référence (DVR) pour chaque élément qui est ensuite altérée par différents facteurs définis dans la norme ISO 15686-1 [1]. Le principe consiste à multiplier sept facteurs d'influence :

- A : qualité de l'élément ;
- B : niveau de conception ;
- C : niveau d'exécution ;
- D : environnement interne ;
- E : environnement externe ;
- F : condition d'utilisation ;
- G : niveau de maintenance.

Ces sept facteurs prennent chacun une valeur comprise entre 0.8 et 1.2. Le facteur final se calcule en multipliant chacun de ces facteurs. Puis, il est appliqué à la durée de vie de référence de l'élément considéré. Cette procédure permet d'obtenir alors la durée de vie estimée (ESL).

Sur le même principe que cette méthode, d'autres sources utilise la même approche d'ajustement de la durée de vie de référence en fonction de facteurs de vieillissement. Le point de départ de ces méthodes est donc la définition de la durée de vie de référence. Cependant, il n'y a pas de valeur faisant l'unanimité, quel que soit l'élément choisi. Selon la source considérée ou le type d'objectif recherché (calcul économique, gestion d'un parc de bâtiment, calcul énergétique ou environnemental), la durée de vie de référence peut sensiblement varier.

Certaines sources complètent les termes « durée de vie de référence » par « durée de vie utile de référence » [7]. Le processus pour estimer la durée de vie utile d'un composant consiste à comparer les conditions de référence et les conditions réelles du projet ou du bâtiment. Plus le bâtiment est bien caractérisé, plus la durée de vie estimée est fiable. Cependant, cette approche n'est pas toujours mise en pratique à ce niveau de détails, notamment en planification où les conditions d'exposition et d'utilisation ne sont pas connues avec précision. Il existe donc une multitude de scénarios d'usage entraînant un niveau d'incertitudes élevé sur la durée de vie réelle des éléments.

D'après Dulling [2], en plus de la méthode des facteurs de l'ISO 15686-1 [1], la durée de vie estimée peut être évaluée par :

- des indices statistiques ;
- des analyses de vieillisement accéléré ;
- des probabilités ;
- l'analyse des effets et modes de défaillance (FMEA)[1];
- diverses approches d'ingénierie.

Cependant, ces approches sont soit théoriques, soit limitées à des retours d'expériences (essais de vieillissement). Ils ne permettant pas de généraliser les valeurs obtenues.

Au niveau opérationnel, quelques travaux ont déjà été menés en Suisse dans le domaine (programme PI BAT [6], projet et méthodes MERIP [8] et EPIQR [9]) pour mieux évaluer la durée de vie résiduelle[2] des éléments de construction et aider le propriétaire à anticiper les coûts de remise en état de ses bâtiments. Ces projets visaient surtout à fournir des méthodes d'aide à la décision pour le gestionnaire de parc.

Des facteurs pas seulement techniques

La difficulté de prévision des durées de vie des éléments constitutifs des bâtiments peut être fortement influencée par des facteurs externes « non techniques » liés aux décisions de rénovation prises par les propriétaires (institutionnels, privés, gestionnaire de parcs). Par exemple, les éléments du bâtiment peuvent être remplacés avant que ceux-ci n'aient atteint leur durée de vie technique (ou leur durée de vie de planification), pour des motifs tels que :

- des effets d'aubaines liés à des incitations financières ponctuelles lors des rénovations (subventions généreuses sur certains éléments particuliers) ;
- l'objectif de maximiser la valeur du bâtiment en vue d'une opération de cession ;
- l'obligation de respecter de nouvelles dispositions légales (p.ex. obligation de remplacer certains systèmes de chauffage selon le niveau de polluants émis ou selon nouvelle stratégie énergétique cf. l'exemple du remplacement actuel des chauffages électriques en Suisse[3]).

A l'inverse, certains propriétaires peuvent ne pas rénover un élément de construction même si la durée de vie théorique (i.e., celle fournie par les normes de planification) est déjà atteinte. Des écarts peuvent alors exister entre les durées de vie utilisées dans la planification et les durées de vie effectives[4] correspondant à la durée, depuis la dernière rénovation ou depuis la construction du bâtiment, au bout de laquelle un élément est remplacé. Il existe, à l'heure actuelle, peu de travaux qui documentent l'année au bout de laquelle les éléments de construction et les installations techniques sont rénovés dans la pratique[5].

La Figure 2 présente une visualisation des durées de vie d'éléments d'un bâtiment existant construit en 1972 et rénové en 2015. Pour chaque élément, la durée de vie utilisée en planification est reportée en trait plein vert. Cet exemple montre qu'au moment de la rénovation en 2015, huit éléments avaient déjà dépassé leur durée de vie selon le guide CRB [10] visible par les traits jaunes pleins représentant des années supplémentaires par rapport à la durée de vie utilisée en planification.

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[1] Méthode structurée d'analyse de défaillance consistant à passer en revue les composants détaillés d'un système afin d'identifier les défaillances pouvant survenir ainsi que leurs causes et leurs conséquences.

[2] Durée de vie entre le moment de l'évaluation et le prochain remplacement prévu du composant

[3] https://www.endk.ch/fr/ablage_fr/conseil.../remplacement-chauffage-electrique.pdf

[4] Ce terme est introduit par les auteurs de ce rapport. La durée de vie effective représente la durée de vie réelle issue de la pratique. Celle-ci est souvent dictée par des facteurs décisionnels tels que les coûts (p.ex. de maintenance) ou une défectuosité technique (casse, baisse de performances, vétusté, etc.).

[5] Ce constat a fait l'objet d'un travail de recherche spécifique dans le rapport WP2 du projet DUREE

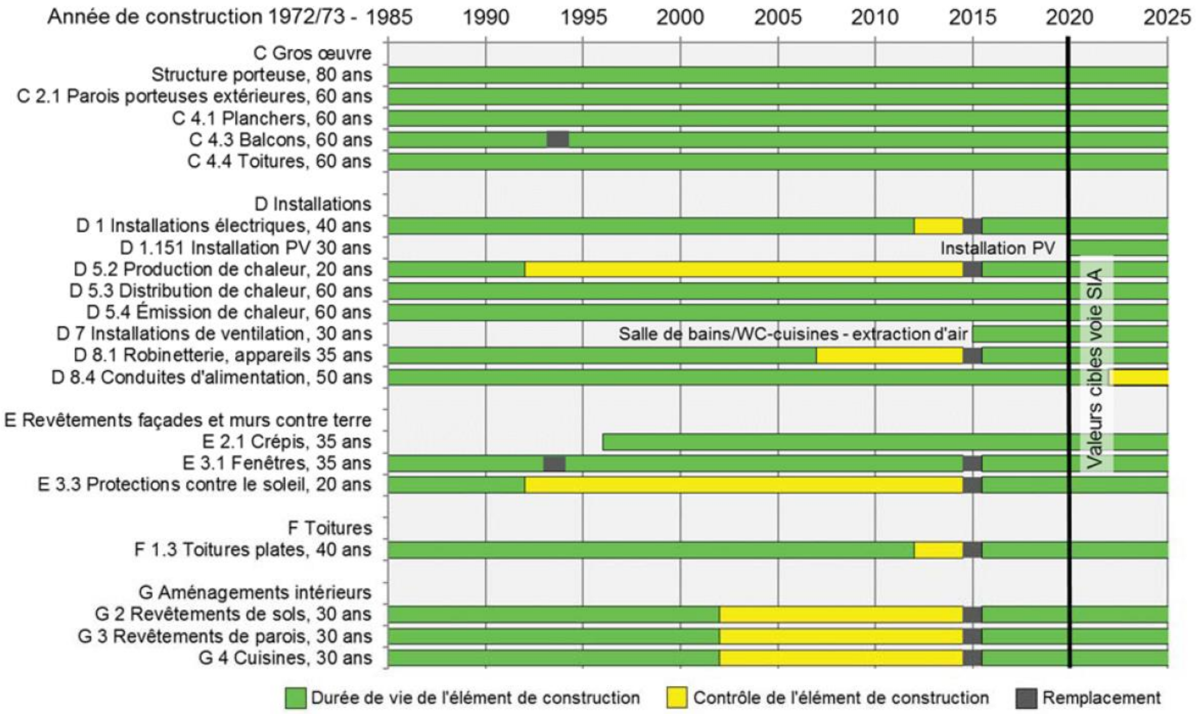

Figure 2: Représentation d'une partie du cycle de vie d'un bâtiment existant construit en 1972 et rénové en 2015 adapté du cahier technique SIA 2047 [4] *; les barres vertes représentent la durée d'utilisation prévue (indiquée à droite du nom de l'élément) selon le manuel LCC du CRB* [10]

Ces dépassements des durées de vie théorique ou planifiées peuvent s'expliquer, dans cet exemple, par des raisons financières et des plans de rénovation qui obligent à décaler ultérieurement certaines opérations. Cette hypothèse pourrait alors expliquer en partie pourquoi le taux de rénovation est actuellement si faible en Suisse [11]. Ainsi, même si l'élément de construction est arrivé au bout de sa durée de vie (selon les valeurs de durées de vie technique ou d'amortissement des normes de planification), il sera maintenu tant que sa fonction est conservée mais aussi tant que le propriétaire n'a pas la capacité financière pour effectuer les travaux. Finalement, d'autres facteurs comme l'amélioration du confort ou l'esthétique entrent aussi en ligne de compte pour prioriser les remplacements d'éléments.

1.3 Synthèse

Ce travail préparatoire a montré la grande diversité des définitions qui se rattachent à la notion de « durée de vie ». Il ressort aussi que les travaux existants ont souvent mis au point des modèles de prévisions des durées de vie. Ces modèles, développés par des spécialistes de la science des matériaux et de la durabilité, s'attachent à prévoir le comportement futur de l'élément selon son environnement. Cependant, cette approche, bien qu'utile, reste parcellaire et ne couvre pas tous les mécanismes qui conduisent aux remplacements d'éléments en pratique. Il existe de nombreux facteurs non techniques qui peuvent influencer la durée de vie (p.ex. effets d'aubaine lié à des subventions pour la rénovation, nouvelle disposition légale, esthétique, amélioration du confort, intégration à un plan de rénovation etc.). Deux questions de recherche se posent : 1) dans quelle mesure les durées de vie définies dans la littérature (Suisse et International) reportent des valeurs similaires ? sont-elles influencées par le point de vue des personnes qui les ont définies (expert technique, norme énergétique, d'écobilan, de calcul de coût sur le cycle de vie, gestionnaire de parc etc.); 2) existe-t-il des écarts entre ces valeurs de la littérature et les durées de vie effectives observées dans la pratique des rénovations de bâtiments en Suisse ? La première problématique est traitée dans la suite de ce rapport tandis que la deuxième est abordée dans l'étude DUREE WP2.

2 Collecte de données de durées de vie

2.1 Méthode de recherche utilisée

Les sources de la littérature contenant des valeurs de durée de vie des composants du bâtiment ont été recherchées en français, en anglais et en allemand. La recherche bibliographique a été réalisée de mars à juin 2017. Deux moteurs de recherche spécifiques à la recherche bibliographique, Google Scholar et Science Direct, ainsi que le moteur de recherche général Google ont été utilisés. En parallèle, les normes ou cahiers techniques suisses (SIA) ainsi que les normes européennes et internationales (EN, ISO) ont été prises en considération. Des données ont également été obtenues par le biais de centres d'expertises en Suisse, tels que le CRB. Les sources citées dans les documents recueillis au fur et à mesure de la collecte des sources ont également été consultées.

La recherche de données s'est concentrée dans la mesure du possible sur des sources de données fournissant des durées de vie pour les catégories de composants suivantes :

- Structure porteuse ;
- Installations techniques ;
- Éléments et revêtements de façades ;
- Éléments de toiture ;
- Aménagements intérieurs ;

Ces catégories correspondent à une partie des catégories de la norme norme SIA 480 [3] d'analyse de coûts sur le cycle de vie et du manuel CRB associé (catégories C, D, E, F et G[6]). Ces catégories permettent également de couvrir les principaux éléments du périmètre de calcul de l'écobilan d'un bâtiment selon le cahier technique SIA 2032 [5][12].

En complément de cette recherche bibliographique systématique, la participation du LESBAT au projet "Annex 72" du programme IEA-EBC dès 2017 a permis d'obtenir des données supplémentaires via un sondage sur les méthodologies d'écobilans de bâtiments des pays partenaires.

2.2 Liste des sources collectées

La recherche de données par mots-clés a permis d'identifier près de 100 références bibliographiques qui ont ensuite été classées selon leur nature dans le Tableau 2.

Cette liste de références sur les durées de vie n'est certainement pas exhaustive mais permet d'avoir un bon aperçu des sources de données existantes en langues française, anglaise et allemande notamment. Les sources de durées de vie proviennent de normes énergétiques, de normes sur les écobilans (LCA), de normes pour l'analyse de coûts sur le cycle de vie (LCC), d'organismes publics, ou de rapports d'experts. Elles peuvent aussi se baser sur des documents plus spécifiques édités par des associations, des gestionnaires, des banques et des assurances. Enfin, certaines sources proviennent de travaux académiques ou d'articles scientifiques.

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[6] Ces catégories sont présentées dans la suite de ce chapitre

Tableau 2: Liste des sources collectées contenant des valeurs de durées de vie sur les éléments de construction

Type de sources	Origine	Références identifiées
Normes	Suisse	[5] [12] [13] [3] [4]
	International	[1] [14] [15][16][17]
Organismes publics	Suisse	[18] [19] [6] [7] [20] [21] [22]
	International	[23] [24] [25] [26] [27] [28] [29]
Rapport d'experts et/ou outils de calcul	Suisse	[30] [31] [32]
	International	[33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51]
Association de propriétaires et locataires	Suisse	[52] [53]
	International	-
Autres (banques, assurances, portails...)	Suisse	[54] [55] [56] [57] [58]
	International	-
Travail universitaire (thèse de master ou thèse de doctorat)	Suisse	[59]
	International	[60] [61] [62]
Articles scientifiques	Suisse	[63]
	International	[64] [65] [66] [67] [68] [69] [70] [71] [72] [73] [74] [75] [76] [77] [78] [79] [80] [81] [82] [83] [84] [85] [86] [87] [88] [89] [90] [91] [92] [93] [94] [95] [96] [97] [98] [99] [100] [101]

2.3 Présentation des sources retenues

Ce chapitre présente les sources intégrées à ce jour dans la base de données DUREE (cf. chapitre 3). Toutes les sources identifiées à la section 2.1 n'ont pas toujours été prises en compte. Premièrement, l'intégration d'une source demande un temps de saisie qui dépend du nombre de données fournies et la structure de la source en question. Elles ont été choisies principalement en fonction des valeurs de durées de vie reportées pour les composants du bâtiment qu'elles détaillent mais également de la qualité de la documentation et de la représentativité des données fournies. Certaines sources, comme la norme ISO 15686-1 [1], définissent un cadre méthodologique mais ne fournissent pas ou peu de valeurs de durées de vie. Ce type de document n'a pas donc pas été retenu. Le choix des sources de données s'est aussi porté sur des valeurs utilisées dans la pratique opérationnelle (p.ex., valeurs reportées par des acteurs du domaine bancaire, assurance, associations de locataires notamment).

Au total, 67 sur les 96 sources identifiées ont été prises en compte dans la base de données. Elles sont présentées dans la suite de ce chapitre.

2.3.1 Suisse

Cahier technique SIA 2032 – L'Energie grise dans le bâtiment [5][12]

Le cahier technique SIA 2032 [5], édité en 2010, est utilisé pour les calculs d'écobilans des bâtiments en Suisse. La table originale des durées de vies d'amortissement a été mise à jour en 2012 dans une version « Korrigenda C1 » [12]. Cette version présente 31 composants de bâtiment, classées selon le code des coûts de la construction en Suisse (eCCC-Bat). La plupart de ces composants sont référencés directement comme une rubrique dans la classification eCCC-Bat (par exemple, « Producteur de chaleur »), mais quelques composants plus spécifiques sont précisés en complément (par exemple, « Sondes géothermiques »). Dans cette étude, ces valeurs sont également utilisées comme référence pour les comparer aux résultats statistiques de l'ensemble des données analysées.

Norme 480 – Calcul de rentabilité pour les investissements dans le bâtiment [13][3]

La norme SIA 480 est utilisée pour le calcul de rentabilité pour les investissements dans le bâtiment. Elle fournit une méthode qui permet de savoir si un objectif d'investissement peut être atteint et comment. Il existe deux versions de la norme SIA 480 : la première date de 2004 et la seconde de 2016.

En 2004, la norme parle de durées de vie techniques, en sollicitation moyenne et intensive, la notion de sollicitation étant relative à la catégorie de bâtiment. Cette version contient 32 valeurs de durée de vie, c'est-à-dire deux valeurs pour chacun des 16 composants considérés [13].

En 2016, la norme ne considère plus la durée de vie technique mais la durée d'utilisation. Le Tableau 3 indique les composants du bâtiment considérés par la norme SIA 480 :2016 [3]. Il n'y a plus que 10 composants, qui ne sont pas détaillés. La durée de vie d'utilisation est définie dans la norme comme étant la *« période effective attendue entre la mise en service et le remplacement d'une partie d'ouvrage ou d'installation »*. La durée d'utilisation est limitée par la durée de vie technique ou par un éventuel remplacement en raison de l'évolution des besoins (confort, esthétique, nouvelle utilisation, etc.) ou d'une exécution améliorée (meilleures performances, meilleur bilan énergétique, etc.) ».

Dans cette étude, le périmètre retenu regroupe les composants C à G uniquement (les catégories du bâtiment, A : terrain, B : préparation, H : installation spécifique du bâtiment, I : alentours du bâtiment et J : équipements, ne sont pas prises en compte). Cette édition de la norme donne une valeur minimale, une valeur moyenne et une valeur maximale pour chaque composant. Cela représente un total de 15 données de durée de vie pour les catégories C à G.

Tableau 3 : Composants du bâtiment considérés par la norme SIA 480 :2016 pour le calcul des coûts prises en compte dans cette étude

N°	Nom de la catégorie
C	Construction du bâtiment
D	Technique du bâtiment
E	Revêtements extérieurs des murs
F	Toiture du bâtiment
G	Second œuvre

CRB - Bases pour la planification des coûts du cycle de vie [7]

Ce document s'adresse aux planificateurs et aux gestionnaires de biens immobiliers. L'objectif est d'évaluer la durée de vie des différents composants du bâtiment pour définir les coûts de rénovation et planifier les différentes interventions. Le document constitue la mise en œuvre suisse de la norme ISO 15686-5 [17]. Les durées d'utilisation sont données pour les composants du bâtiment définis selon la classification eCCC-Bât, qui est le code des coûts de construction pour le bâtiment, document de référence en Suisse. Au total, trois durées de vie (minimum, moyenne et maximum) sont données pour 121 composants, soit 363 valeurs. Les composants du bâtiment sont définis en catégories « groupes principaux » (niveau de détail le plus global, 15 valeurs), « groupes d'éléments » (niveau de détail intermédiaire, 69 valeurs), « éléments » (niveau de détail le plus précis pour cette source, 279 valeurs). Il est utile de préciser que les valeurs des groupes principaux correspondent à celles de la norme SIA 480 :2016 présentée ci-dessus.

Cahier technique SIA 2047 – Rénovation énergétique des bâtiments [4]

Le cahier technique SIA 2047, mis à jour en 2015, a pour objectif d'accompagner le maître d'ouvrage et le concepteur dans la rénovation de bâtiments de façon à atteindre les objectifs intermédiaires à 2050 de la société à 2000-Watts (voie SIA vers l'efficacité énergétique). Les catégories de bâtiment visées sont uniquement les bâtiments d'habitation, les écoles et les bâtiments administratifs ayant des installations techniques simples. L'objectif de ce document est donc de guider le calcul d'écobilan en prenant en compte les coûts en partie, mais sans aller jusqu'au calcul de coûts complet. Pour cela, le cahier technique donne des durées de vie techniques pour les composants du bâtiment, répartis en trois catégories : les systèmes primaire, secondaire et tertiaire, nécessitant un investissement à long, moyen et court terme respectivement. Pour chaque catégorie, il fournit une valeur minimale ainsi qu'une valeur maximale. Ces six valeurs permettent de renseigner 35 composants de la base de données.

Etat de Vaud - Toitures plates - concept 50 ans [18]

Cette publication a été réalisée en 2001 par le Service des bâtiments du Département des Infrastructures du canton de Vaud, avec l'aide de plusieurs mandataires techniques (bureau d'ingénieurs Weinmann Energies SA, bureau d'architectes SIA Catella – Hauenstein – Ehrensperger, l'institut de technique du bâtiment de l'EPFL et le groupement des étancheurs vaudois). L'objectif de ce document est de revaloriser les toitures plates en termes d'aspect et de qualité d'exécution, de façon à pouvoir par la suite définir une valeur standard de durée de vie de 50 ans. Pour cela, elle fait état des différents types de toitures plates et indique comment les optimiser afin de maximiser leurs durées de vie en fonction de leur composition. Au total, il fournit 8 durées de vie.

Armasuisse : BFE Beurteilung von Energiesystemen und Energiesparmassnahmen [19]

Ce document, réalisé par l'OFEN à destination du département de l'armée suisse Armasuisse en 2014, est un outil de travail pour effectuer des économies d'énergie. Armasuisse possède un large parc de bâtiments et ce document sert de directive pour la gestion de ce parc. Cette source comporte notamment une base de données de durées d'utilisation normalisées de 351 composants du bâtiment.

ModEnHa 2015 - Modèle d'encouragement harmonisé des cantons [21]

Le modèle d'encouragement harmonisé des cantons (ModEnHa 2015) a pour but de définir la structure des programmes d'encouragement cantonaux visant à l'économie et à l'utilisation rationnelle de l'énergie ainsi qu'à la promotion des énergies renouvelables. Il permet de calculer l'efficacité de différentes mesures d'encouragement liées à l'assainissement du bâtiment, tant au niveau énergétique, environnemental (réduction des émissions de gaz à effet de serre) que financier. Les durées de vie de différents composants telle que l'enveloppe thermique ou les systèmes de production de chaleur entrent en compte dans ces calculs. Au total, une dizaine de durées de vie sont mentionnées.

Asloca -Tabelle paritaire des amortissements [52]

L'ASLOCA est l'association des locataires en Suisse romande. En 2007, elle a défini conjointement avec l'association des propriétaires de Suisse romande les durées d'amortissement des composants du bâtiment. Il sert à résoudre les conflits qu'il peut y avoir entre locataires et propriétaires. Il n'est donc pas porté particulièrement sur la partie extérieure du bâtiment mais plutôt sur les aménagements intérieurs et les installations techniques. Il spécifie une durée d'amortissement pour 266 composants. Le document définit la durée d'amortissement comme étant « la durée de vie moyenne pour des installations et des équipements de qualité ordinaire dans un contexte d'usure normale ».

Mietrechtspraxis/mp - Paritätische Lebensdauertabelle [53]

Le site internet « Mietrechtspraxis mp » traite du droit de la location de locaux pour les propriétaires. Ce site donne notamment une table des durées de vie « paritaires » de 92 composants du bâtiment. Cette table a été réalisée par l'association des propriétaires et l'association des locataires de Suisse allémanique. Elle est soutenue par l'association suisse de l'immobilier (SVIT), l'association suisse d'assurance (SVV), l'association des investisseurs immobiliers (VII), l'association des sociétés immobilières de Zürich (VZI), l'association « vivre en Suisse », la coopérative du logement de Suisse et la chambre tessinoise de l'économie foncière (CATEF). En Suisse romande, cette table est également prise en considération par l'association romande des locataires (ASLOCA), la fédération romande immobilière (FRI) et l'union suisse des professionnels de l'immobilier (UPSI).

Crédit Suisse [54]

Le Crédit Suisse est une banque d'investissement suisse qui investit dans de nombreux domaines dont l'immobilier. Afin de préserver ou d'accroître la valeur de ses biens ou des biens qu'elle gère, elle a créé un document indiquant tantôt une valeur moyenne, tantôt un maximum et un minimum pour la durée de vie de 45 composants du bâtiment. Au total, 83 durées de vie sont indiquées. Ce document donne également des conseils pour l'entretien et la maintenance préventive de ces composants. Ce sont donc des valeurs « à dire d'expert » ayant pour objectif la gestion de biens et de parcs immobiliers. Le Crédit Suisse se base également sur ce document pour établir les hypothèques des logements qu'il vend à crédit.

Infomaison – durées de vie des éléments de construction [55]

Le site internet « Infomaison » fournit des informations aux propriétaires et aux locataires pour l'entretien de leur bien ou de leur logement. En 2016, il a édité un document intitulé *« Quelle est la durée de vie des éléments de construction ? »*. Il fournit pour 30 composants du bâtiment une durée de vie minimale et une durée de vie maximale, ainsi que des intervalles d'entretien. Il présente donc au total 60 données de durées de vie. Ces valeurs sont utilisées de façon à savoir quand une rénovation partielle ou totale est nécessaire. Elles aident ainsi à planifier les coûts d'entretien d'un bâtiment.

La Mobilière [56]

Il s'agit d'une compagnie d'assurance suisse qui publie sur son site internet des conseils relatifs aux dommages qui peuvent subvenir sur un bien en location. Cela permet d'établir vers qui se porte la responsabilité en cas de dégradation du logement. Le tableau de durées de vie proposé regroupe aussi bien des éléments intérieurs (portes, revêtements) que des équipements (appareils de cuisine, salle de bains, mobilier, etc.). Au total, les durées de vie d'utilisation de 67 composants sont présentées.

SVIT – Union suisse des fiduciaires immobilières [58]

L'Union suisse des fiduciaires immobilières (SVIT) propose également des valeurs de durées de vie pour les principaux éléments de construction. Elle distingue les rénovations partielles tous les 12-13 ans (p.ex. pour les travaux de peinture intérieure ou de revêtements de sol) des rénovations complètes tous les 25 ans (p.ex. pour l'installation de chauffage ou la rénovation de l'enveloppe thermique).

Homegate.ch - Tableau des durées de vie [57]

Ce site se décrit comme étant « Le portail suisse de l'immobilier ». Il s'adresse aux différents acteurs de marché (propriétaires, futures propriétaires et locataires) et leurs fournit différents conseils relatifs au bien immobilier qu'ils possèdent, souhaitent acquérir ou louent. Le tableau des durées de vie se trouve dans une section du site consacrées au déménagement, intitulée « Restitution du logement ». Il s'agit donc de durées de vies normales de différents aménagements qui peuvent servir de référence au propriétaire et au locataire afin de déterminer si l'usure d'un composant durant la période de location se trouve dans les normes. Le tableau est constitué de 17 éléments, qui sont principalement des revêtements (sol, parois, plafond).

CECB [22]

Le manuel CECB fournit des durées d'utilisation d'éléments de construction et d'installations pour servir de bases de calcul de rentabilité pour les experts CECB.

SANETAP - Nachhaltige Gebäudeerneuerung in Etappen [30]

Ce rapport de projet SANETAP finance par l'Office Fédéral de l'Energie (OFEN) fournit des valeurs de durées de vie d'éléments et d'installations techniques associées à des coûts d'investissement. Au total, 17 valeurs de durées de vie sont reportées. Ces valeurs se basent sur l'outil INSPIRE téléchargeable sur la page internet de Suisse Energie [32], sur les avis du comité de suivi du projet et sur d'autres avis d'experts.

Window and advanced glazing systems life cycle assessment [63]

Cet article scientifique reporte des valeurs de durées de vie pour des éléments de systèmes de vitrages avancés.

2.3.2 International

Norme EN 15459-1:2017 Systèmes de chauffage et systèmes de refroidissement à eau dans les bâtiments [16]

Cette norme européenne vise à harmoniser l'évaluation de la performance énergétique des systèmes de chauffage dans les pays européens en fournissant une méthode de calcul économique de référence. Les données d'entrée du calcul peuvent quant à elles dépendre du contexte national. Un tableau de durées de vie de composants de système de chauffage est fourni dans l'annexe C. Il regroupe une centaine de composants pour la plupart desquels une seule valeur est donnée. Ces durées de vies sont fournies à titre informatif et peuvent être remplacées ou complétées par des données propres à chaque pays.

Guide de la maintenance des bâtiments (J. Perret) [33]

Cet ouvrage est un livre scientifique français édité en 1997 ayant pour objectif de donner les lignes directrices concernant la maintenance dans le bâtiment. Le but est d'optimiser la maintenance afin d'en limiter les coûts et de conserver la valeur financière d'un ouvrage ou d'une partie de l'ouvrage. Il contient 308 fiches techniques pour la maintenance des différents composants d'un bâtiment (structure, installations techniques, etc.). 308 données de durées de vie sont fournies. Ce document technique explique pour chaque composant les degrés d'usure et les priorités d'intervention (« urgences »).
Le document se base sur trois critères, définis ainsi :

- La durabilité : durée de fonctionnement potentielle d'un ouvrage ou d'un équipement pour la fonction qui lui a été assignée dans les conditions d'utilisation et de maintenance données.
- La durée de fonctionnement : estimation de la durée pendant laquelle un équipement accomplira effectivement la fonction qui lui est assignée.
- La durée de vie : estimation de la durée de la bonne tenue d'un composant d'un ouvrage mis en œuvre. La durée de vie d'un composant du bâtiment est fonction des paramètres suivants :
    - Qualité de la mise en œuvre ;
    - Conditions climatiques d'exposition et d'environnement ;
    - Présence ou absence d'entretien préventif ou curatif ;
    - Rythme d'utilisation et typologie des occupants.

BNB - Nutzungsdauern von Bauteilen [23]

Ce document est édité par le BBSR (Bundesinstitut für Bau-, Stadt- und Raumforschung), l'institut fédéral allemand de recherche sur la construction, l'urbanisme et le développement territorial. Il est basé sur une étude allemande, qui a obtenu des valeurs de durées de vie moyenne d'utilisation de 262 composants grâce à une enquête auprès d'experts du domaine de la construction. Ce document est utilisé pour les calculs de coûts (LCC) et d'écobilans (LCA). La durée de référence du bâtiment est de 50 ans : les valeurs plus grandes sont donc référencées à 50 ans, bien que ce soit souvent beaucoup plus pour certains éléments comme le gros œuvre. Cette valeur est utilisée comme référence pour calculer le taux de remplacement d'un composant.

Bundesamt LBB - Leitfaden Nachhaltiges Bauen, 2001, 2004, 2006 [25]

Cette source correspond en réalité à trois documents officiels édités par le Bundesministerium für Verkehr, Bau- und Wohnungswesen. La dernière version date de 2006. Les trois sources donnent des valeurs de durée de vie minimale, maximale et moyenne pour de nombreux éléments de construction. Les valeurs données n'ont pas évolué entre les différentes éditions de ce document, c'est pourquoi les trois versions sont considérées comme une seule et même source. Cette source contient 597 valeurs, correspondant à une valeur minimum, maximum et moyenne pour 199 composants cités. L'abréviation « LBB » signifie « Lebensdauer von Bauteilen und Bauschichten ». Les données de durées de vie servent d'indication pour les calculs de coûts et d'écobilans. Elles ont été établies principalement sur la base de retours d'expérience.

Lebensdauer von Bauteilen, Zeitwerte, 2010 [36]

Ce document est le résultat d'un travail de recherche allemand consistant à déterminer la durée de vie des éléments de construction. Ces valeurs s'adressent aux professionnels de la construction et aux gestionnaires de bâtiments pour faciliter la gestion et la rénovation d'une partie ou de la totalité d'un bâtiment. Les valeurs prises en compte dans cette étude (DUREE WP1) sont celles issues de la recommandation du groupe de travail BTE sachant que ce document reporte également des valeurs statistiques basées sur des retours d'expériences et de sondages[7]. Cette source regroupe un total de 249 composants et 314 valeurs de durées de vie associées.

ATD Home Inspection guidelines: 2016 [28]

ATD Home Inspection est une entreprise basée aux Etats-Unis spécialisée dans l'évaluation de l'état d'un bien immobilier. En se basant sur leur 40 ans d'expérience dans le domaine, ils fournissent par l'intermédiaire de leur site internet des espérances de vie pour plus de 200 composants, répartis entre les matériaux de construction (gros œuvre, isolation, revêtements, etc.), les équipements techniques, le mobilier et les accessoires divers. Même si généralement une seule valeur est fournie, pour certains composants des intervalles de durées de vie sont renseignés. Des commentaires mettent parfois en lumière certains critères additionnels qui peuvent influencer sur la durée de vie des composants.

BLP durability Assessment – National Audit Office MMC Evaluation [38]

Building Life Plans (BLP) fournit des assurances dans le domaine de la construction ainsi qu'un service de consulting dans le domaine du cycle de vie et de la durabilité du bâtiment. Ce rapport est destiné au National Audit Office, groupe parlementaire responsable des audits de département, de ministères ou autres organismes publics au Royaume-Uni. Il vise à permettre l'évaluation des Méthodes de Construction Modernes et se base sur des données sources provenant d'une base données propre à BLP, alimentée par des valeurs issues de son expérience dans la planification de risques sur le long terme. Les valeurs fournies tiennent compte à la fois de la qualité des composants mais également de la mise en œuvre, de l'environnement proche, de l'utilisation des occupants et de la maintenance. Ce sont des durées de vies estimées au sens de la norme ISO 15686-1. Les durées de vie de chaque composant sont données pour différents types de construction tels que la maçonnerie standard, la construction en béton cellulaire et l'ossature bois. Une période de référence de 60 ans, standard au Royaume-Uni, est considérée.

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[7] L'ajout de ces deux types de valeurs constituerait une redondance car les valeurs recommandées par le groupe de travail BTE se basent justement sur ces valeurs de retours d'expérience.

Manuel de planification du remplacement d'immobilisations [39]

Il s'agit d'un document produit par l'Association canadienne d'habitation et de rénovation urbaine (ACHRU) en collaboration avec la Fédération de l'habitation coopérative du Canada et l'Ontario Non-Profit Housing Association. Il est mentionné en préambule qu'il est destiné aux organismes de logements coopératifs et sans but lucratif. Les durées de vie des 230 composants se trouvant dans l'annexe F sont directement tirées d'un document intitulé « La durée de vie utile des matériaux et équipements techniques des édifices résidentiels de moyenne et grande hauteur », publié par la Société canadienne d'hypothèques et de logement en 2000. Ces valeurs sont le résultat d'une enquête auprès de nombreux experts du bâtiment sur l'ensemble du territoire canadien. Il s'agit donc d'estimations réelles basées sur l'expérience de professionnels du domaine.

eToolsLDC - Typical Life Expectancy of Building Component [40]

eToolsLDC est un outil d'analyse de cycle de vie développé en Australie. Il permet d'effectuer l'écobilan d'un bâtiment sur l'ensemble de son cycle de vie en tenant compte aussi bien des matériaux de construction que de l'énergie consommée durant la phase d'utilisation. Il considère les remplacements de matériaux ou des systèmes techniques au cours de la vie du bâtiment mais nécessite la saisie manuelle de ces valeurs par l'utilisateur. Sur son site internet, l'éditeur du logiciel propose un document détaillant les durées de vie typiques de ces différents composants. Au total, 125 éléments sont décrits.

InterNACHi - Typical Life Expectancy of Building Components [41]

InterNACHi est une association de professionnels spécialisés dans l'analyse de l'état de dégradation des bâtiments (Home inspectors). Ils publient par l'intermédiaire de leur site internet une tabelle de durées de vie dont le périmètre couvre l'intégralité du bâtiment. La classification est similaire à celle utilisée par l'« ATD : Home Inspection guidelines » [28]. Au total, près de 300 composants sont évalués, en se basant sur l'expérience des membres de l'association. Les valeurs proposées sont données pour des conditions d'utilisation et de maintenance standard, qui excluent par exemple les climats extrêmes ou la négligence des occupants ou propriétaires.

Eco-Häuser, Attraktive Häuser mit günstigen Unterhaltskosten (J. Kottjé) [42]

Le livre de J. Kottjé intitulé *«Eco-Häuser, Attraktive Häuser mit günstigen Unterhaltskosten»* est paru en 2007. Il présente le concept d'architecture durable, en utilisant des matériaux considérés comme respectueux de la santé de l'homme et de l'environnement. Afin d'évaluer l'impact sur l'environnement, le livre fournit en introduction une table des durées de vie moyennes de 53 éléments constructifs. Cette table présente assez peu de composants car elle intègre uniquement ceux utilisés dans les bâtiments présentés par la suite. Les valeurs proposées correspondent aux valeurs moyennes des intervalles donnés dans les fiches techniques Bundesamt LBB.

Rénover en basse consommation (M. Bourgeois, S. Bronchard, J.-F. Rixen) [43]

Ce livre présente plusieurs projets de rénovation de bâtiment à titre d'exemple des bonnes pratiques. Il vise un public professionnel (architectes, maîtres d'ouvrages) pour le sensibiliser à la rénovation énergétiquement performante. Pour montrer que ce type de rénovation présente également un intérêt environnemental et en apprécier le coût, chaque projet présenté intègre un calcul d'écobilan et d'analyse financière. Les durées de vie des composants utilisés dans ces projets sont alors données en début d'ouvrage, pour être utilisés dans les calculs.

Life cycle analysis model for New Zealand houses [76]

Cet article scientifique, rédigé par des chercheurs de l'Université d'Auckland, détaille la méthodologie pour évaluer les impacts environnementaux d'une maison en Nouvelle Zélande, en tenant compte à la fois des matériaux utilisés et des flux intervenant durant la phase d'utilisation du bâtiment. Cette méthodologie tient compte de la maintenance du bâti et donc du remplacement des différents composants au cours du cycle de vie. Un tableau de durées de regroupant une trentaine de composants est publié dans cet article.

Prendre en compte le cycle de vie des bâtiments et de leurs composants (IBGE) [26]

Cette publication de l'Institut Bruxellois pour la Gestion de l'Environnement (IBGE) présente les principes de l'approche par analyse de cycle de vie et fournit aux concepteurs un tableau de la durée de vie des principaux composants de la construction. Selon l'IBGE, les durées de vie sont issues de valeurs moyennes et ne fournissent que des tendances. Elles doivent être mises en parallèle avec les informations sur le choix écologique des matériaux de construction (résultats d'ACV).

Bremer Energie Institut [37]

Cette source de données reporte des durées de vie techniques pour 4 à 6 composants (isolants, fenêtres, chaudières, installations solaires thermiques) dans un rapport d'analyse de l'effet du programme CO_2 pour la rénovation énergétique en Allemagne.

Autres données de durées de vie fournies par les partenaires de l'IEA EBC Annex 72 [51]

Dans le cadre de la participation du LESBAT à l'IEA EBC Annex 72 *« Assessing Life Cycle Related Environmental Impacts Caused by Buildings »* [51], des sources de durées de vie supplémentaires ont pu être obtenues début 2019. Elles sont majoritairement utilisées dans des calculs d'écobilans de bâtiments et ont été fournies par les pays partenaires suivants dans le cadre d'un sondage sur les méthodologies nationales d'écobilans[8] :

- Méthode LCA pour le logiciel français PleaidesACV (orienté éco-conception) [47]
- Méthode LCA pour la Nouvelle Zélande (estimation BRANZ) [51]
- Méthode LCA pour les Pays-Bas (Dutch SBR publication, Levensduur van bouwproducten, 1998) [48]
- Méthode LCA pour la Belgique (TOTEM) [49]
- Méthode LCA pour la République Tchèque (SBTool CZ) [50]

En complément, 28 sources de durées de vie issues d'articles scientifiques regroupées dans l'article de revue de la littérature de Dixit 2019 [88] ont pu être prises en compte.

2.4 Composants et valeurs de durées de vie

La Figure 3 présente le nombre de composants renseignés pour chaque source de données ainsi que le nombre de valeurs de durées de vie fournies. Le nombre de composants est très variable, allant de 6 à 351. Ces composants ne sont pas toujours détaillés par couche ce qui explique un mombre réduit (durée de vie fournie pour le composant "toiture" regroupant l'étanchéité et l'isolation par exemple). A l'inverse, un nombre élevé traduit une décomposition très fine des composants du bâtiment et des durées de vie associées. Par ailleurs, certaines sources fournisseent plusieurs durées de vie pour un même élément (cas du CRB ou du LBB) avec une valeur moyenne et des valeurs minimales et maximales.

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[8] Les pays pour lesquels les durées de vie avaient déjà été collectés précédemment n'ont pas été inclus à nouveau (p.ex. l'Allemagne et les durées de vie du BNB)

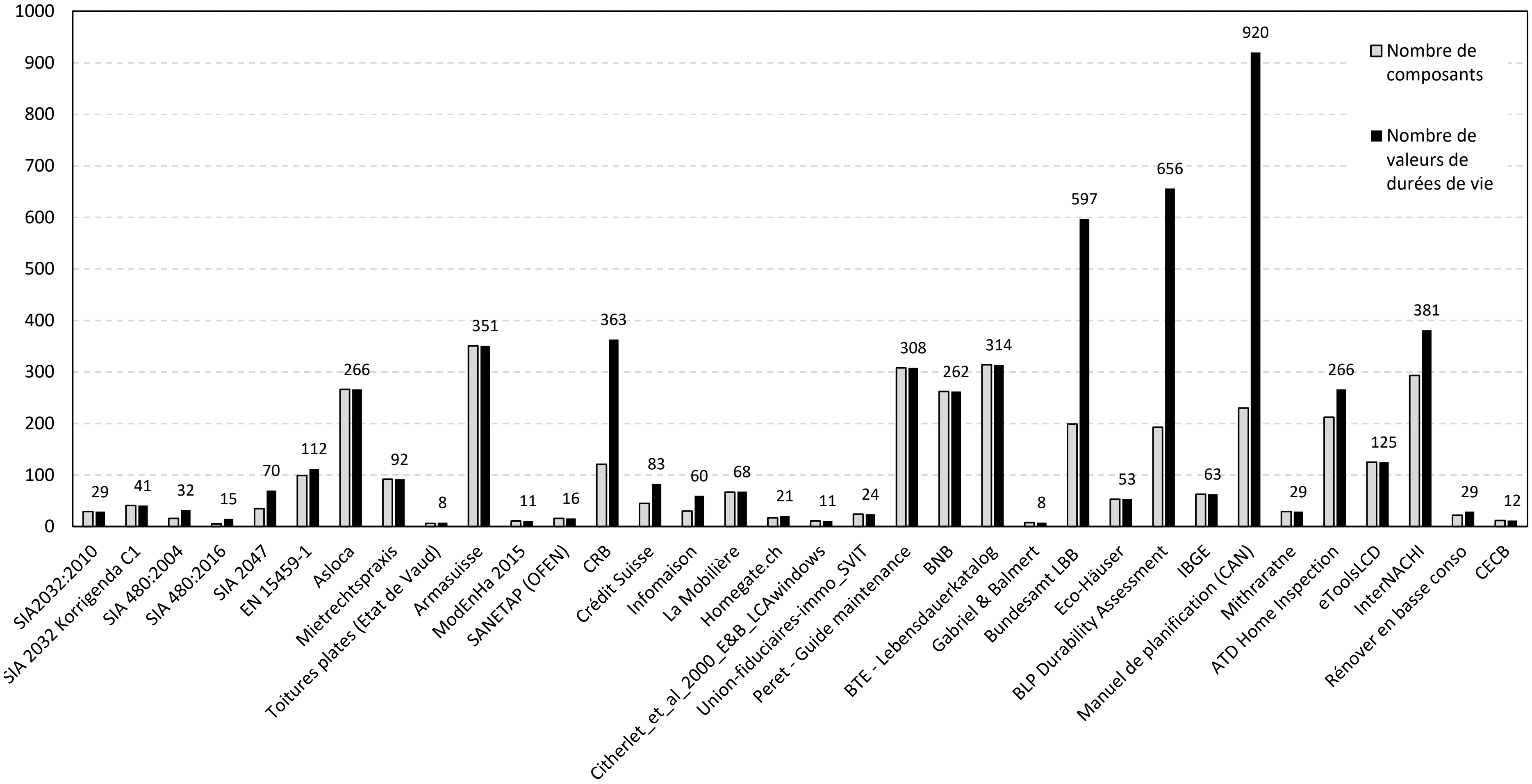


Figure 3 : Représentation du nombre de composants et de valeurs de durées de vie pour une partie des sources considérées ; les étiquettes de données correspondent au nombre de valeurs de durées de vie reportées pour chaque source (les données supplémentaires collectées via l'IEA-EBC Annex 72 ne sont ici pas reportées)

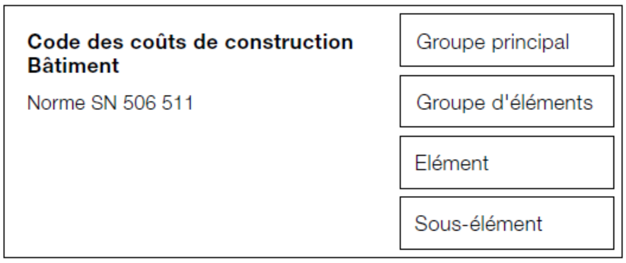
3 Intégration dans une base de données

Les sources de données présentées au chapitre précédent comporte un nombre variable de valeurs de durées de vie (cf. Figure 3). Il n'est donc pas aisé de pouvoir les comparer en l'état. Pour cela, une base de données (dénommée DUREE) utilisant sur une nomenclature comportant plusieurs niveaux de décomposition d'un bâtiment a été développée[9].

3.1 Nomenclature eCCC-Bât

La nomenclature de la base de donnes reprend la structure mise en place dans la norme suisse SN 506 511 [102] qui régit la planification et les calculs de coûts de construction dans les bâtiments neufs et transformés[10]. Elle est constituée de quatre niveaux de détail :

- Le niveau groupe principal, très général ;
- Le niveau groupe d'élément, intermédiaire ;
- Le niveau élément, détaillé ;
- Le niveau sous-élément, très détaillé mais réalisé uniquement pour les installations hospitalières (groupe principal H).



Code des coûts de construction Bâtiment

Norme SN 506 511

Groupe principal

Groupe d'éléments

Elément

Sous-élément

Figure 4 : Présentation des différents niveaux de détail des composants du bâtiment, extrait du code des coûts de construction bâtiment (eCCC-Bât)

La Figure 5 montre le détail sur trois niveaux d'un groupe principal du bâtiment, en prenant l'exemple des toitures.

F	**Toitures**
F 1	**Couvertures**
F 1.1	Etanchéités enterrées
F 1.2	Toitures plates
F 1.3	Toitures inclinées
F 1.4	Protection contre la foudre
F 2	**Eléments incorporés dans toitures**
F 2.1	Eléments incorporés dans toitures plates
F 2.2	Eléments incorporés dans toitures inclinées

Figure 5: extrait de la norme SN 506 511 [103]*, vue des trois niveaux de détail pour le groupe principal « Toitures »*

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[9] Dans le suite de ce rapport, le terme « durée de vie » est utilisé de manière indifférenciée même si certaines sources de la littérature utilise un autre terme pour qualifier leurs valeurs (cf. Tableau 1)

[10] En allemand, il s'agit de la classification e-BKP (Baukostenpläne)

Comme précisé à la section 2.1, seule une partie des composants du bâtiment est évaluée dans cette étude. Parmi les quatorze groupes principaux de la structure eCCC-Bât complète, seuls cinq sont pris en compte, les autres étant attachés au terrain ou à des aménagements particuliers. Les cinq groupes principaux en question sont représentés à la Figure 6.

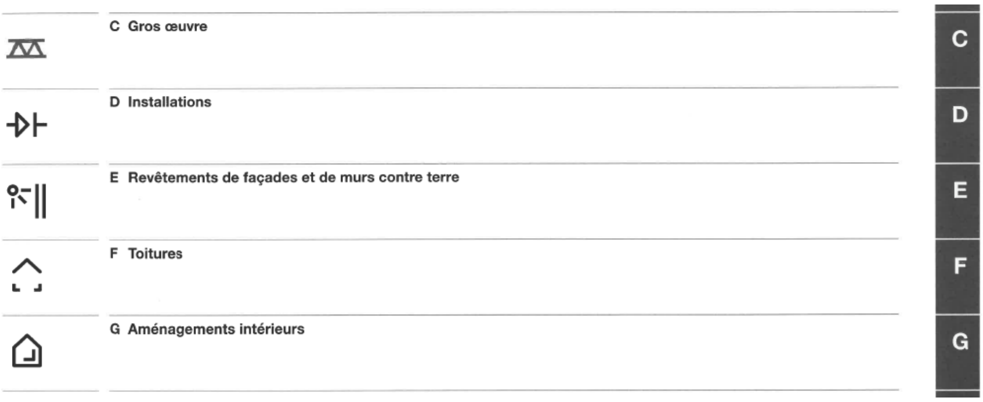
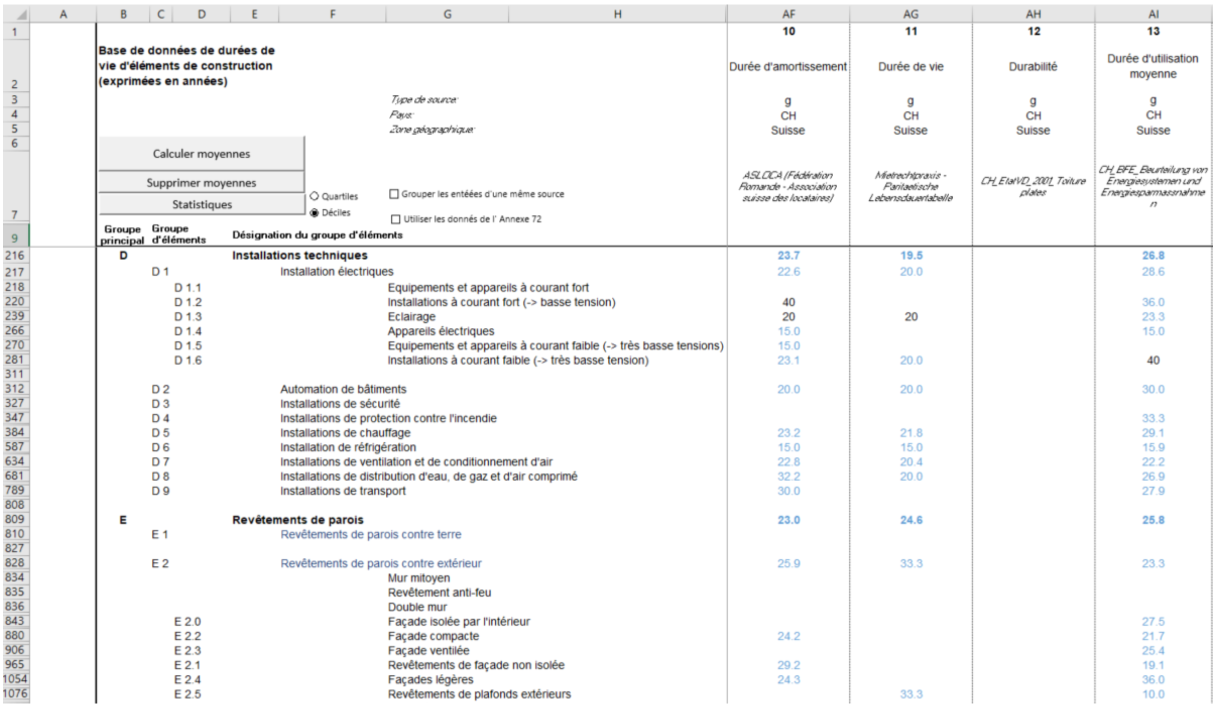


Figure 6: extrait de la norme SN 506 511 [103]*, groupes principaux spécifiques du bâtiment qui ont été considérés*

3.2 Structure générale de la base de données

La base donnée se présente sous la forme d'un fichier Excel construit selon la nomenclature eCCC-Bât exposée ci-dessus. La classification eCCC-Bât est déployée sur les lignes, tandis que les colonnes correspondent aux différentes sources considérées. La Figure 7 présente un extrait de la base de données pour une partie des catégories D et E dans lequel seules quatre sources sont affichées. Les valeurs en noir correspondent à des valeurs fournies par le document (p.ex. 20 ans pour l'éclairage selon la source 10 dans la figure ci-dessous). Les valeurs en bleu ont été calculées automatiquement à partir des durées de vie définies par la source pour des sous-éléments non visibles sur cette figure.



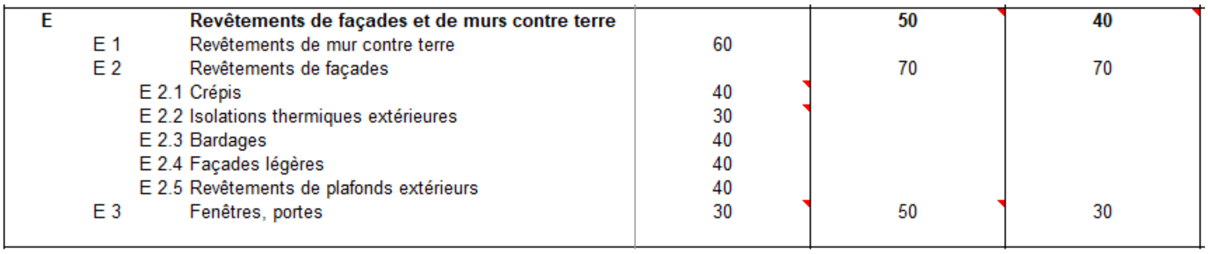
	A	B	C	D	E	F	G	H	AF	AG	AH	AI
1									**10**	**11**	**12**	**13**
2		**Base de données de durées de vie d'éléments de construction (exprimées en années)**							Durée d'amortissement	Durée de vie	Durabilité	Durée d'utilisation moyenne
3							*Type de source:*		g	g	g	g
4							*Pays:*		CH	CH	CH	CH
5							*Zone géographique:*		Suisse	Suisse	Suisse	Suisse
6												
7		Calculer moyennes Supprimer moyennes Statistiques				○ Quartiles ● Déciles	☐ Grouper les entéées d'une même source ☐ Utiliser les donnés de l' Annexe 72		*ASLOCA (Fédération Romande - Association suisse des locataires)*	*Mietrechtpraxis - Paritaetische Lebensdauertabelle*	*CH_EtatVD_2001_Toiture plates*	*CH_BFE_Beurteilung von Energiesystemen und Energiesparmassnahmen*
9		**Groupe principal**	**Groupe d'éléments**		**Désignation du groupe d'éléments**							
216		**D**			**Installations techniques**				**23.7**	**19.5**		**26.8**
217			D 1			Installation électriques			22.6	20.0		28.6
218				D 1.1			Equipements et appareils à courant fort					
220				D 1.2			Installations à courant fort (-> basse tension)		40			36.0
239				D 1.3			Eclairage		20	20		23.3
266				D 1.4			Appareils électriques		15.0			15.0
270				D 1.5			Equipements et appareils à courant faible (-> très basse tensions)		15.0			
281				D 1.6			Installations à courant faible (-> très basse tension)		23.1	20.0		40
311												
312			D 2			Automation de bâtiments			20.0	20.0		30.0
327			D 3			Installations de sécurité						
347			D 4			Installations de protection contre l'incendie						33.3
384			D 5			Installations de chauffage			23.2	21.8		29.1
587			D 6			Installation de réfrigération			15.0	15.0		15.9
634			D 7			Installations de ventilation et de conditionnement d'air			22.8	20.4		22.2
681			D 8			Installations de distribution d'eau, de gaz et d'air comprimé			32.2	20.0		26.9
789			D 9			Installations de transport			30.0			27.9
808												
809		**E**			**Revêtements de parois**				**23.0**	**24.6**		**25.8**
810			E 1			Revêtements de parois contre terre						
827												
828			E 2			Revêtements de parois contre extérieur			25.9	33.3		23.3
834							Mur mitoyen					
835							Revêtement anti-feu					
836							Double mur					
843				E 2.0			Façade isolée par l'intérieur					27.5
880				E 2.2			Façade compacte		24.2			21.7
906				E 2.3			Façade ventilée					25.4
965				E 2.1			Revêtements de façade non isolée		29.2			19.1
1054				E 2.4			Façades légères		24.3			36.0
1076				E 2.5			Revêtements de plafonds extérieurs			33.3		10.0

Figure 7: structure de la base de données selon l'eCCC-Bât adaptée

3.3 Extension de la structure eCCC-Bât

La structure retenue présente l'avantage d'être simple à renseigner pour autant que les sources ne fournissent pas de données plus détaillées que les trois niveaux eCCC-Bât. Cependant, dès lors qu'une source décrit de façon plus précise un élément, par exemple en allant jusqu'à décrire les différentes couches ou composants, il devient difficile de saisir toutes les informations dans cette structure.

La Figure 8 présente la décomposition initiale du groupe principal E selon la classification eCCC-Bât.



E	**Revêtements de façades et de murs contre terre**		**50**	**40**
E 1	Revêtements de mur contre terre	60		
E 2	Revêtements de façades		70	70
E 2.1	Crépis	40		
E 2.2	Isolations thermiques extérieures	30		
E 2.3	Bardages	40		
E 2.4	Façades légères	40		
E 2.5	Revêtements de plafonds extérieurs	40		
E 3	Fenêtres, portes	30	50	30

Figure 8: groupe principal E selon la classification eCCC-Bât

Les éléments E2.1 (crépis), E2.2 (isolations thermiques extérieures) et E2.3 (bardages) représentent respectivement les revêtements de façades non isolées, les systèmes d'isolation périphérique utilisés en façade compacte (y compris leur revêtement extérieur) et les façades ventilées (y.c. l'isolant et le bardage extérieur). Selon cette structure, les systèmes d'isolation intérieure ne peuvent pas être saisis dans la rubrique E. Il est possible de les insérer dans la rubrique G3 (Revêtements de parois), mais il devient alors compliqué de comparer les trois modes actuels d'isolation des façades d'un bâtiment dans la catégorie E : l'isolation extérieure compacte, l'isolation extérieure ventilée et l'isolation par l'intérieur[11]. De ce fait, un élément E2.0 « façade isolée par l'intérieur » a été créé pour pouvoir valoriser la base de données DUREE dans un projet européen traitant des façades isolées par l'intérieur (projet Horizon 2020 RIBuild[12]) dans lequel le LESBAT participe. Les catégories E2.2 et E2.3 ont été renommées en « façade compacte » et « façade ventilée ». Ces modifications sont visibles sur la capture d'écran de la base de données à la Figure 7.

Certaines sources fournissent des données très détaillées. Par exemple, une source peut reporter une durée de vie différente pour un isolant et le bardage qui le recouvre. Si la structure eCCC-Bât originale était conservée, il faudrait supprimer une partie de l'information contenue dans certaines sources afin de pouvoir les intégrer dans la base de données. Cela impliquerait un prétraitement de l'information qui risquerait d'altérer les résultats de l'étude. Pour ces raisons, la structure de la base de données a été étendue. Les trois premiers niveaux de détails (groupe principal, groupe d'éléments, éléments) ont été conservés, puis les éléments ont été décomposés jusqu'à descendre, pour certains d'entre eux, jusqu'au niveau du matériau (p.ex. isolation en EPS ou isolation en verre cellulaire).

Afin d'optimiser la navigation dans la base de données, huit filtres ont été introduits. Ils sont repérés par un cadre rouge et un cadre marron sur la Figure 9. Ils permettent de filtrer les différents niveaux de détails de la base de données. Les trois filtres rouges correspondent aux niveaux de la nomenclature eCCC-Bât. Les cinq filtres marrons correspondent aux niveaux rajoutés pour renseigner les sources dans la base de données.

La Figure 9 présente une partie de la structure correspondant à la distribution de chaleur des installations de chauffage. Pour visualiser directement les sources de données qui renseignent la durée de vie d'un échangeur à plaques, l'arborescence doit être déroulée jusqu'au niveau le plus bas.

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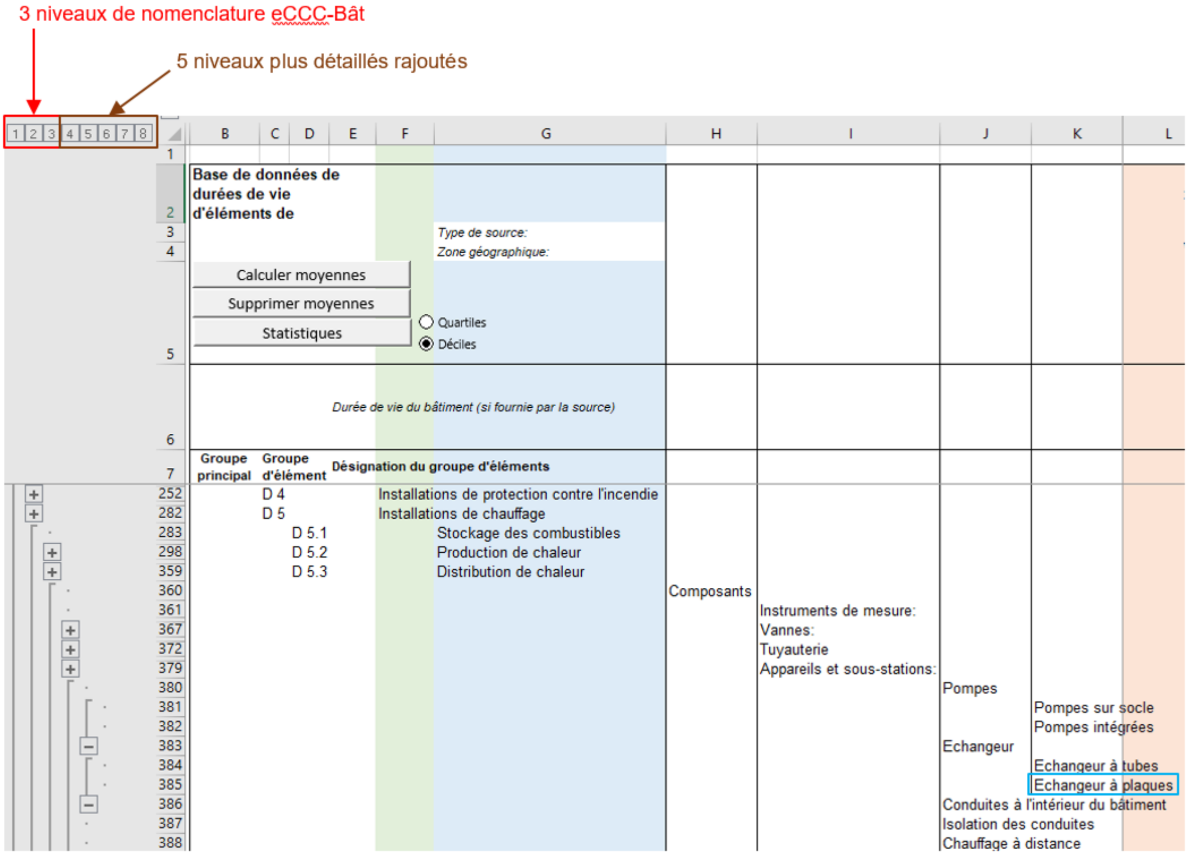
[11] Par exemple, si la façade extérieure bénéficie d'une protection du service du patrimoine

[12] Lien vers le site internet du projet RIBuild, volet suisse : https://www.ribuild.eu/switzerland



Base de données de durées de vie d'éléments de

Type de source:
Zone géographique:

Durée de vie du bâtiment (si fournie par la source)

Row	Groupe principal	Groupe d'élément	Désignation du groupe d'éléments				
252		D 4	Installations de protection contre l'incendie				
282		D 5	Installations de chauffage				
283		D 5.1	Stockage des combustibles				
298		D 5.2	Production de chaleur				
359		D 5.3	Distribution de chaleur				
360				Composants			
361					Instruments de mesure:		
367					Vannes:		
372					Tuyauterie		
379					Appareils et sous-stations:		
380						Pompes	
381							Pompes sur socle
382							Pompes intégrées
383						Echangeur	
384							Echangeur à tubes
385							Echangeur à plaques
386						Conduites à l'intérieur du bâtiment	
387						Isolation des conduites	
388						Chauffage à distance	

Figure 9: vue du chemin d'accès pour un élément au niveau de détail le plus précis dans la base de données

La base de données est constituée de plus de 2000 composants regroupés à différents niveaux de détails conformément à la répartition suivante :

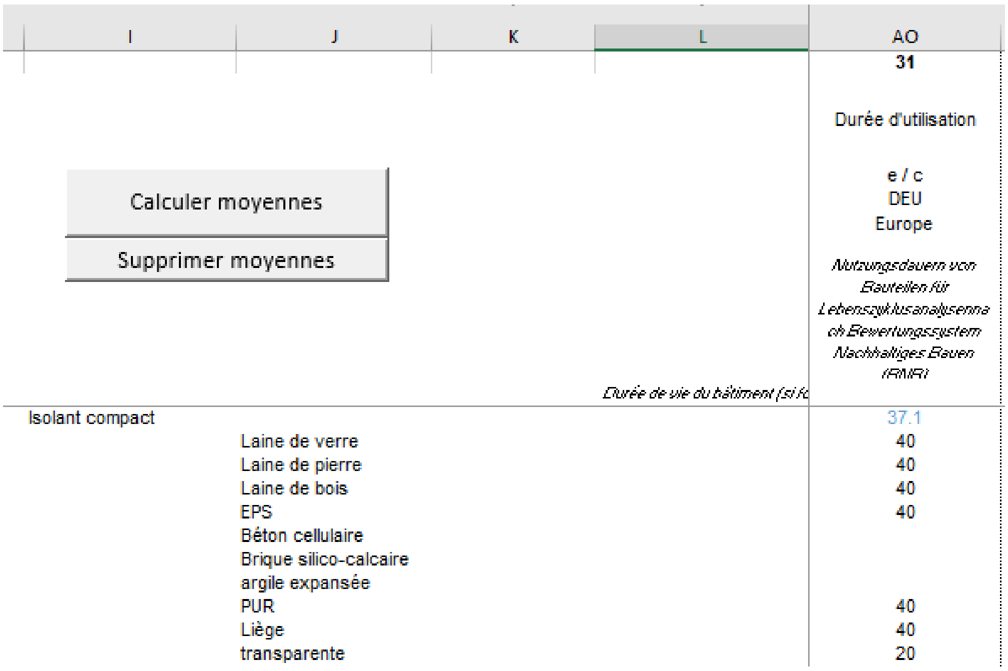
- 10 groupes principaux ;
- 24 groupes d'éléments ;
- 110 éléments ;
- 416 composants au niveau de détail inférieur au niveau élément, appelés sous-éléments (colonne H) ;
- 915 composants au niveau de détail inférieur au niveau sous-élément (colonne I) ;
- 503 composants au niveau de détail inférieur au précédent (colonne J) ;
- 127 composants au niveau de détail inférieur au précédent bas (colonne K) ;
- 29 composants au niveau de détail le plus bas (colonne L).

La structure est ainsi déroulable pour chaque source de données sur 8 colonnes et plus de 2140 lignes.

3.4 Calcul automatique de valeurs de durées de vie

Etant donné l'hétérogénéité des nomenclatures des documents de la littérature, il peut arriver que des valeurs de durées de vie soient fournies à des niveaux très détaillés et qu'à l'inverse aucune valeur ne soit fournie à des niveaux supérieurs.

Par exemple, la Figure 10 montre que pour la source 31, des valeurs sont présentes pour différents types d'isolants en façade compacte (laine minérale, EPS, etc.). Il s'agit des valeurs représentées en noir. Par contre, aucune durée de vie n'est définie dans cette source pour un isolant « générique » de façade compacte.



I	J	K	L	AO
			Durée de vie du bâtiment (si f	**31** Durée d'utilisation e / c DEU Europe *Nutzungsdauern von Bauteilen für Lebenszyklusanalysennach Bewertungssystem Nachhaltiges Bauen (BNB)*
Isolant compact				37.1
	Laine de verre			40
	Laine de pierre			40
	Laine de bois			40
	EPS			40
	Béton cellulaire			
	Brique silico-calcaire			
	argile expansée			
	PUR			40
	Liège			40
	transparente			20

Figure 10: Exemple de remontée de l'information

Une fonction permettant de remonter l'information vers les niveaux supérieurs a alors été créée. Elle parcourt la base de données et moyenne les durées de vie des composants de mêmes niveaux afin de pouvoir renseigner le composant parent si celui ne dispose pas d'une valeur de durée de vie. Dans l'exemple illustré ci-dessus, les durées de vie des différents types d'isolant sont moyennées afin d'obtenir une durée de vie de 37 ans. Cette valeur calculée par la base de données est ensuite ajoutée en bleu dans la cellule appropriée[13]. Ce calcul automatique par la base de données est également visible à la Figure 7.

Le bouton « Calculer moyennes » (cf. Figure 10) , situé dans la partie supérieure de la feuille principale, permet d'appeler cette fonction qui parcourt la base de donnée et complète les données manquantes lorsque cela est possible. Le bouton « Supprimer moyennes » efface toutes les valeurs moyennes calculées, pour ne laisser apparaître que celles qui ont été directement saisies. En revanche, si une source fournit uniquement des valeurs de durées de vie à un niveau supérieur, la base de durées de vie n'applique pas les valeurs de durées de vie aux niveaux inférieurs.

Ce choix a ses limites notamment à l'heure actuelle où aucune pondération n'est appliquée lors du calcul des moyennes des composants pour le niveau supérieur. Il permet, néanmoins, de réaliser des analyses statistiques pour différents niveaux de détails en tirant partie d'un maximum de sources de données de la littérature.

3.5 Classification des sources

Au total, 67 sources suisses et internationales ont été intégrées à la base de données à partir des 96 références bibliographiques reportées au chapitre 2.2. Certaines sources fournissent uniquement une valeur moyenne, tandis que d'autres précisent des valeurs minimum, maximum et éventuellement une valeur moyenne. Cela permet de renseigner 95 entrées dans la base de données.

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[13] Une colonne pondération a été ajoutée pour pouvoir tenir compte de coefficients de pondération lors du calcul de la valeur de la durée de vie du niveau supérieur à partir du niveau inférieur. Cependant, à l'heure actuelle, aucune pondération n'est prise en compte faute de données disponibles pour ajuster cette durée de vie recalculée automatiquement.

Chaque source de données répond à un ou plusieurs objectifs précis souvent en liaison avec son domaine d'application et sa définition du terme « durée de vie » (cf. chapitre 1.1). A partir du premier classement effectué lors de la collecte de données (cf. Tableau 2), les durées de vie peuvent être regroupées en trois catégories selon trois contextes différents d'utilisation :

- Calculer l'écobilan (LCA) de bâtiment en phase de planification (intègre aussi les calculs énergétiques du bâtiment le cas échéant) ;
- Analyser les coûts du cycle de vie (LCC) ;
- Résoudre des problèmes pratiques de gestion de bâtiment (pour les gestionnaires de bâtiment, les conflits locataires/propriétaires, les banques, les assurances) et les autres applications.

Les tableaux 4, 5 et 6 présentent le détail des sources correspondantes à chacun de ces trois catégories en précisant également le type et l'origine (Suisse ou International)[14].

Tableau 4: Classification des sources utilisées pour des calculs d'écobilans (LCA)

Calcul d'écobilans (LCA)	**Réf.**	**Type**	**Origine**
Cahier technique SIA 2032 L'Energie grise des bâtiments	[5]	Norme	Suisse
Korrigenda C1 zu SIA 2032	[12]	Norme	Suisse
Window and advanced glazing systems life cycle assessment	[63]	Article scientifique	Suisse
BNB - Nutzungsdauern von Bauteilen	[23]	Organisme public	International
Bundesamt LBB - Leitfaden Nachhaltiges Bauen	[25]	Organisme public	International
Typical 'Life Expectancy' of building component	[40]	Rapport d'experts	International
ECO-Häuser - Attraktive Häuser mit günstigen Unterhaltskosten	[42]	Rapport d'experts	International
Rénover en basse consommation	[43]	Rapport d'experts	International
Life cycle analysis model for New Zealand houses	[76]	Article scientifique	International
Institut Bruxellois pour la gestion de l'environnement (IBGE)	[26]	Organisme public	International
Collecte de données supplémentaires via l'Annex 72 (à partir de Dixit [88][15] *pour les articles scientifiques)*			
LCA method France (PleaidesACV)	[47]	Rapport d'experts	International
LCA method Nouvelle Zélande (estimation BRANZ)	[51]	Rapport d'experts	International
LCA method Netherlands	[48]	Organisme public	International
LCA method Belgique (TOTEM)	[49]	Organisme public	International
LCA method République Tchèque (SBTool CZ)	[50]	Rapport d'experts	International
Adalberth 1997; Kohler 1997; Blanchard & Reppe, 1998; Fay & Treloar 1998; Harris & Boyles, 1998; Fay et al 2000; Treloar et al, 2000; Chen et al, 2011 ; Keoleian et al 2001 ; Johnstone 2001 ; Roth et al 2002 ; Scheuer et al 2003 ; Ding 2007 ; Worth 2007 ; John et al 2008 ; Crawford et al 2008 ;	[29], [78]–[82], [84]–[87], [89]–[101]	Articles scientifiques	International

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[14] L'affectation des sources a été faite dans la mesure du possible sur la base des documentations et des objectifs d'utilisation de chaque source. Il peut arriver qu'une source soit mise dans deux catégories si elle est actuellement utilisée pour ces deux objectifs.

[15] Certaines sources reprises par Dixit dans son article de revue ont déjà été collectées par la méthode de recherche du §2.1. Elles ne sont donc pas reportées à nouveau.

Calcul d'écobilans (LCA)	Réf.	Type	Origine
Leckner & Zmeureanu 2011 ; Rauf & Crawford 2011 ; Iddon & Firth 2013 ; Rauf & Crawford 2015 ; Atmaca & Atmaca 2015; Monteiro et al 2016 ; EPA 2014			

Tableau 5: Classification des sources utilisées en planification pour des calculs de coût global (LCC)

Calcul de coûts sur le cycle de vie (LCC)	Réf.	Type	Origine
SIA 480 (2004)	[13]	Norme	Suisse
SIA 480[16] (2016)	[3]	Norme	Suisse
CRB - Bases pour la planification des coûts du cycle de vie	[7]	Organisme public	Suisse
Manuel utilisateur de l'outil en ligne CECB	[22]	Rapport d'experts	Suisse
Nachhaltige Gebäudeerneuerung in Etappen - SANETAP	[30]	Rapport d'experts	Suisse
EN 15459-1:2017	[16]	Norme	International
BNB - Nutzungsdauern von Bauteilen	[23]	Organisme public	International
Bundesamt LBB - Leitfaden Nachhaltiges Bauen	[25]	Organisme public	International
BLP Durability Assessment - National Audit Office MMC evaluation	[38]	Rapport d'experts	International
ECO-Häuser - Attraktive Häuser mit günstigen Unterhaltskosten	[42]	Rapport d'experts	International
Rénover en basse consommation	[43]	Rapport d'experts	International
Collecte de données supplémentaires via l'Annex 72 (à partir de Dixit [88] *pour les articles scientifiques)*			
Keoleian et al 2001 ; Worth 2007 ; Leckner & Zmeureanu 2011	[86], [93], [96]	Article scientifique	International

Tableau 6: Classification des sources utilisées dans des logiques de gestion de biens et autres types de sources

Gestion et autres sources Gestion de biens immobiliers (maintenance, rénovation) Gestion des conflits Gestion financière (maintien ou augmentation de la valeur vénale d'un bien)	Réf.	Type	Origine
SIA 2047	[4]	Norme	Suisse
Etat de Vaud - Toitures plates - concept 50 ans	[18]	Organisme public	Suisse
Armasuisse - BFE Beurteilung von Energiesystemen und Energiesparmassnahmen	[19]	Organisme public	Suisse
CRB - Bases pour la planification des coûts du cycle de vie	[7]	Organisme public	Suisse
ModEnHa 2015 - Modèle d'encouragement harmonisé des cantons	[21]	Organisme public	Suisse
Asloca -Tabelle paritaire des amortissements	[52]	Association de propriétaires et locataires	Suisse

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[16] Cette source comporte également les valeurs du manuel CRB LCC pour les groupes principaux. La source « CRB - Bases pour la planification des coûts du cycle de vie » a quant à elle été reportée dans la catégorie gestion.

Gestion et autres sources Gestion de biens immobiliers (maintenance, rénovation) Gestion des conflits Gestion financière (maintien ou augmentation de la valeur vénale d'un bien)	**Réf.**	**Type**	**Origine**
Mietrechtspraxis/mp - Paritätische Lebensdauertabelle	[53]	Association de propriétaires et locataires	Suisse
Crédit Suisse - Durée de vie moyenne des éléments de construction	[54]	Autres (banques, assurances, portails...)	Suisse
Infomaison - Quelle est la durée de vie des différents éléments de construction	[55]	Autres (banques, assurances, portails...)	Suisse
La Mobilière - Tableau de la durée de vie	[56]	Autres (banques, assurances, portails...)	Suisse
Homegate.ch - Tableau des durées de vie	[57]	Autres (banques, assurances, portails...)	Suisse
Union suisse des fiducières immobilières (SVIT)	[58]	Autres (banques, assurances, portails...)	Suisse
Nachhaltige Gebäudeerneuerung in Etappen - SANETAP	[30]	Rapport d'experts	Suisse
ATD - Average Life Span of Homes, Appliances, and Mechanicals	[28]	Organisme public	International
Guide de la maintenance des bâtiments - Diagnostic d'un patrimoine bâti existant, prévention des désordres et actions pour y remédier	[33]	Rapport d'experts	International
Lebensdauer von Bauteilen, Zeitwerte	[36]	Rapport d'experts	International
BLP Durability Assessment - National Audit Office MMC evaluation	[38]	Rapport d'experts	International
SCHL - Manuel de planification du remplacement d'immobilisations	[39]	Rapport d'experts	International
Typical 'Life Expectancy' Table for common building materials & systems	[41]	Rapport d'experts	International
Bremer energie Institut (Jürgen Gabriel und David Balmert)	[37]	Rapport d'experts	International
Collecte de données supplémentaires via l'Annex 72 (à partir de Dixit [88])[17]			
RICS, 2001; NIBS, 2000; NAHB, 2007	de [42] à [44]	Organisme public & Rapports d'experts	International

3.6 Paramètres statistiques calculés

Le traitement des données et l'analyse des résultats sont réalisés au moyen de statistiques descriptives. Dans la pratique, la moyenne et l'écart-type d'un échantillon de données sont parfois utilisés. Cependant, l'utilisation de ces paramètres suppose que l'échantillon suive une loi normale ce qui doit être vérifié à l'aide de tests statistiques. Dans cette étude (WP1), les données de durées de vie collectées peuvent être asymétriques et l'échantillon très dispersé. Pour cela, les résultats de la base de données DUREE sont présentés à l'aide de paramètres usuels de statistiques descriptives : la médiane, les quartiles et les déciles. Ils coupent respectivement l'échantillon de données en deux

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[17] La source ATD [28] reportée par Dixit a déjà été identifiée par le LESBAT et n'est donc pas reportée.

parties, quatre parties et dix parties. La Figure 11 représente ces différents paramètres sous forme d'une boîte à moustaches (également appelée en anglais « boxplot »).

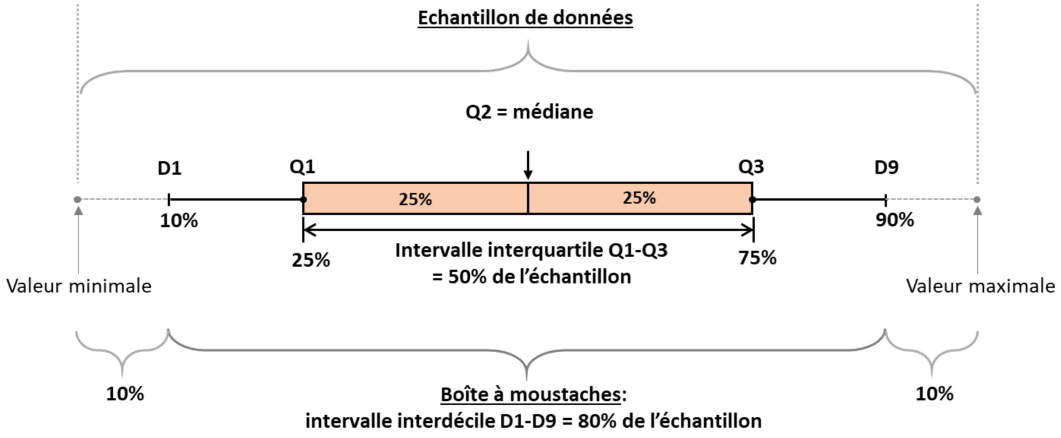


Figure 11: Représentation d'une boîte à moustaches

Ce mode de représentation permet de représenter graphiquement la forme de la distribution de données. La boîte est tracée entre les quartiles Q1 et Q3 représentant respectivement 25% et 75% de l'échantillon. La médiane, délimitant les deux parties de l'échantillon (50%), est représentée par un trait continu à l'intérieur de la boîte. Les moustaches représentent dans cette étude l'intervalle entre les déciles D1 et D9 (soit 80% de l'échantillon de données total). D'autres choix de valeurs pour les moustaches peuvent exister dans la littérature.

3.7 Calcul automatique des statistiques descriptives

3.7.1 Niveaux de détails et échantillons

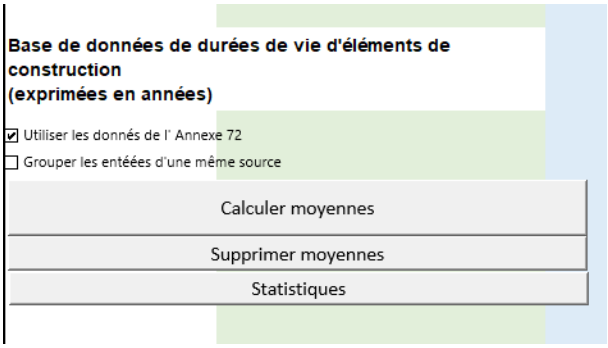
Les calculs de médianes, quartiles et déciles ont été intégrés directement dans le tableur Excel au moyen de macros Visual Basic. Il est ainsi possible de calculer les statistiques descriptives à différents niveaux :

- Au niveau des groupes principaux pris en compte dans le périmètre d'évaluation des calculs de rentabilité dans le bâtiment (norme SIA 480 et CRB) ;
- Au niveau des groupes d'éléments et des éléments considérés dans le périmètre du calcul d'un écobilan de bâtiment (cahier technique SIA 2032) ;
- Au niveau de certains composants rajoutés dans la classification, qui semblent pertinents de spécifier dans l'analyse.

Ces statistiques peuvent être calculées pour différents échantillons distincts :

- Pour l'ensemble des sources de la base de données ;
- Pour un contexte d'utilisation spécifique (calcul LCA, calcul LCC, gestion & autres contextes) ;
- Pour une zone géographique donnée : Suisse, International (Europe et reste du monde).

Deux paramétrages sont possibles pour les calculs statistiques (cf. Figure 12). Une case à cocher permet de grouper ou de séparer les entrées d'une même source. De même, une deuxième case à cocher permet d'intégrer les données de durées de vie obtenues via le projet IEA-EBC Annex 72 début 2019. Le bouton « Statistiques » permet ensuite de lancer les calculs.



Base de données de durées de vie d'éléments de construction
(exprimées en années)

☑ Utiliser les donnés de l' Annexe 72
☐ Grouper les entéées d'une même source

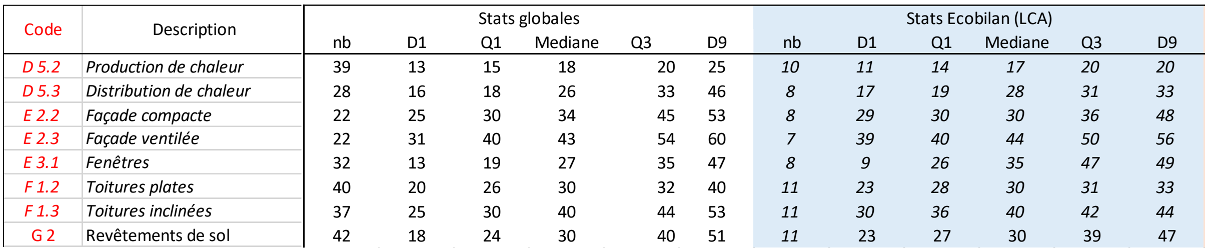
Figure 12 : interface de la base de données pour réaliser les calculs statistiques

3.7.2 Fichiers de résultats

Les statistiques, correspondant aux niveaux mentionnés au chapitre 3.7.1, sont disponibles dans différents onglets du fichier Excel :

- *Stats macro-éléments* : statistiques et graphiques de résultats pour les 5 groupes principaux selon la norme SIA 480 et CRB ;
- *Stats SIA 2032 réduit & tous* : statistiques et graphiques de résultats pour les groupes d'éléments et éléments pris en compte dans le cahier technique SIA 2032 ;
- *Stats Installations techniques (D)* : statistiques et graphiques de résultats pour les systèmes de production de chaleur, du niveau le plus haut (D - installations techniques) au niveau le plus bas (systèmes détaillés p.ex. pompe à chaleur) ;
- *Annexe rapport WP1* : statistiques décrivant pour 100 éléments utilisables dans des calculs LCA et LCC, les statistiques descriptives complètes.

La Figure 13 illustre les statistiques sur quelques composants du périmètre de calcul d'un écobilan selon la SIA 2032. La colonne « Code », en rouge doit être saisie manuellement par l'utilisateur. Elle permet de choisir le groupe principal, le groupe d'éléments ou l'élément à considérer. La colonne « Description » se met à jour automatiquement une fois le code entré. Cela permet de vérifier que le code correspond bien au composant recherché. Les résultats sont indiqués en sortie selon les regroupements de données retenus (p.ex. « Stats globales » et « Stats Ecobilan (LCA) » ci-dessous). D'autres groupements de colonnes supplémentaires existent également pour les statistiques LCC, de gestion, suisses, européennes et extra-européennes mais ne sont pas représentés dans la figure ci-dessous.



Code	Description	Stats globales						Stats Ecobilan (LCA)					
		nb	D1	Q1	Mediane	Q3	D9	nb	D1	Q1	Mediane	Q3	D9
D 5.2	*Production de chaleur*	39	13	15	18	20	25	*10*	*11*	*14*	*17*	*20*	*20*
D 5.3	*Distribution de chaleur*	28	16	18	26	33	46	*8*	*17*	*19*	*28*	*31*	*33*
E 2.2	*Façade compacte*	22	25	30	34	45	53	*8*	*29*	*30*	*30*	*36*	*48*
E 2.3	*Façade ventilée*	22	31	40	43	54	60	*7*	*39*	*40*	*44*	*50*	*56*
E 3.1	*Fenêtres*	32	13	19	27	35	47	*8*	*9*	*26*	*35*	*47*	*49*
F 1.2	*Toitures plates*	40	20	26	30	32	40	*11*	*23*	*28*	*30*	*31*	*33*
F 1.3	*Toitures inclinées*	37	25	30	40	44	53	*11*	*30*	*36*	*40*	*42*	*44*
G 2	Revêtements de sol	42	18	24	30	40	51	*11*	23	27	30	39	47

Figure 13: Exemple de tableau paramétrable pour l'analyse des résultats pour différents niveaux de la nomenclature eCCC-Bât et différents découpages de l'échantillon de données

Ce tableau permet de reporter les paramètres de calcul utilisés pour représenter les boîtes à moustaches pour chaque groupe principal, groupe d'éléments ou élément considéré et pour chaque source.

4 Résultats

Ce chapitre présente les résultats statistiques des durées de vie selon plusieurs échantillons :

- en fonction du type de sources (écobilan : LCA ; coûts sur le cycle de vie : LCC ; gestion) ;
- en fonction de la zone géographique (Suisse vs. International).

Pour chaque échantillon, les statistiques sont analysées selon trois niveaux de détails :

- Pour cinq groupes principaux ;
- Pour huit composants principaux pouvant faire l’objet d’un remplacement lors d’une rénovation énergétique de bâtiment et pris en compte dans le périmètre de calcul de la SIA 2032 (calcul d’écobilan de bâtiment) ;
- Pour sept composants au sein des installations techniques et de chauffage pour évaluer l’influence du niveau de détails sur la valeur de la durée de vie des producteurs de chaleur.

Il s’agit d’une part d’évaluer les ordres de grandeur des durées de vie pour ces composants principaux. D’autre part, il s’agit aussi de vérifier si le type de source et la zone géographique ont une influence sur les valeurs de durées de vie. Les statistiques sont présentées sous la forme de boîtes à moustaches dans la suite (parties 4.2 et 4.3) puis les valeurs médianes sont comparées avec les valeurs moyenne du guide CRB LCC et du cahier technique SIA 2032 dans la partie 4.4.

4.1 Statistiques globales

Au préalable, les statistiques globales pour environ cent composants ont été calculées. Elles ne sont pas reportées dans ce rapport mais elles sont consultables dans le tableau de données de l’article sur le projet DUREE WP1 publié dans le journal scientifique Data-in-Brief (en anglais) [104]. Les paramètres des boîtes à moustaches sont reportés ainsi que les valeurs minimales et maximales. Ces statistiques correspondent à une extraction des trois niveaux de détails de la base de données DUREE et de la nomenclature eCCC-Bât en fournissant, lorsque c’est pertinent, certains niveaux de détails supplémentaires comme pour les producteurs de chaleur (p.ex. chaudière, PAC). Il ne comporte volontairement pas l’ensemble des niveaux de détails pris en compte dans la base de données DUREE pour éviter d’avoir des statistiques établies à partir d’un très faible nombre de sources.

4.2 Statistiques par type de sources

La Figure 14 présente une répartition des sources et entrées de durées de vie selon le type de sources.

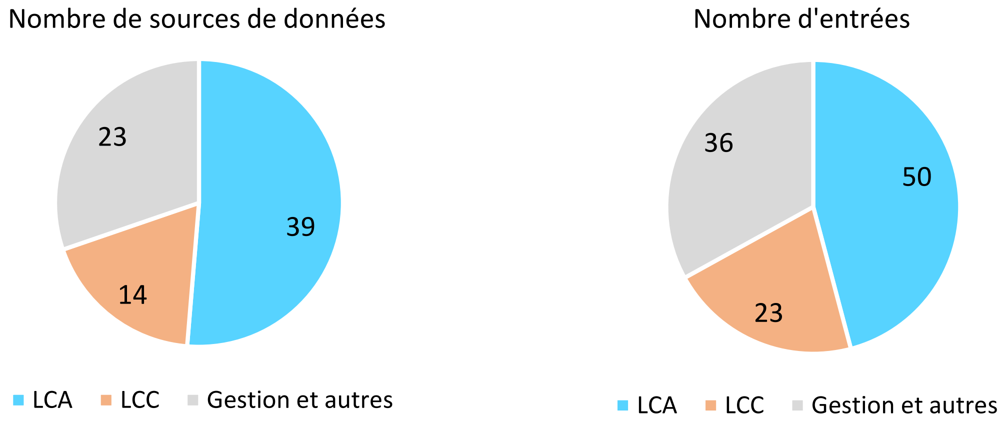


Figure 14: Nombre de sources (à gauche) et d’entrées (à droite) reportées par contexte d’application

Les sources de durées de vie de l'ensemble LCA sont les plus nombreuses avec près de 40 sources et 50 entrées. Les sources de calcul de coûts (LCC) et de gestion représentent respectivement 14 et 23 sources pour 23 et 36 entrées. Parmi les sources référencées, certaines sont utilisées dans plusieurs contextes, par exemple à la fois pour des calculs d'écobilan (LCA) ou pour des calculs de coûts sur le cycle de vie (LCC) et de gestion de biens (cf. tableaux 4, 5 et 6). Le nombre total de sources (67) ou d'entrées (95) de la base de données DUREE est donc inférieur à la somme des sources (15 + 23 + 40 = 78) ou des entrées (23 + 36 + 50 = 109) présentée à la Figure 14[18].

4.2.1 Groupes principaux

La Figure 15 présente les résultats statistiques obtenus pour chaque groupe principal. Les données brutes du graphique sont disponibles en annexe 1, Tableau 10.

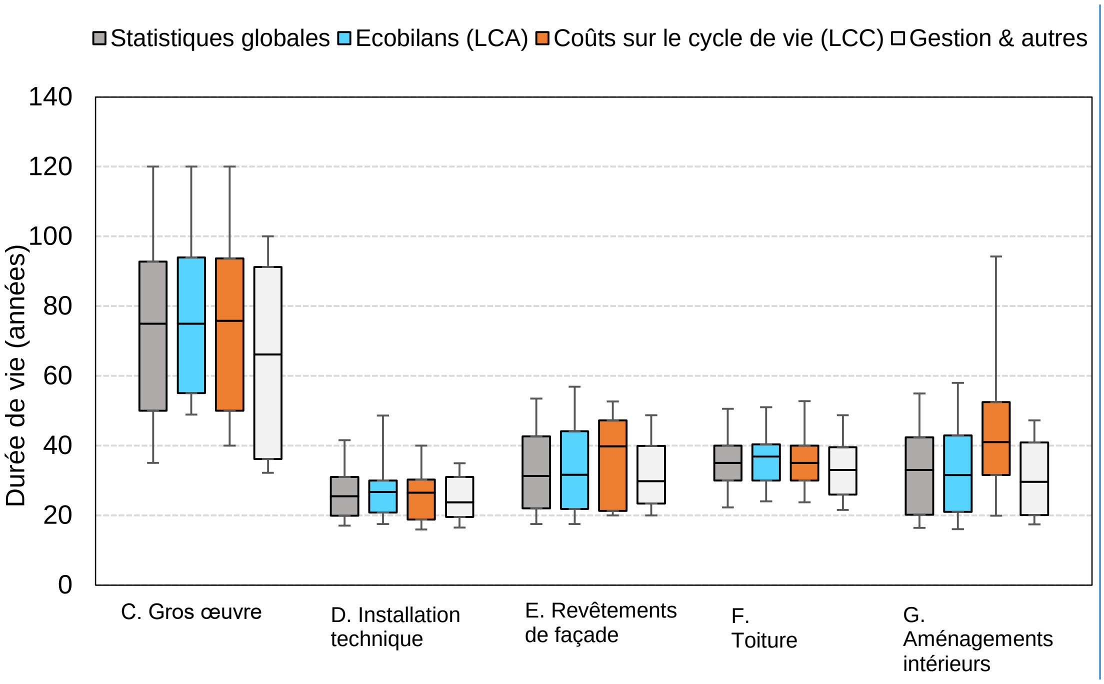


Figure 15 : Boîtes à moustaches des durées de vie pour les groupes principaux classées par type de sources

Les résultats montrent que le gros œuvre reporte, sans surprise, des durées de vie supérieures aux autres groupes avec environ 66 à 76 ans en médiane quelle que soit la statistique considérée (Global, LCA, LCC, Gestion). La variabilité est cependant substantielle avec des boîtes qui varient de 36 à 94 ans et des intervalles interdéciles de 35 à 120 ans. Les autres groupes suivent ensuite avec des durées de vie médianes comprises entre 24 et 41 ans environ. Il n'est pas possible de clairement différencier les groupes E, F et G sur la base de leurs durées de vie médianes. Ces dernières se situent entre 30 et 40 ans mais sont classées différemment selon le type de source (LCA, LCC, Gestion). Les installations techniques présentent des valeurs médianes sous les 30 ans (24 à 27 ans) avec des intervalles interquartiles limités (entre 19 et 31 ans). Le constat est similaire pour les toitures (médiane :

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[18] L'analyse préliminaire des sources de données montre également que le niveau de décomposition des éléments est beaucoup plus important dans les sources de gestion que dans les sources d'écobilan (LCA). En effet, même si près de 50% des données sont utilisées pour des calculs LCA, le nombre de composants total de l'échantillon LCA est « seulement » de 26-30% (1634 composants possédant une ou plusieurs entrées ou valeurs de durée de vie) contre près de 50% pour les sources de gestion (soit 2785 composants décrits). Pour l'échantillon LCC, les proportions sont similaires entre nombre de sources ou d'entrées et nombre de composants possédant une valeur de durées de vie (environ 20%).

33 à 37 ans et des boîtes variant de 26 à 40 ans environ). Les groupes E et G sont quant à eux plus dispersés avec des boîtes variant de 21 à 47 ans pour le groupe E et de 20 à 52 ans pour le groupe G.

Dans le détail, pour les 5 groupes principaux, les sources de gestion présentent des durées de vie médianes très légèrement plus basses que les sources LCA et LCC. A l'inverse les sources LCC présentent les durées de vie médianes les plus élevées pour les groupes E (revêtements de façades) et G (aménagements intérieurs) notamment.

Ces premiers résultats montrent, au sein de chaque groupe, que les écarts entre les médianes des types de sources restent plus faibles que la variabilité observée au sein de chaque type de sources (représentée par l'intervalle interquartile et interdécile). Il est alors intéressant de poursuivre l'analyse à un niveau de détail plus grand en décomposant ces groupes principaux en éléments et sous-éléments.

4.2.2 Composants principaux

L'analyse est poursuivie au niveau de certains composants qui sont considérés dans le calcul d'écobilan selon le cahier technique SIA 2032 [12]. Le cahier technique SIA 2032 fournit en effet des durées de vie pour 31 composants, correspondant à des éléments de la classification eCCC-Bât. Le choix s'est orienté sur les composants suivants :

- Les revêtements de façade isolée (compacte ou ventilée) ;
- La toiture (plate et ventilée) ;
- Les revêtements de sol et de planchers ;
- L'installation de chauffage (production et distribution notamment) ;
- Les menuiseries (fenêtres et portes).

Ces composants peuvent également être assainis lors d'une rénovation énergétique (au côté d'autres éléments tels que le système de ventilation ou le ballon d'eau chaude sanitaire par exemple). La Figure 16 présente une représentation de ces composants.

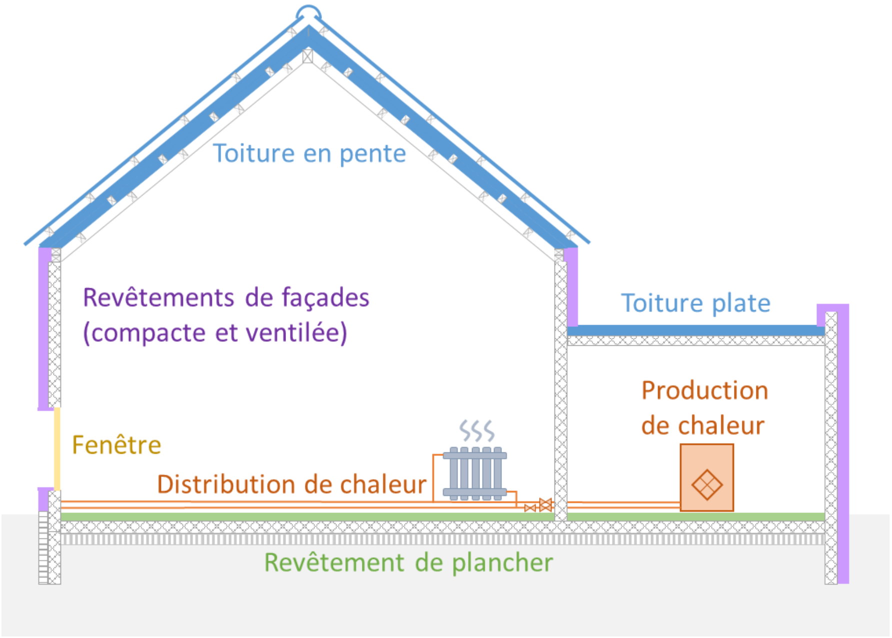

Figure 16 : Représentation des composants retenus

Dans la suite de ce chapitre, seuls ces huit composants du cahier technique SIA 2032 sont présentés. Pour le système de chauffage, les résultats pour la production et la distribution sont reportés. Les valeurs de durées de vie pour les autres composants du périmètre de calcul SIA 2032[19] sont disponibles dans le Tableau 12 de l'annexe 1. Les statistiques sont effectuées pour chaque type de source ainsi que pour l'échantillon global.

La Figure 17 présente les boites à moustaches des durées de vie pour les huit composants en fonction du type de source. L'annexe 1 (Tableau 11) reporte les valeurs de ces mêmes durées de vie. Les résultats révèlent à nouveau une forte dispersion pour les huit composants. Les façades ventilées présentent les durées de vie médianes les plus élevées avec 43 à 47 ans en médiane suivies par les toitures inclinées (médianes à 40-42 ans pour les trois échantillons). La production de chaleur montre quant à elle la durée de vie médiane la plus basse entre 18 et 20 ans quel que soit le type de source. Les autres composants (distribution de chaleur, façade compacte, fenêtre, toiture plate, revêtement de sol) affichent des durées de vie médianes qui varient le plus souvent entre 25 ans et 40 ans. Ces médianes sont parfois proches des quartiles 1 ou 3, ce qui illustre l'asymétrie des distributions. C'est notamment le cas pour la distribution de chaleur (sources LCC). Des analyses par composant sont reportées dans la suite.

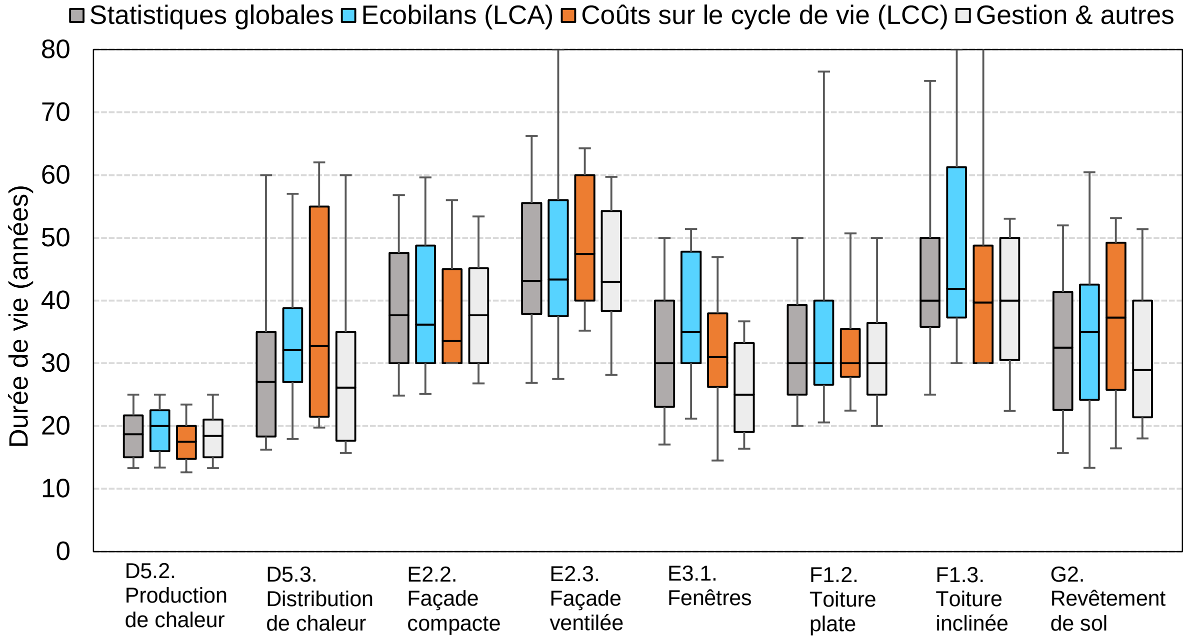

Figure 17: Boîtes à moustaches des durées de vie pour les composants du périmètre réduit SIA 2032 classées par type de sources

Production de chaleur : les durées de vie médiane sont comprises entre 18 et 20 ans quel que soit le type de source, avec un intervalle interquartile allant de 15 ans à 23 ans. A titre de comparaison, le cahier technique SIA 2032 [12] et le CRB [7] reportent une durée de vie pour cet élément de 20 ans, valeur cohérente avec les médianes de ces types de sources.

Distribution de chaleur : ce composant présente des durées de vie médianes de 27 à 33 ans, très proche de la valeur de la SIA 2032 (30 ans) avec des intervalles interdéciles élevés mais similaires entre les types de sources (entre 16 et 62 ans). Une forte variabilité des boîtes à moustaches est observée selon le type de sources (27-39 ans pour le LCA contre 22-62 ans pour le LCC). A la différence de la production de chaleur, il n'y a pas de consensus entre les sources : la dispersion reste élevée. Une

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[19] D1 Installations électriques, D 5.4 Emission de chaleur, Collecteur solaire thermique, D7 Installations de ventilation, Installations sanitaires, E2.1 Crépis, E2.4 Façades légères, E2.5 Revêtements de plafonds extérieurs, E3 Fenêtres, portes, F2 Eléments incorporés dans toiture, G1 Cloisons, portes, G3 Revêtements de parois et de piliers et G4 Revêtements de plafonds.

partie des sources de coûts et de gestion considèrent par exemple que la distribution n'est pas changée lors du remplacement du producteur de chaleur[20] et attribue une durée de vie entre 40 et 50 ans. Le CRB [7], pris en compte dans les sources de gestion et de calcul de coûts, donne, par exemple, une valeur moyenne de 40 ans. Du point de vue technique, la variabilité des valeurs de durées de vie peut s'expliquer par la nécessité ou non de déposer la distribution lors de travaux annexes. Lors d'une rénovation de l'enveloppe par exemple, il est possible de profiter de l'occasion pour installer un système neuf. Ce type de situation peut expliquer l'absence de consensus. Néanmoins, le retour d'expériences en Suisse montre qu'il est plus probable que la distribution soit maintenue que remplacée lors de rénovations énergétiques, en raison des coûts associés[21].

Façades compacte et ventilée : pour les façades compactes, les médianes des différents échantillons (Global, LCA, LCC, Gestion) sont très proches les unes des autres (entre 34 et 38 ans) de même que les intervalles interquartiles qui varient de 30 à 45-49 ans. Une asymétrie des échantillons est observée avec des médianes proches du premier quartile surtout pour les échantillons LCA et LCC. La valeur du cahier technique SIA 2032 [12] fixée à 30 ans correspond au premier quartile tandis que la valeur moyenne du CRB [7] (35 ans) reste proche des médianes de tous les échantillons. Toutes les valeurs médianes des sources pour la façade compacte sont inférieures à celles de la façade ventilée.

Pour la façade ventilée, les valeurs médianes et intervalles interquartiles sont très proches entre les types de sources avec respectivement des valeurs de 45 ans environ et une plage de 38 à 56 ans. Les valeurs pour l'échantillon LCC sont légèrement plus élevées (47 ans et 40 à 60 ans). En comparaison, le cahier technique SIA 2032 [12] et le CRB préconisent une durée de vie moyenne de 40 ans pour les façades ventilées, donc légèrement plus basse que les médianes reportées ici.

Fenêtres : ce composant est, avec la distribution de chaleur, celui qui présente le plus de différences entre les types de sources (LCA, LCC, Gestion). Les durées de vie sont très dispersées avec les valeurs les plus basses pour les sources de Gestion (médiane à 25 ans), suivies par les sources LCC (médiane à 31 ans) puis LCA (médiane à 35 ans). Les boîtes renforcent cette tendance avec un intervalle interquartile de 19 à 33 ans pour les sources de gestion contre 30 à 48 ans pour les sources d'écobilan, les sources de coûts se situant entre les deux (26 à 38 ans). La valeur de la SIA 2032 (30 ans) est donc plus proche de la médiane des sources de coûts alors que la valeur CRB (35 ans) se rapproche de la médiane des sources d'écobilan.

Toitures plate et inclinée : pour la toiture plate, tous les types de sources conduisent à une durée de vie médiane de 30 ans, soit la valeur retenue par le cahier technique SIA 2032. Les boîtes sont également relativement similaires et resserrées (de 25 à 40 ans environ). Seul l'intervalle interdécile des sources d'écobilan se singularise avec une variation de 20 à 77 ans contre au maximum 50 ans environ pour le décile 9 pour les autres sources. Pour la toiture plate, le CRB [7] indique une durée de vie moyenne de 25 ans, égale au premier quartile des sources de Gestion.

Comparativement à la toiture plate, la toiture inclinée présente des durées de vie médiane plus élevées et très proches entre elles quel que soit le type de source (de 40 à 42 ans). Ces valeurs sont cohérentes avec celles de la SIA 2032 et du CRB (40 ans). Les boites des sources de coûts (LCC) et de gestion sont bien centrées autour de la médiane (entre 30 et 50 ans). La boîte des sources d'écobilan, asymétrique, est plus élevée et varie de 37 à 61 ans. Cette asymétrie se retrouve dans les intervalles interdéciles des sources d'écobilan et de coûts avec un étalement du décile 9 jusqu'à respectivement 80 et 87 ans.

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[20] Cela dépend, en pratique, de la compatibilité des systèmes de distribution et de production lors du remplacement de ce dernier. Par exemple, si une chaudière à gaz ancienne est remplacée par une chaudière à gaz neuve, le système de distribution adapté est le même ; en revanche, si la chaudière à gaz est remplacée par une pompe à chaleur, les températures de distribution sont différentes. Ceci peut amener à un remplacement des émetteurs terminaux (par exemple, des radiateurs en fonte par du chauffage au sol) ainsi que du réseau de distribution entre le producteur et l'émetteur de chaleur.

[21] Communication orale avec un gestionnaire de parc

Revêtements de sol : pour cet élément, la durée de vie médiane selon les sources de gestion est de 29 ans contre 33 à 37 ans pour les autres échantillons (global, LCA et LCC). Néanmoins, les boîtes sont proches et varient 21 à 43 ans voire 49 ans pour les sources LCC. Les intervalles interdéciles ne sont pas beaucoup plus dispersés (de 16 à 53 ans voire 60 ans pour les sources LCA). Pour ce groupe d'élément, le cahier technique SIA 2032 [12] indique une durée de vie moyenne de 30 ans, ce qui est en adéquation avec les sources de Gestion. A l'inverse, le CRB [7] indique une valeur moyenne de 35 ans, qui correspond à la médiane des sources d'écobilan.

4.2.3 Groupe principal « installations techniques »

Afin d'observer les différences entre les différents niveaux de la classification eCCC-Bât, l'exemple choisi a été de présenter les résultats depuis le groupe principal « Installation techniques » jusqu'aux types de producteurs de chaleur (niveau « système » sous le niveau « élément » selon l'eCCC-Bât). Dans cette partie, 8 composants sont considérés avec quatre niveaux de détail différents. Les producteurs de chaleur choisis sont ceux ayant le plus de sources présentes dans la base de données. Il s'agit des chaudières, des pompes à chaleur, des installations solaires thermiques et des chauffe-eaux non électriques. Ces composants sont représentés à la Figure 18.

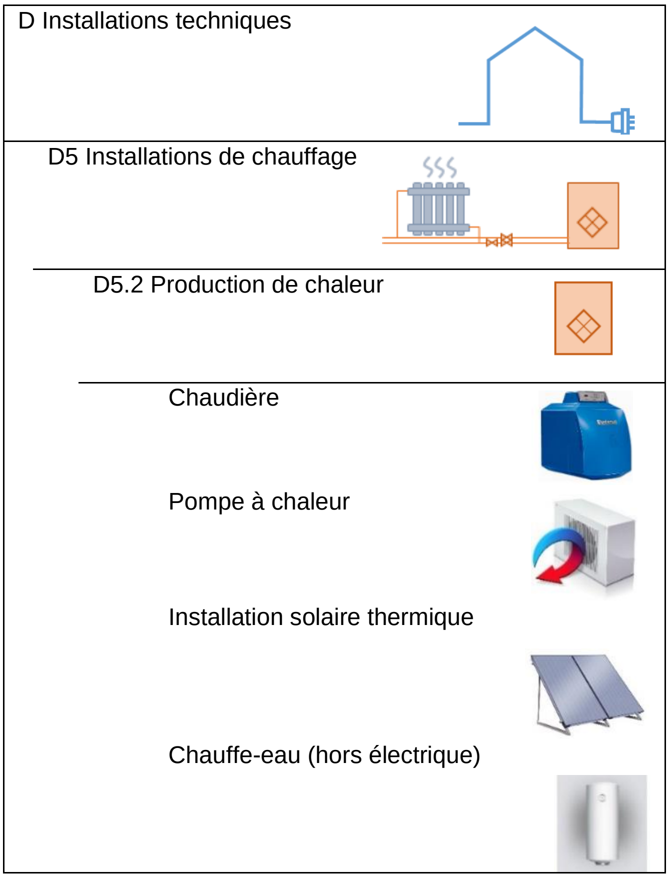

Figure 18 : Structure du groupe principal « D. Installations techniques » jusqu'aux producteurs de chaleur

La Figure 19 présente les résultats de durées de vie médianes et les écarts interdéciles obtenus pour ces différents composants du plus petit niveau de détails (installations techniques, à gauche) jusqu'aux productions de chaleur (à droite). Le Tableau 13 en annexe 1 reporte les valeurs de durées de vie correspondantes.

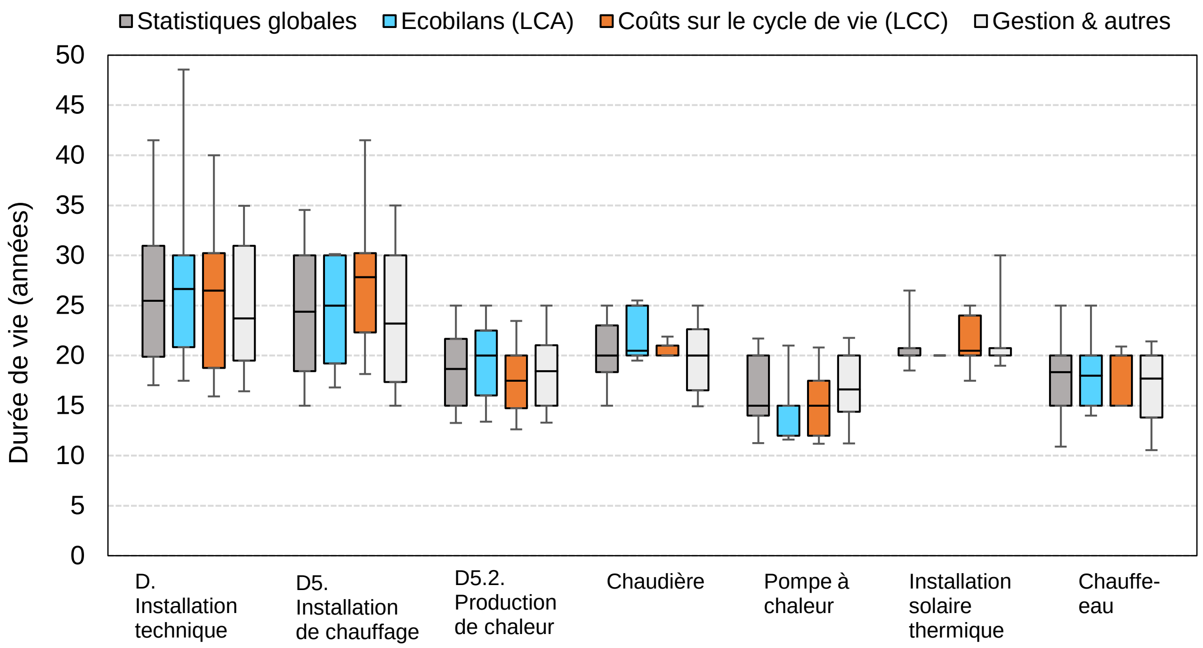

Figure 19: Boîtes à moustaches des durées de vie de systèmes de production de chaleur, du groupe principal aux composants spécifiques

Les résultats obtenus montrent que la variabilité des données est généralement plus grande pour les deux premiers niveaux de détails (D et D5) que pour des systèmes définis. Ce résultat est logique car, plus il existe de types de composants différents, plus la probabilité de regrouper des durées de vie différentes est élevée. Par ailleurs, certaines sources, comme le CRB en Suisse, fournissent une plage de valeurs pour les installations techniques ou de chauffage afin de tenir compte de durées de vie différentes entre les composants. Dans le détail, les niveaux D, D5 et D5.2 sont beaucoup plus renseignés (de 60 à 72 valeurs pour l'échantillon global) que les producteurs de chaleur et installations solaires thermiques (de 18 à 39 valeurs au global). Selon le type de sources, le nombre de valeurs peut être inférieur à 10 ce qui amène à des boîtes à moustaches très singulières (absence de boîte ou médiane décentrée).

Installations techniques (D) : ce niveau présente des boîtes à moustaches très similaires variant de 20 à 30 ans environ pour des médianes allant de 24 à 27 ans. L'intervalle interdécile limité à 35 ans pour les sources de gestion monte jusqu'à 40 pour les sources de coûts et 50 ans pour les sources d'écobilans. En comparaison, la valeur moyenne du CRB [7] (35 ans) se situe dans la partie haute des différents échantillons de données (entre le quartile 3 et le décile 9). Cependant, le CRB fournit également des durées de vie minimales et maximales égales à 15 et 50 ans respectivement. Ces deux valeurs se situent en dehors des boîtes à moustaches (qui ne contiennent que 80% des données).

Installations de chauffage (D5) : ce niveau présente des boites relativement proches du précédent (D), variant de 17 à 30 ans pour des médianes allant de 23 à 28 ans. Les intervalles interdéciles sont plus resserrés que pour le niveau D. A titre comparatif, le CRB [7] propose des valeurs de 30, 45 et 60 ans pour les durées de vie minimale, moyenne et maximale, soit à nouveau des valeurs situées dans la partie haute des boîtes à moustaches[22].

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[22] L'installation de chauffage regroupe des éléments de production de chaleur à durée de vie faible (environ 20 ans) mais aussi d'autres éléments (citerne, réseau de distribution, radiateurs) qui ont des durées de vie plus élevées d'après le CRB. Il en résulte une plage de valeurs qui englobe les durées de vie de ces différents composants.

Production de chaleur (D5.2), chaudière et pompe à chaleur : à la différence des deux niveaux de détails précédents, la production de chaleur a une durée de vie plus courte d'environ 18 à 20 ans en valeur médiane (cf. 4.2.2). Au niveau des chaudières et des PAC, peu de sources de type LCA et LCC fournissent des valeurs pour ce type de composants. Rien qu'en Suisse, ni le cahier technique SIA 2032 ni le CRB ne vont jusqu'à ce niveau de détails. Les pompes à chaleur et les chaudières sont considérées par ce cahier technique comme un système de production de chaleur standard dont la durée de vie est également de 20 ans. Seules les sondes géothermiques utilisées par les certains types de PAC ont une durée de vie différenciée (40 ans).
Pour ces deux composants (chaudière et PAC), les résultats ne sont pas concordants selon les types de sources. Cela s'explique par un nombre insuffisant de données. Néanmoins, quelques tendances sont à relever. Les durées de vie médianes des chaudières sont d'environ 20 ans contre 15-17 ans pour les PAC, les boîtes variant quant à elles de 15 à 25 ans et de 10 à 20 ans respectivement. Les sources de gestion mieux documentées (16 à 20 sources pour les chaudières/PAC) confirment cette tendance d'une durée de vie légèrement plus basse pour les PAC que pour les chaudières. Ces résultats ne sont pas en phase avec les affirmations des fabricants de pompes à chaleur qui revendiquent parfois des durées de vie plus élevées (jusqu'à 30 ans) [105]. Enfin, le CRB fournit des durées de vie minimale et maximale de 15 et 25 ans pour la production de chaleur ce qui permet d'englober une partie de ces variations.

Installations solaires thermiques : toutes les sources reportent une valeur médiane de 20 ans, ce qui correspond à la valeur du cahier technique SIA 2032 [12]. A nouveau, ces résultats représentent un faible nombre de données. Certaines sources de gestion proposent des valeurs jusqu'à 30 ans.

Chauffe-eaux : cet équipement présente des boîtes resserrées et relativement proches entre les différents types de sources, variant de 14 à 20 ans.

4.3 Statistiques par zone géographique

La Figure 20 présente une répartition des sources et entrées par zone géographique. Au total, 67 sources et 95 entrées ont été identifiées et renseignées dans la base de données DUREE. Environ un tiers des données collectées sont suisses (19 au total), le reste provenant de l'étranger avec une majorité de sources extra-européennes. Un peu moins d'un quart (22%) provient de pays européens (majoritairement de France, Allemagne, Belgique, Royaume-Uni) alors que le reste émane de pays tels que les Etats- Unis, le Canada ou l'Australie.

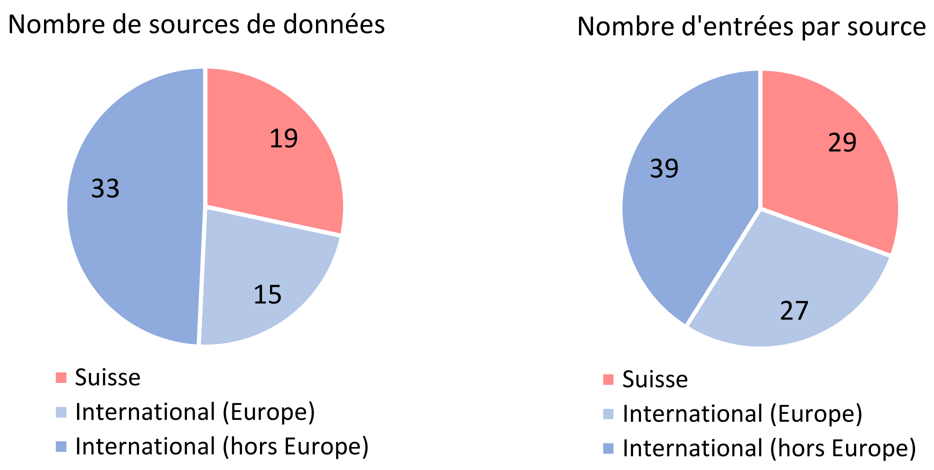

Figure 20: Répartition des sources et entrées par lieu de publication

Le Tableau 7 répertorie le nombre de sources de type écobilan (LCA), coûts sur le cycle de vie (LCC) et gestion en fonction de leur provenance géographique. Une même source peut parfois répondre à plusieurs objectifs en même temps ce qui explique que la somme des sources ou entrées LCA, LCC et Gestion soit plus élevée que le total des sources ou entrées (cf. tableaux 4, 5 et 6). La majorité des sources suisses intégrées dans la base de données vise principalement la gestion d'un bien immobilier. C'est l'inverse pour les sources internationales où une majorité de sources d'écobilan (36) sont reportées[23] contre seulement 10 sources orientées sur la gestion de biens. Dans les résultats suivants, les données internationales « Europe « et « hors Europe » sont regroupées pour pouvoir les comparer à l'échantillon de données suisses.

Tableau 7: Répartition de la provenance des sources et des entrées en fonction de leur type

Géographie	**Nombre de sources**				**Nombre d'entrées**			
	Total	LCA	LCC	Gestion	Total	LCA	LCC	Gestion
Suisse (CH)	19	3	5	13	29	3	10	20
International (Europe)	15	10	6	4	27	19	10	6
International (hors Europe)	33	26	3	6	39	28	3	10
International (total)	48	36	9	10	66	47	13	16
Total	67	39	14	23	95	50	23	36

Par la suite, les résultats des boîtes à moustaches sont présentés de manière analogue à la section précédente. Ils sont discutés et mis en perspectives avec les résultats précédents.

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[23] Ces sources sont principalement issues des données transmises par les partenaires de l'IEA-EBC Annex 72

4.3.1 Groupes principaux

La Figure 21 présente les durées de vie des groupes principaux en fonction de la provenance géographique. Les tableaux de données sont disponibles en annexe 1 (Tableau 10). Comme pour les résultats par type de sources, les résultats montrent à nouveau que le gros œuvre reporte des durées de vie supérieures aux autres groupes avec de 58 à 80 ans en médiane pour les échantillons suisse et international. La boîte à moustache des sources suisses est proche de celle des sources de gestion avec un intervalle interquartile de 40 à 80 ans tandis que la boîte à moustache internationale est plutôt proche de celles sur les sources d'écobilan et de coûts sur le cycle de vie (cf. Figure 15). Ces résultats s'expliquent par le nombre important de sources de gestion dans l'échantillon suisse et inversement par le nombre important de sources LCA et LCC pour l'échantillon international. De même, l'échantillon global de la base de données est très proche des sources internationales. En effet, les sources suisses ne représentent qu'un tiers de l'échantillon total, comme le Tableau 7 l'a montré. Les autres groupes suivent ensuite avec des durées de vie médianes comprises entre 24 ans et 35 ans environ. Les durées de vie médianes sont identiques quelle que soit la provenance pour les groupes E et F et sont légèrement plus faibles pour l'échantillon suisse pour les groupes D et G (24 contre 26 ans et 28 contre 34 ans respectivement). Les variabilités des différents groupes sont similaires à celles déjà observées par types de sources (LCA, LCC et Gestion) à la Figure 15 et ne sont pas rediscutées.

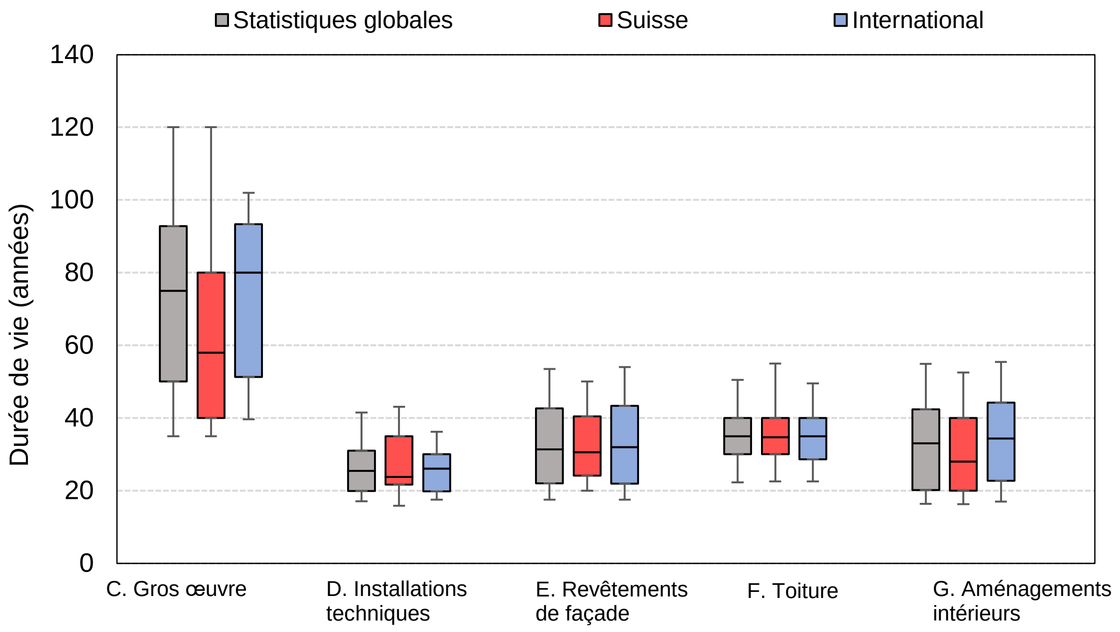

Figure 21 : Boîtes à moustaches des durées de vie des groupes principaux classées par zone géographique

Ces résultats illustrent à nouveau, au sein de chaque groupe, que les écarts entre les médianes des types de sources restent plus faibles que la variabilité observée au sein de chaque type de sources (représentée par l'intervalle interquartile ou interdécile). Une majorité des intervalles interquartiles sont communs entre sources suisses et étrangères. La zone géographique ne permet donc pas de différencier nettement les durées de vie au sein d'un groupe. Par exemple, pour le gros œuvre, la boîte est légèrement plus basse que l'échantillon international pour la raison évoquée plus haut (échantillon déterminé principalement par des sources de gestion suisse).

4.3.2 Composants principaux

Comme pour les résultats précédents par type de sources, seuls huit composants du périmètre de calcul d'écobilan selon la SIA 2032 sont présentés. Les valeurs de durées de vie pour les autres composants du périmètre de calcul SIA 2032 sont reportés au Tableau 12 de l'annexe 1. Ces durées de vie sont présentées par zone géographique (Suisse et International).

La Figure 22 présente les durées de vies pour les huit composants du périmètre SIA 2032 réduit tandis que l'annexe 1 (Tableau 11) présente les valeurs numériques utilisées pour tracer les boîtes à moustaches. Les résultats présentent à nouveau une forte dispersion. A la différence des résultats par type de sources (cf. Figure 17), les boîtes à moustaches sont, pour certains composants des sources suisses relativement resserrées. C'est le cas notamment des façades compactes, ventilées et des toitures plates avec 50% des données comprises entre 29-31 ans, 38-40 ans et 35-40 ans respectivement. Les façades ventilées et les toitures inclinées présentent à nouveau les durées de vie médianes les plus élevées avec 40 à 44 ans et 40 à 42 ans pour les sources suisses et étrangères respectivement. La production de chaleur reste le composant avec la médiane la plus basse (18-20 ans). Les autres composants (distribution de chaleur, façade compacte, fenêtre, toiture plate, revêtement de sol) ont des durées de vie médianes qui varient le plus souvent entre 25 ans et 40 ans. Ces médianes sont parfois proche des quartiles 1 ou 3 ce qui illustre l'asymétrie des distributions. C'est notamment le cas à nouveau pour la distribution de chaleur et la toiture inclinée (sources suisses). Dans la suite, les résultats sont discutés par composant.

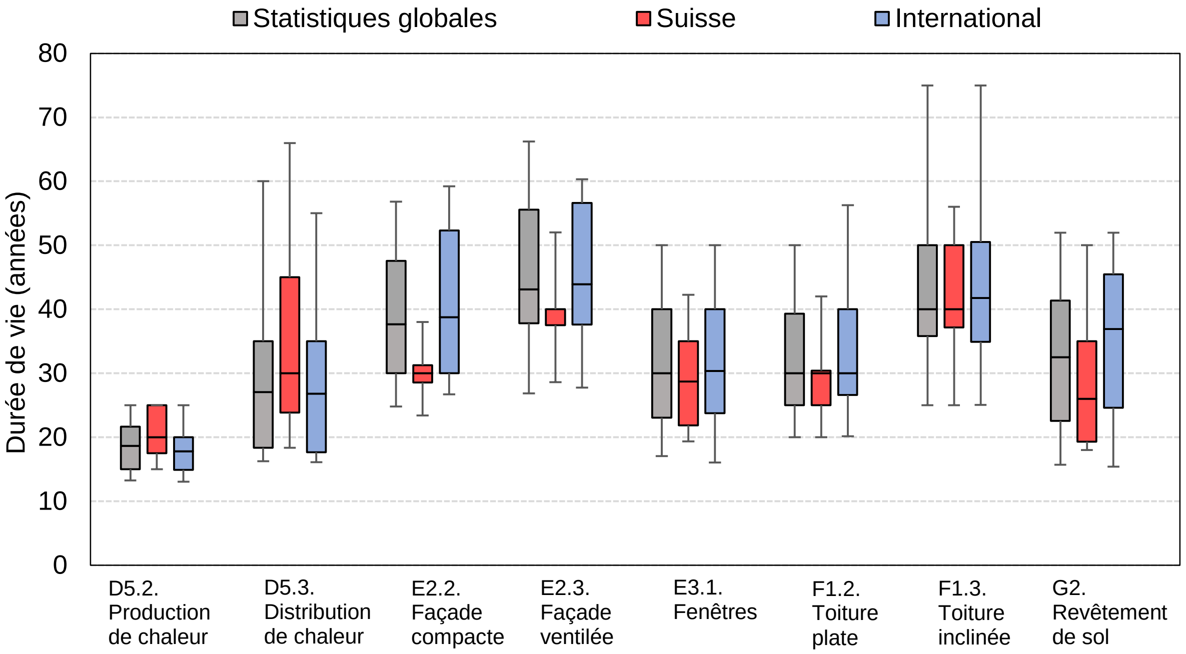

Figure 22: Boîtes à moustaches des durées de vie de composants du périmètre SIA 2032 réduit classées par zone géographique

Production de chaleur : les durées de vie médianes sont comprises entre 18 et 20 ans, soient des valeurs identiques à celles présentées à la section 4.2.2. Ce résultat montre qu'il existe un très bon consensus sur la durée de vie de ce composant quel que soit l'échantillon considéré (LCA, LCC, gestion, Suisse, International). Pour ce composant, la boîte des sources suisses est très proche de celle des sources d'écobilan (intervalle interquartile de 18 à 25 ans) tandis que pour les sources internationales, elles sont équivalentes aux sources de coûts sur le cycle de vie ou de gestion (intervalle interquartile de 15-20 ans).

Distribution de chaleur : ce composant présente des durées de vie médianes de 27 à 30 ans, très proche de la valeur de la SIA 2032 (30 ans). Les intervalles interdéciles sont toujours très élevés allant de 16 à 55 ans et 18 à 66 ans pour les sources suisses et internationales. Les valeurs suisses sont légèrement plus élevées que les valeurs internationales, la boîte suisse allant de 24 à 45 ans contre 18 à 35 ans pour les sources internationales. Elles sont notamment tirées vers le haut avec les entrées CRB, qui recommande des durées de vie moyenne et maximale respectivement de 60 et 80 ans ce qui contribuent à étirer la boite à moustache. Le découpage par provenance montre à nouveau qu'il n'y a pas de consensus autour d'une plage de valeur réduite comme c'est le cas de la production de chaleur.

Façades compacte et ventilée : la boîte à moustaches de l'échantillon suisse est très resserrée (29-31 ans). Elle se distingue nettement de la boîte de l'échantillon international qui est beaucoup plus étalée (intervalle interquartile variant de 30 à 52 ans) mais du même ordre de grandeur que celles des sources LCA, LCC et gestion. Les valeurs suisses pour la façade compacte se distinguent nettement également de la façade ventilée centrée sur 40 ans.
Pour cette deuxième façade, le constat est analogue. La boîte à moustaches de l'échantillon suisse est très resserrée autour de 38-40 ans tandis que la boîte des sources internationales est beaucoup plus dispersée (intervalle Q1-Q3 de 38 à 57 ans). Les résultats indiquent donc un relatif consensus en Suisse indépendamment du type de source (LCA, LCC, gestion) pour ces deux types de façades. Une nuance toutefois concerne le faible nombre de données suisses (8) et un intervalle interdécile élevé pour la façade ventilée (de 29 à 52 ans).

Fenêtres : les valeurs médianes des durées de vie sont quasiment identiques entre sources suisses et étrangères : 29 et 30 ans soit la durée de vie de la SIA 2032. Les boîtes vont de 22 à 35 ans et 24 à 40 ans respectivement ce qui reste proche. L'origine géographique ne conduit pas à de grandes différences contrairement aux résultats par types de sources (LCA, LCC et gestion) où les durées de vie sont plus basses pour les sources de gestion (médiane à 25 ans) que pour les autres (LCA/LCC).

Toitures plate et inclinée : comme pour les façades compacte et ventilée, les résultats indiquent des valeurs plus basses pour les toitures plates qu'inclinées. Pour les toitures plates, quel que soit l'échantillon (suisse ou international), la médiane est de 30 ans. La boîte des données suisses est resserrée (25-30 ans) et dissymétrique avec une médiane égale au quartile 3 tandis que la boîte des sources internationales est plus étirée (de 35 ans à 51 ans).
Les médianes sont également très proches pour la toiture inclinée (40-42 ans) et les intervalles interquartiles proches pour les sources suisses ou internationales (37-50 ans et 35-51 ans). Une dispersion importante est notée pour l'intervalle interdécile des données internationales (de 25 à 75 ans). L'origine géographique ne conduit pas à de grandes différences pour ce composant.

Revêtements de sols (G2) : pour cet élément, la durée de vie médiane des sources suisses est de 26 ans contre 37 ans pour les sources étrangères et 33 ans pour l'échantillon global. L'échantillon de données suisse se caractérise par un étalement de la boîte de 19 à 35 ans soit un peu plus faible que l'étendue de la boîte des sources étrangères (de 25 à 45 ans). Néanmoins, en tenant compte de 80% des données de chaque échantillon, les plages de variation des durées de vie sont proches : de 18 à 50 ans pour les données suisses et 15 à 52 ans pour les sources étrangères et 16 à 52 ans au global.

4.3.3 Groupe principal « installations techniques »

La Figure 23 présente les résultats selon différents niveaux de définition de la durée de vie pour les installations de chauffage du groupe principal aux types de système de production de chaleur. Les résultats obtenus montrent, à nouveau, que la variabilité des données est généralement plus grande pour les deux premiers niveaux de détails (D et D5) que pour les types de systèmes de production de chaleur. Les résultats analysés par composant sont présentés en suivant.

Installations techniques (D) : ce niveau présente des boîtes à moustaches très similaires à celles par type de sources (LCA, LCC, gestion) variant de 20 à 35 ans environ pour des médianes allant de 24 ans (suisse) à 26 ans (étranger). L'intervalle interdécile limité à 36 ans pour les sources internationales monte jusqu'à 43 pour les sources suisses. En comparaison, la valeur moyenne du CRB [7] (35 ans) est égale au quartile 3 de la distribution de données suisses. Cependant, le CRB fournit également des durées de vie minimales et maximales égales à 15 et 50 ans respectivement. Ces deux valeurs se situent en dehors des boîtes à moustaches (qui ne contiennent que 80% des données).

Installations de chauffage (D5) : ce niveau présente des boites relativement proches du précédent (D) variant de 17 à 30 ans pour des médianes allant de 23 à 25 ans. L'intervalle interdécile est plus élevé pour les données suisses (16-45 ans) qu'étrangères (15-31 ans). A titre comparatif, le CRB [7] propose pour la Suisse des valeurs de 30, 45 et 60 ans pour la durée de vie minimale, moyenne et maximale ce qui contribue à étirer vers le haut la distribution de données suisses.

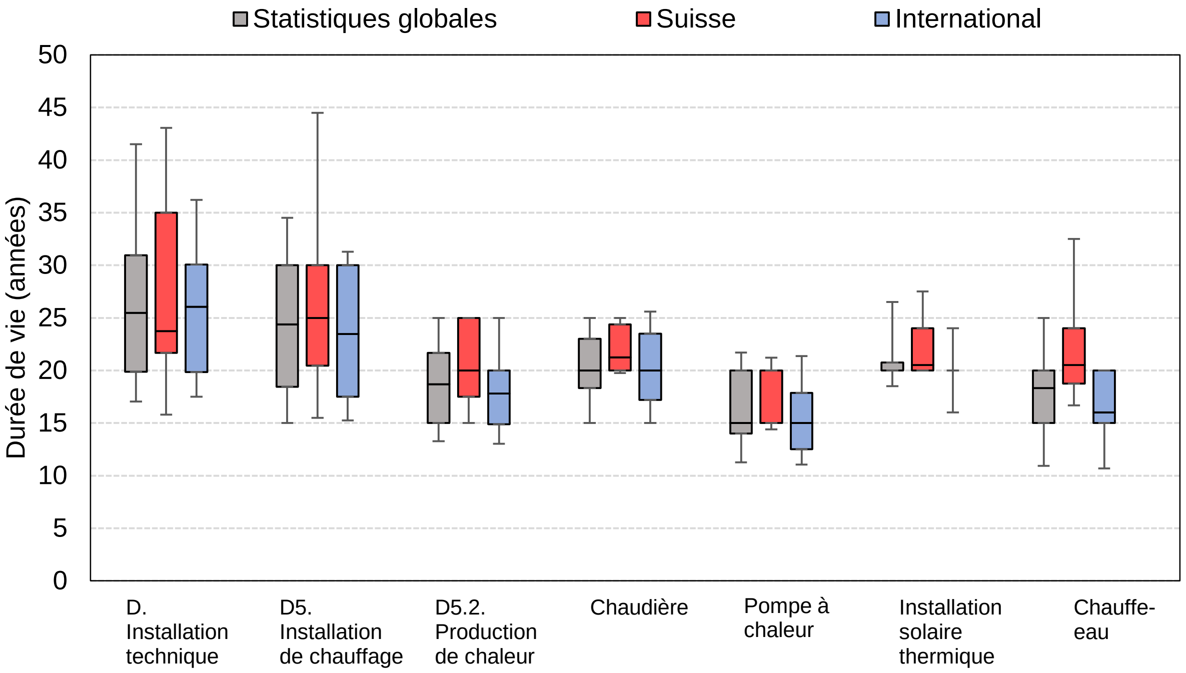

Figure 23: Boîtes à moustaches des durées de vie pour la production de chaleur du groupe principal aux systèmes spécifiques classées par zone géographique

Production de chaleur (D5.2), chaudière et pompe à chaleur : à la différence des deux niveaux de détails précédents, la production de chaleur a une durée de vie plus courte d'environ 18 à 20 ans en valeur médiane comme la première analyse l'a montré (cf. section 4.2.2). Au niveau des chaudières et des pompes à chaleur (PAC), peu de sources suisses fournissent des valeurs pour ce type de composants : cinq sources seulement contre 22 sources internationales. Pour les sources suisses, elles sont exclusivement issues de gestionnaires de parc comme Armasuisse [19].

Les résultats médians selon la provenance sont concordants pour les chaudières (durées de vie de 20-21 ans) mais sont différents pour les PAC. La durée de vie médiane est de 15 ans pour les sources internationales contre 20 ans en Suisse. Cependant, pour cette dernière, la distribution est dissymétrique avec une durée de vie médiane des PAC égale au troisième quartile (20 ans). Les intervalles interdéciles sont de 11 à 21 ans (International) et de 14 à 21 ans (Suisse). Dans le détail, certaines sources de gestionnaires de parc suisse fournissent des valeurs de 12, 13 ou 15 ans pour ces PAC (cas de Armasuisse). Elles sont plus en phase avec la médiane des sources internationales. Le faible nombre de données dans l'échantillon suisse limite la représentativité des résultats médians.

Installations solaires thermiques : les deux catégories (Suisse et International) reportent une valeur médiane de 20 ans établie à partir de 6 sources et 13 sources respectivement. A nouveau, ces résultats représentent un faible nombre de données. Les valeurs peuvent aller de 20 à 28 ans pour les sources suisses et 16 à 24 ans pour les sources étrangères.

Chauffe-eaux : les sources suisses et internationales indiquent des durées de vie de 20 ans et de 16 ans respectivement pour ce composant. L'intervalle interquartile pour les sources internationales est similaire à ceux observés par type de sources (LCA, LCC et gestion cf. Figure 19) c'est-à-dire compris entre 15 et 20 ans. La boîte à moustache des données suisses est plus élevée (de 19 à 24 ans).

4.4 Comparaison des résultats avec la SIA 2032 et le CRB

Le cahier technique SIA 2032 et le document du CRB constituent des documents de référence en Suisse pour les calculs d'écobilans et pour la gestion de biens immobiliers. Dans cette partie, les médianes des statistiques présentées dans les sous-chapitres précédents par type de sources et zones géographiques sont comparées aux valeurs moyennes de la SIA 2032 et du CRB pour les composants du périmètre réduit SIA 2032[24].

4.4.1 Valeurs du cahier technique SIA 2032

Les statistiques des sources d'écobilan (LCA), suisse et globales de la base de données DUREE sont comparées aux valeurs définies par le cahier technique SIA 2032 pour :

- Les sources d'écobilan (LCA), toutes origines confondues ;
- Les sources suisses, tous objectifs confondus (LCA, LCC, gestion) ;
- L'ensemble des valeurs récoltées, indépendamment de la localisation ou de l'objectif.

Le Tableau 8 présente les résultats obtenus pour les composants du deuxième niveau d'analyse.

Tableau 8: comparatif des durées de vie SIA 2032 avec les valeurs médianes des sources récoltées

	Durée de vie (médiane)						
	SIA 2032 [ans]	Stats Ecobilan (LCA) [ans]	*Différence avec SIA 2032 [%]*	Stats suisses [ans]	*Différence avec SIA 2032 [%]*	Stats Globales [ans]	*Différence avec SIA 2032 [%]*
D5.2 Production de chaleur	20	20	*0%*	20	*0%*	19	*-5%*
D5.3 Distribution de chaleur	30	32	*+7%*	30	*0%*	27	*-10%*
E 2.2 Façade compacte	30	36	*+20%*	30	*0%*	38	*+27%*
E2.3 Façade ventilée	40	43	*+10%*	40	*0%*	43	*+8%*
E3.1 Fenêtre	30	35	*+17%*	29	*-4%*	30	*0%*

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[24] Il s'agit des seuls composants permettant ce type d'analyse comme la SIA 2032 ne fournit pas de valeurs de durées de vie pour les groupes principaux ni pour des systèmes de production de chaleur spécifique (PAC ou chaudières notamment).

	Durée de vie (médiane)						
	SIA 2032 [ans]	Stats Ecobilan (LCA) [ans]	*Différence avec SIA 2032 [%]*	Stats suisses [ans]	*Différence avec SIA 2032 [%]*	Stats Globales [ans]	*Différence avec SIA 2032 [%]*
F1.2 Toiture plate	30	30	*0%*	30	*0%*	30	*0%*
F1.2 Toiture inclinée	40	42	*+5%*	40	*0%*	40	*0%*
G2 Revêtements de sol	30	35	*+17%*	26	*-14%*	33	*+10%*

Globalement, le cahier technique SIA 2032 est en adéquation avec l'ensemble de sources suisses. Pour six des huit composants considérés, les valeurs médianes sont exactement identiques. Pour les fenêtres, l'écart n'est que d'une année (-4%) alors la durée de vie médiane des revêtements de sol est inférieure de 14% à la proposition du cahier technique SIA 2032.

De manière identique, certaines durées de vie médianes de l'échantillon constitué des sources « écobilan » correspondent relativement bien aux valeurs du cahier technique SIA 2032. C'est le cas pour les toitures et la production et distribution de chaleur. Les durées de vie des revêtements de sol, fenêtres et façades compactes sont 17% à 20% plus élevées pour les sources écobilan de même que les façades ventilées (+10%). Pour l'échantillon global, la tendance est similaire. La durée de vie médiane des fenêtres correspond désormais à la valeur SIA 2032 (30 ans) et celle pour la distribution de chaleur est légèrement plus basse que la SIA 2032 (27 ans contre 30 ans).

4.4.2 Valeurs du manuel LCC CRB

Le document CRB représente la source suisse de référence pour l'analyse des coûts sur le cycle de vie (LCC) et de gestion. Il fournit trois valeurs distinctes pour les groupes principaux : durée de vie minimum, moyenne et maximum. L'étude complémentaire ci-dessous évalue l'écart entre les valeurs moyennes issues du document CRB avec :

- Les sources de gestion, toutes localisations confondues ;
- Les sources suisses, tous objectifs confondus ;
- L'ensemble des valeurs récoltées, indépendamment de la localisation ou de l'objectif.

Le Tableau 9 présente les résultats obtenus pour les composants du deuxième niveau d'analyse.

Tableau 9: Comparaison des valeurs CRB avec les valeurs médianes des sources

	Durée de vie (médiane)						
	CRB [ans]	Stats gestion [ans]	*Différence avec CRB [%]*	Stats suisses [ans]	*Différence avec CRB [%]*	Stats Globales [ans]	*Différence avec CRB [%]*
D5.2 Production de chaleur	20	18	*-5%*	20	*0%*	19	*-5%*
D5.3 Distribution de chaleur	60	26	*-45%*	30	*-50%*	27	*-45%*
E 2.2 Façade compacte	35	38	*+6%*	30	*-15%*	38	*+9%*
E2.3 Façade ventilée	40	43	*+8%*	40	*0%*	43	*+8%*
E3.1 Fenêtre	35	25	*-29%*	29	*-27%*	30	*-29%*
F1.2 Toiture plate	25	30	*+20%*	30	*+20%*	30	*+20%*
F1.2 Toiture inclinée	40	40	*0%*	40	*0%*	40	*0%*
G2 Revêtements de sol	35	29	*-17%*	26	*-26%*	33	*-6%*

Les différences entre les valeurs moyennes indiquées par le CRB et les médianes des autres échantillons paraissent globalement élevées. Il faut tout d'abord rappeler qu'en plus d'une durée de vie moyenne, le CRB indique également des valeurs minimum et maximum. Pour tous les composants à l'exception de la distribution de chaleur, les médianes des échantillons suisses et Gestion se trouvent à l'intérieur de cet intervalle.

La toiture inclinée constitue le seul composant pour lequel il existe un consensus parfait. Concernant la toiture plate, les sources de gestion et suisses conduisent à 30 ans alors que le CRB préconise plutôt 25 ans. Le constat inverse est fait pour les fenêtres : le CRB indique une durée de vie moyenne de 35 ans, soit 14 à 29% plus élevée que les médianes des échantillons précités. Pour les revêtements de sol, la moyenne du CRB est plus représentative des sources de gestion mais relativement éloignée de la médiane des sources suisses (10 ans d'écart). Concernant la distribution de chaleur du bâtiment (D5.3), les résultats sont très différents avec les valeurs de la littérature. Les 20 ans suggérés par le CRB pour la production de chaleur sont par contre en adéquation avec les médiane suisses et Gestion.

Des résultats comparatifs complémentaires sont reportés en Annexe 2 pour les autres composants pris en compte dans le périmètre de calcul d'un écobilan de bâtiment de la SIA 2032 et dont certains sont repris dans l'étude DUREE WP3.

5 Discussions

Les plages de valeurs de durées de vie pour environ cent composants ont été calculées et les statistiques descriptives des principaux composants sont reportées en annexe 1 et dans la publication Open Access du journal Data-in-Brief [104]. Ces résultats globaux ont ensuite été analysés au chapitre 4 pour un nombre réduit de composants pour trois axes d'analyses. Dans cette partie, trois points sont discutés : 1) la variabilité des durées de vie, 2) les limites des résultats notamment sur les durées de vie des équipements d'énergie renouvelable, 3) les hypothèses de la base de données DUREE et les recommandations d'utilisation des différents échantillons.

Les résultats montrent une variabilité des valeurs de durées de vie de la littérature quel que soit le type d'échantillon (global, LCA, LCC, Gestion, Suisse ou International) pour chaque type de composant et pour les différents niveaux de détails. Il n'existe donc pas de valeur consensuelle de durées de vie commune à toutes les sources. Une singularité – attendue – est à relever : plus le niveau de détails utilisé pour définir la durée de vie est élevé, moins les éléments sont renseignés. Il n'y a alors plus beaucoup de valeurs qui composent la distribution statistique. C'est le cas notamment des sources utilisées dans des calculs d'écobilan (LCA) dans le cas des producteurs de chaleur. Peu de sources reportent des durées de vie par système 8chaudière, PAC…) à la différence des sources de gestion. Pour ces dernières, un niveau de détail élevé est parfois fourni pour pouvoir anticiper les coûts de remplacement au plus juste ou régler des conflits dans le cas des sources de gestion entre locataires et propriétaires [52].
Le regroupement des données selon cinq échantillons différents (LCA, LCC, Gestion, Suisse, International) n'amène pas à des résultats significativement différents. Aucune tendance systématique n'est relevée i.e., des valeurs de durées de vie toujours plus basses pour des applications en calcul de coûts sur le cycle de vie (LCC) par rapport aux écobilan (LCA) ou aux sources de gestion. Les conclusions sont spécifiques à chaque composant. Dans certains cas, les valeurs médianes des sources de gestion sont certes plus basses que les autres sources (LCA, LCC). Ce type de résultats n'est toutefois pas conclusif car la variabilité des valeurs autour de la durée de vie médiane (mesurée avec l'intervalle interquartile et interdécile) est très souvent plus grande que les écarts entre les médianes des sources. Il n'est donc pas possible de conclure avec certitude sur cette tendance.
Pour les durées de vie des sources suisses et internationales, la tendance est similaire, avec quelques nuances. Une distinction peut être faite sur certains composants. Par exemple, il existe un consensus en Suisse autour de 30 ans pour la façade compacte et 40 ans pour la façade ventilée avec une faible variabilité comparée aux sources internationales (médiane plus élevée et variabilité plus grande). A l'inverse, pour d'autres composants comme les fenêtres et les toitures inclinées, les résultats ont montré des valeurs proches en médiane et autant dispersée quelle que soit la zone géographique (Suisse ou International).

La base de données DUREE visait aussi à intégrer des valeurs de durées de vie sur un nombre élevé de composants de bâtiments. Les durées de vie pour l'enveloppe du bâtiment sont relativement bien documentées dans les sources de la littérature. Pour les installations techniques, le niveau de renseignement de la base de données n'est pas toujours élevé au sein de chaque système, comme cela a été mentionné à la section précédente. C'est notamment le cas des équipements d'énergie renouvelable : collecteurs solaire thermique, sondes géothermiques ou panneaux photovoltaïques. Ces composants mériteraient des études complémentaires pour avoir un meilleur recul sur les valeurs de durées de vie considérées. Actuellement, dans les documents utilisés, peu de sources reportent des valeurs pour ces composants même s'ils sont de plus en plus mis en œuvre dans les nouvelles constructions et les rénovations énergétiquement performantes. Le manuel LCC CRB par exemple, plutôt orienté sur l'enveloppe du bâtiment, ne fournit aucune valeur pour ces trois composants.

Une partie des résultats s'appuie sur un calcul automatique des valeurs de durées de vie (voir les conditions de ce calcul à la section 3.4). Cette hypothèse de travail a permis de calculer des données –

au départ fournies à des niveaux de détails différents – pour des niveaux identiques et ainsi les intégrer aux résultats du chapitre 4. Cependant, il n'est pas impossible que des biais soient présents lorsque les durées de vie de petits composants (p.ex. brûleur, circulateur, soupape de sécurité pour une chaudière) servent à fixer la durée de vie du système complet. Actuellement, la durée de vie de l'élément supérieur est calculée par une moyenne des durées de vie des éléments inférieurs sans pondération. Sur ce point, nous considérons que ces biais sont potentiellement présents mais restent limités[25]. Un travail complémentaire serait utile pour améliorer les valeurs.

De même, certaines sources de données peuvent parfois se baser sur des estimations similaires (cf. description des sources au chapitre 2.3) au sein d'un pays ce qui tend parfois à pondérer deux fois une même source de données. Les sources allemandes sont également dominantes dans l'échantillon des sources européennes ce qui influencent les résultats des sources internationales.

Les résultats présentés dans cette étude se basent sur un nombre important de données pour l'échantillon global. L'échantillon de données a pu être augmenté significativement grâce à un sondage mis en place dans le projet IEA-EBC Annex 72 [51]. Des tableaux de résultats en Annexe 3 présente l'influence de l'augmentation de la taille de l'échantillon global pour quelques éléments analysés dans l'étude WP1 et WP2[26]. De manière générale, les distributions restent similaires pour l'échantillon global avant et après mise à jour. La médiane reste par exemple très stable. Seules les bornes de l'intervalle interdécile peuvent légèrement varier.

Comme la variabilité des valeurs ne permet pas d'établir des tendances claires et systématiques par type de sources ou zone géographique, il est recommandé pour déterminer des lois de distribution statistique (normale, log-normale…) de se baser sur l'échantillon global de la base de données DUREE.

6 Conclusions

Un travail conséquent de recherche de valeurs publiées dans la littérature a été mené. L'analyse des documentations a mis en évidence différentes terminologies pour qualifier la durée de vie d'un élément. Selon le document, il peut s'agir de la durée d'utilisation d'un composant, de sa durée de vie technique, de la durée de retour sur investissement, de sa durée d'amortissement, etc. Ces données de la littérature ont été classées par zone géographique : Suisse et International. De même, elles ont été regroupées selon trois objectifs différents : calculs d'écobilan (LCA), calcul d'analyse des coûts sur le cycle de vie (LCC) et une autre catégorie pour regrouper les sources orientées vers la gestion d'un bien immobilier. Au total, cette recherche a permis d'identifier une centaine de documents parmi lesquels 67 ont été retenus pour l'analyse. Regroupés au sein de la base de données DUREE au format eCCC-Bât dans un tableur Excel, ces différentes données ont été analysées au moyen de statistiques descriptives pour différents niveaux de détails.

Les plages de valeurs de durées de vie pour environ 100 éléments ont été calculées et les statistiques descriptives reportées en annexe 1 pour le sprincipaux composants et dans un article Open Acces du journal Data-in-Brief [104]. Elles peuvent être désormais utilisées pour des besoins spécifiques par des personnes intéressées en complément des sources de données individuelles. Ces résultats ont ensuite été analysés selon trois directions : pour les cinq groupes principaux selon eCCC-Bât correspondant en Suisse au niveau retenu pour les calculs économiques du bâtiment en phase de planification (SIA 480:2016) ; pour huit composants principaux – pris en compte dans le calcul d'écobilan selon la SIA 2032 et qui peuvent être remplacés lors d'une rénovation énergétique – et enfin pour la catégorie

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[25] Seul un nombre réduit de sources présente cette particularité. Par ailleurs, même si l'influence est forte sur la durée de vie calculée pour la source en question (dans un calcul bottom up), le calcul statistique des valeurs des 67 sources et 96 entrées à tendance à réduire l'influence de ces valeurs recalculées lorsqu'on présente 50% ou 80% de la distribution des données.

[26] L'étude WP2 se base sur l'échantillon global de la base de données DUREE sans les données de l'Annex 72 pour des raisons de travaux menés en parallèle entre le WP1 et le WP2. Cependant, les tendances présentées à l'Annex 4 montre que les tendances restent similaires par composant avant et après mise à jour de la base de données DUREE.

des installations techniques du niveau le plus général jusqu'au niveau des différents types de producteurs de chaleur.

Les résultats ont monté qu'il n'existe pas de tendance générale, c'est-à-dire qu'un type de source ou qu'une zone géographique ne présente pas des valeurs de durées de vie systématiquement plus basses (respectivement plus élevées). Cela dépend du type d'élément étudié. La variabilité relativement importante des durées de vie est par contre à relever quel que soit le composant ou le niveau de détail étudié. Dans l'ensemble, les durées de vie proposées par le cahier technique SIA 2032 correspondent relativement bien aux données suisses récoltées sur les composants en commun. En revanche, cette étude a montré que les durées de vie moyennes proposées par le CRB sont plus élevées que les autres sources de même provenance ou poursuivant un objectif similaire à l'exception des toitures, pour lesquels les valeurs sont en adéquation.

Remerciements

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Annexe 1 : Résultats détaillés par type de sources et zone géographique

Les tableaux suivants reportent les statistiques détaillées ayant servi de base aux graphiques de résultats du chapitre 4.

Tableau 10 : Résultats détaillés par type de sources pour les groupes principaux

	Echantillon	*Nombre de données*	D1	Q1	**Médiane**	Q3	D9
C : Gros-œuvre	Global	69	35	50	75	93	120
	LCA	33	49	55	75	94	120
	LCC	20	40	50	76	94	120
	Gestion	28	32	36	66	91	100
	Suisse	21	35	40	58	80	120
	International	50	40	51	80	93	102
D : Installations techniques	Global	72	17	20	25	31	42
	LCA	31	18	21	27	30	49
	LCC	21	16	19	26	30	40
	Gestion	32	16	19	24	31	35
	Suisse	25	16	22	24	35	43
	International	48	18	20	26	30	36
E. Revêtements de façade	Global	89	18	22	31	43	53
	LCA	48	18	22	32	44	57
	LCC	21	20	21	40	47	53
	Gestion	34	20	23	30	40	49
	Suisse	28	20	24	31	40	50
	International	63	18	22	32	43	54
F: Toitures	Global	89	22	30	35	40	51
	LCA	47	24	30	37	40	51
	LCC	23	24	30	35	40	53
	Gestion	33	22	26	33	40	49
	Suisse	26	23	30	35	40	55
	International	65	23	29	35	40	50
G : Aménagements intérieurs	Global	85	16	20	33	42	55
	LCA	42	16	21	32	43	58
	LCC	23	20	32	41	52	94
	Gestion	34	17	20	30	41	47
	Suisse	27	16	20	28	40	52
	International	59	17	23	34	44	55

Tableau 11 : Résultats détaillés par type de sources et par zone géographique pour les principaux composants du périmètre SIA 2032 réduit

	Echantillon	*Nombre de données*	D1	Q1	**Médiane**	Q3	D9
D5.2 Production de chaleur	Global	60	13	15	**19**	22	25
	LCA	25	13	16	**20**	23	25
	LCC	16	13	15	**18**	20	23
	Gestion	31	13	15	**18**	21	25
	Suisse	19	15	18	**20**	25	25
	International	42	13	15	**18**	20	25
	CT SIA 2032				*20*		
D5.3 Distribution de chaleur	Global	34	16	18	**27**	35	60
	LCA	14	18	27	**32**	39	57
	LCC	10	20	22	**33**	55	62
	Gestion	18	16	18	**26**	35	60
	Suisse	8	18	24	**30**	45	66
	International	26	16	18	**27**	35	55
	CT SIA 2032				*30*		
E 2.2 Façade compacte	Global	39	25	30	**38**	48	57
	LCA	22	25	30	**36**	49	60
	LCC	11	30	30	**34**	45	56
	Gestion	17	27	30	**38**	45	53
	Suisse	8	23	29	**30**	31	38
	International	33	27	30	**39**	52	59
	CT SIA 2032				*30*		
E 2.3 Façade ventilée	Global	38	27	38	**43**	56	66
	LCA	21	28	38	**43**	56	80
	LCC	9	35	40	**47**	60	64
	Gestion	17	28	38	**43**	54	60
	Suisse	8	29	38	**40**	40	52
	International	32	28	38	**44**	57	60
	CT SIA 2032				*40*		
E 3.1 Fenêtre	Global	66	17	23	**30**	40	50
	LCA	37	21	30	**35**	48	51
	LCC	14	15	26	**31**	38	47
	Gestion	27	16	19	**25**	33	37
	Suisse	14	19	22	**29**	35	42
	International	54	16	24	**30**	40	50
	CT SIA 2032				*30*		
F 1.2 Toiture plate	Global	61	20	25	**30**	39	50
	LCA	28	21	27	**30**	40	77
	LCC	15	22	28	**30**	35	51
	Gestion	31	20	25	**30**	36	50
	Suisse	19	20	25	**30**	30	42
	International	43	20	27	**30**	40	56
	CT SIA 2032				*30*		
F 1.3 Toiture inclinée	Global	57	25	36	**40**	50	75
	LCA	28	30	37	**42**	61	80
	LCC	14	30	30	**40**	49	87
	Gestion	27	22	31	**40**	50	53
	Suisse	15	25	37	**40**	50	56
	International	43	25	35	**42**	51	75
	CT SIA 2032				*40*		
G2 Revêtements de sol	Global	68	16	23	**33**	41	52
	LCA	31	13	24	**35**	43	60
	LCC	18	16	26	**37**	49	53
	Gestion	31	18	21	**29**	40	51
	Global	21	18	19	**26**	35	50
	LCA	48	15	25	**37**	45	52
	CT SIA 2032				*30*		

Le tableau suivant présente les statistiques détaillées des autres composants pris en compte dans le calcul d’écobilan selon le cahier technique (CT) SIA 2032 mais dont les résultats ne sont pas présentés dans le corps du rapport. Les composants structurels de la catégorie C ou ceux mis à 60 ans dans le cahier technique ne sont pas reportés. Les statistiques de durées de vie pour ces différents composants restent disponibles pour l’échantillon global dans l’article Data-in-Brief [104].

Tableau 12 : Résultats détaillés par type de sources et par zone géographique pour les autres composants du périmètre du cahier technique SIA 2032 non analysés dans le rapport

	Echantillon	*Nombre de données*	D1	Q1	**Médiane**	Q3	D9
D1 Installations électriques	Global	64	15	20	**30**	39	50
	LCA	27	15	20	**25**	37	50
	LCC	16	18	24	**30**	46	50
	Gestion	31	16	21	**30**	37	50
	Suisse	21	16	20	**30**	40	50
	International	43	15	20	**30**	38	50
	CT SIA 2032				*30*		
Installation photovoltaïque	Global	10	17	19	**22**	25	30
	LCA	4	23	24	**28**	30	30
	LCC	1	25	25	**25**	25	25
	Gestion	6	15	18	**19**	21	23
	Suisse	2	26	26	**28**	29	30
	International	8	16	18	**21**	23	27
	CT SIA 2032				*30*		
Installation solaire thermique	Global	18	19	20	**20**	21	27
	LCA	5	20	20	**20**	20	20
	LCC	6	18	20	**21**	24	25
	Gestion	10	19	20	**20**	21	30
	Suisse	6	20	20	**21**	24	28
	International	13	16	20	**20**	20	24
	CT SIA 2032				*20*		
Sondes géothermiques	Global	4	25	28	**33**	36	39
	LCA	2	31	33	**35**	38	39
	LCC	1	23	23	**23**	23	23
	Gestion	2	24	26	**29**	32	34
	Suisse	3	25	29	**35**	38	39
	International	1	30	30	**30**	30	30
	CT SIA 2032				*40*		
D5.4 Emission de chaleur	Global	32	19	21	**29**	35	48
	LCA	11	20	20	**30**	31	35
	LCC	9	20	25	**30**	40	64
	Gestion	19	19	23	**28**	44	51
	Suisse	9	27	30	**30**	40	64
	International	23	20	20	**25**	32	47
	CT SIA 2032				*30*		
D7 Installations de ventilation	Global	51	17	20	**22**	26	33
	LCA	21	20	20	**23**	27	30
	LCC	14	20	20	**21**	27	38
	Gestion	24	16	19	**22**	26	37
	Suisse	15	20	20	**25**	31	46
	International	36	16	20	**21**	25	30
	CT SIA 2032				*30*		
Installations sanitaires	Global	27	20	23	**30**	38	50
	LCA	14	20	25	**30**	34	46
	LCC	8	20	24	**30**	35	50
	Gestion	11	20	20	**30**	35	40
	Suisse	9	20	30	**30**	50	50
	International	18	20	21	**30**	34	43
	CT SIA 2032				*30*		

	Echantillon	*Nombre de données*	D1	Q1	**Médiane**	Q3	D9
E2.1 Crépis	Global	63	10	11	**25**	40	55
	LCA	40	10	10	**20**	40	57
	LCC	11	10	16	**34**	41	56
	Gestion	22	19	25	**31**	38	42
	Suisse	9	18	25	**38**	40	40
	International	55	10	10	**25**	41	57
	CT SIA 2032				*40*		
E2.4 Façades légères	Global	25	25	35	**42**	60	100
	LCA	11	40	40	**45**	70	100
	LCC	1	60	60	**60**	60	60
	Gestion	14	25	28	**39**	43	88
	Suisse	6	25	26	**33**	39	40
	International	19	27	41	**44**	70	100
	CT SIA 2032				*40*		
E2.5 Revêtements de plafonds extérieurs	Global	54	7	10	**14**	27	51
	LCA	36	8	10	**10**	28	50
	LCC	9	12	14	**15**	20	25
	Gestion	17	7	10	**20**	27	42
	Suisse	7	13	18	**25**	37	40
	International	48	7	10	**11**	27	56
	CT SIA 2032				*40*		
E3 Fenêtres, portes	Global	75	19	25	**30**	39	50
	LCA	39	20	30	**34**	43	50
	LCC	16	15	28	**30**	39	49
	Gestion	32	17	20	**25**	33	37
	Suisse	23	16	20	**28**	30	47
	International	54	20	25	**32**	40	49
	CT SIA 2032				*30*		
F2 Eléments incorporés dans toiture	Global	58	21	26	**30**	40	50
	LCA	35	23	30	**36**	42	50
	LCC	11	25	30	**32**	40	50
	Gestion	20	20	23	**29**	40	41
	Suisse	8	20	26	**30**	35	65
	International	50	22	26	**32**	40	50
	CT SIA 2032				*30*		
G1 Cloisons, portes	Global	61	21	30	**40**	50	66
	LCA	30	22	30	**40**	60	74
	LCC	15	21	28	**35**	59	77
	Gestion	26	21	28	**38**	49	55
	Suisse	15	17	28	**30**	38	54
	International	47	23	30	**42**	53	69
	CT SIA 2032				*30*		
G3 Revêtements de parois et de piliers	Global	66	11	21	**30**	42	59
	LCA	32	11	24	**30**	40	60
	LCC	17	9	20	**35**	50	64
	Gestion	29	12	21	**30**	42	59
	Suisse	20	10	20	**27**	30	43
	International	47	18	25	**38**	50	60
	CT SIA 2032				*30*		
G4 Revêtements de plafonds	Global	59	15	20	**35**	48	60
	LCA	27	19	20	**30**	55	71
	LCC	16	20	28	**42**	52	65
	Gestion	27	11	21	**33**	43	51
	Suisse	19	10	21	**30**	40	50
	International	41	19	20	**38**	50	60
	CT SIA 2032				*30*		

Tableau 13 : Résultats détaillés par type de sources et par zone géographique au sein du groupe principal des installations techniques

	Echantillon*	*Nombre de données*	D1	Q1	**Médiane**	Q3	D9
D5 Installation de chauffage	Global	65	15	18	**24**	30	35
	LCA	27	17	19	**25**	30	30
	LCC	18	18	22	**28**	30	42
	Gestion	32	15	17	**23**	30	35
	Suisse	22	16	20	**25**	30	45
	International	44	15	18	**23**	30	31
Chaudière	Global	33	15	18	**20**	23	25
	LCA	10	20	20	**21**	25	26
	LCC	5	20	20	**21**	21	22
	Gestion	20	15	17	**20**	23	25
	Suisse	6	20	20	**21**	24	25
	International	28	15	17	**20**	24	26
Pompe à chaleur	Global	27	11	14	**15**	20	22
	LCA	9	12	12	**15**	15	21
	LCC	7	11	12	**15**	18	21
	Gestion	16	11	14	**17**	20	22
	Suisse	5	14	15	**20**	20	21
	International	22	11	13	**15**	18	21
Installation solaire thermique	Global	18	19	20	**20**	21	27
	LCA	5	20	20	**20**	20	20
	LCC	6	18	20	**21**	24	25
	Gestion	10	19	20	**20**	21	30
	Suisse	6	20	20	**21**	24	28
	International	13	16	20	**20**	20	24
Chauffe-eaux	Global	39	11	15	**18**	20	25
	LCA	16	14	15	**18**	20	25
	LCC	12	15	15	**20**	20	21
	Gestion	20	11	14	**18**	20	21
	Suisse	6	17	19	**21**	24	33
	International	33	11	15	**16**	20	20

* Les statistiques par échantillon des éléments D. Installations techniques et D5.2 Production de chaleur ne sont pas reportées dans ce tableau. Elles sont disponibles aux Tableaux 10 et 11.

Annexe 2 : Résultats comparatifs entre la SIA 2032, CRB et les statistiques médianes de la base DUREE

Tableau 14: comparatif des durées de vie SIA 2032 avec les valeurs médianes des sources récoltées pour d'autres composants du périmètre du cahier technique SIA 2032 non analysés dans le rapport

	Durée de vie (médiane)						
	SIA 2032 [ans]	Stats Ecobilan (LCA) [ans]	*Différence avec SIA 2032 [%]*	Stats suisses [ans]	*Différence avec SIA 2032 [%]*	Stats Globales [ans]	*Différence avec SIA 2032 [%]*
D1 Installations électriques	30	25	*-17%*	30	*0%*	30	*0%*
Collecteurs solaire thermique	20	20	*0%*	21	*5%*	20	*0%*
D5.4 Diffusion de chaleur	30	30	*0%*	30	*0%*	25	*-17%*
D7. Système de ventilation	30	23	*-22%*	25	*-17%*	21	*-30%*
Sanitaires	30	30	*0%*	30	*0%*	30	*0%*
G1 Cloisons, portes	30	40	*33%*	30	*0%*	42	*40%*
G3 Revêtements de parois et de piliers	30	30	*0%*	27	*-10%*	38	*27%*
G4 Revêtements de plafonds	30	30	*0%*	30	*0%*	38	*27%*

Tableau 15: comparatif des durées de vie CRB moyenne avec les valeurs médianes des sources récoltées pour d'autres composants du périmètre du cahier technique SIA 2032 non analysés dans le rapport

	Durée de vie (médiane)						
	CRB (moy) [ans]	Stats gestion [ans]	*Différence avec CRB [%]*	Stats suisses [ans]	*Différence avec CRB [%]*	Stats Globales [ans]	*Différence avec CRB [%]*
D1 Installations électriques	45	30	*-33%*	30	*-33%*	30	*-33%*
Collecteurs solaire thermique	-	20	-	21	-	20	-
D5.4 Diffusion de chaleur	60	28	*-54%*	30	*-50%*	25	*-58%*
D7. Système de ventilation	40	22	*-46%*	25	*-38%*	21	*-48%*
Sanitaires	-	30	-	30	-	30	-
G1 Cloisons, portes	35	38	*7%*	30	*-14%*	42	*20%*
G3 Revêtements de parois et de piliers	30	30	*0%*	27	*-10%*	38	*27%*
G4 Revêtements de plafonds	30	33	*10%*	30	*0%*	38	*27%*

Annexe 3 : Résultats comparatifs de l'échantillon global avant et après mise à jour des données de l'Annex 72

Tableau 16 : Résultats détaillés pour quelques composants pour l'échantillon global après mise à jour des données de l'Annex 72 (étude WP1), pour l'échantillon global avant mise à jour (étude WP2) et pour l'échantillon suisse (non influencé par la mise à jour des données de l'Annex 72)

	Echantillon	Données	D1	Q1	**Médiane**	Q3	D9
D5. Système de chauffage	*Global (avant mise à jour)*	*43*	*16*	*20*	***25***	*30*	*35*
	Global (après mise à jour)	65	15	18	**24**	30	35
	Suisse (CRB + autres sources)	22	16	20	**25**	30	45
D5.2 Production de chaleur	*Global (avant mise à jour)*	*40*	*13*	*15*	***19***	*20*	*25*
	Global (après mise à jour)	60	13	15	**19**	22	25
	Suisse (CRB + autres sources)	19	15	18	**20**	25	25
D5.3 Distribution de chaleur	*Global (avant mise à jour)*	*28*	*16*	*18*	***26***	*33*	*46*
	Global (après mise à jour)	34	16	18	**27**	35	60
	Suisse (CRB + autres sources)	8	18	24	**30**	45	66
E2 Revêtement de façade	*Global (avant mise à jour)*	*43*	*18*	*24*	***30***	*40*	*51*
	Global (après mise à jour)	76	10	20	**35**	47	69
	Suisse (CRB + autres sources)	18	20	27	**36**	48	70
E 2.2 Façade compacte	*Global (avant mise à jour)*	*23*	*26*	*30*	***34***	*45*	*53*
	Global (après mise à jour)	39	25	30	**38**	48	57
	Suisse (CRB + autres sources)	8	23	29	**30**	31	38
E 2.3 Façade ventilée	*Global (avant mise à jour)*	*22*	*31*	*40*	***43***	*54*	*60*
	Global (après mise à jour)	38	27	38	**43**	56	66
	Suisse (CRB + autres sources)	8	29	38	**40**	40	52
E 3.1 Fenêtre	*Global (avant mise à jour)*	*33*	*13*	*19*	***27***	*35*	*47*
	Global (après mise à jour)	66	17	23	**30**	40	50
	Suisse (CRB + autres sources)	14	19	22	**29**	35	42
F 1 Toiture (couverture)	*Global (avant mise à jour)*	*43*	*23*	*30*	***35***	*39*	*47*
	Global (après mise à jour)	81	20	30	**35**	40	54
	Suisse (CRB + autres sources)	20	25	30	**35**	40	51
F 1.2 Toiture plate	*Global (avant mise à jour)*	*42*	*20*	*25*	***30***	*31*	*40*
	Global (après mise à jour)	61	20	25	**30**	39	50
	Suisse (CRB + autres sources)	19	20	25	**30**	30	42
F 1.3 Toiture inclinée	*Global (avant mise à jour)*	*38*	*25*	*30*	***40***	*43*	*53*
	Global (après mise à jour)	57	25	36	**40**	50	75
	Suisse (CRB + autres sources)	15	25	37	**40**	50	56

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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office for Energy SFOE

DUREE Project

WP 2: Survey to determine the effective building element service lives in the renovation context

Final report

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Summary

The lifetimes of building elements can vary within a large interval depending of the data sources used. This can lead to inconsistencies when performing building related assessment (such as economic or environmental assessment, etc.). The DUREE project aims at gathering the lifetime values observed in the Swiss and International literature, assessing what are these values in practice and assessing the effect of this variability using case studies in order to propose consistent values for the practice.

This WP 2 report presents the results of an analysis of empirical lifespans of the main building elements and technical systems replaced during energy-related renovation in owner-occupied and tenant-occupied residential buildings in Switzerland. Its purpose is to provide an understanding of whether and to what extent the actual replacement rates follow the values in buildings' technical norms[1] as reported in the DUREE WP1 final report. It provides information on how replacement rates evolve as elements age - an information that is captured in the form of so-called survival curves of building elements. It thus provides an empirical base against which the technical values in the WP 1 report can be judged. It also reports the results of a multivariate regression analysis highlighting the important factors related to renovation behavior among a sample of Swiss households.

Résumé

La durée de vie des éléments de construction peut varier à l'intérieur d'un intervalle important en fonction des sources de données utilisées. Cela peut entraîner des incohérences lors de l'évaluation d'un bâtiment (par exemple, une évaluation économique ou environnementale, etc.). Le projet DUREE vise à rassembler les valeurs de durée de vie observées dans la littérature suisse et internationale, à évaluer quelles sont ces valeurs dans la pratique et à évaluer l'effet de cette variabilité à l'aide d'études de cas afin de proposer des valeurs uniformes pour la pratique.

Ce rapport du WP 2 présente les résultats d'une analyse empirique de la durée de vie des principaux éléments de construction et des systèmes techniques remplacés lors de rénovation énergétique d'immeubles d'habitation occupés par leur propriétaire ou leur locataire en Suisse. Son but est de permettre de comprendre dans quelle mesure les taux de remplacement réels suivent les valeurs des normes techniques des bâtiments telles que reportées dans le rapport final du WP1. Il fournit de l'information sur l'évolution des taux de remplacement à mesure que les éléments vieillissent, une information qui est saisie sous la forme de ce qu'on appelle les courbes de survie des éléments de construction. Il fournit ainsi une base empirique par rapport à laquelle les valeurs techniques du rapport du WP1 peuvent être évaluées. Il présente également les résultats d'une analyse de régression multivariée mettant en évidence les facteurs importants liés au comportement de rénovation parmi un échantillon de ménages suisses.

Zusammenfassung

Die Lebensdauer von Bauelementen kann je nach verwendeten Datenquellen innerhalb eines großen Intervalls variieren. Dies kann zu Inkonsistenzen bei der Durchführung gebäudebezogener Bewertungen (z.B. Wirtschafts- oder Umweltprüfungen, etc.) führen. Das DUREE-Projekt zielt darauf ab, die in der schweizerischen und internationalen Literatur beobachteten Lebensdauerwerte zu sammeln, diese Werte in der Praxis zu bewerten und die Auswirkungen dieser Variabilität anhand von Fallstudien zu bewerten, um konsistente Werte für Normen vorzuschlagen.

Der vorliegende WP 2-Bericht stellt die Ergebnisse einer Analyse der empirischen Lebensdauer der wichtigsten Gebäudeelemente und technischen Systeme dar, die bei der energetischen Sanierung von selbst genutzten und gemieteten Wohngebäuden in der Schweiz ersetzt wurden. Sie soll Aufschluss

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[1] In this report, the "norms" correspond to all literature values collected and integrated in the DUREE database in the WP1 report. It covers values from existing standards, guidance documents used by the Life Cycle Assessment (LCA), the Life Cycle Cost (LCC), and the management communities (i.e., the association of tenants, the insurance sector, the professional building owners, etc.).

darüber geben, ob und inwieweit die tatsächlichen Wiederbeschaffungsraten den Werten der gebäudetechnischen Normen entsprechen, wie sie im DUREE WP1-Schlussbericht dargestellt sind. Sie gibt Aufschluss darüber, wie sich die Ersatzraten mit dem Alter der Elemente entwickeln, eine Information, die in Form von sogenannten Überlebenskurven von Bauelementen erfasst wird. Damit bildet sie eine empirische Grundlage, an der die technischen Werte im WP 1-Bericht gemessen werden können. Sie berichtet auch über die Ergebnisse einer multivariaten Regressionsanalyse, die die wichtigen Faktoren im Zusammenhang mit dem Renovierungsverhalten einer Stichprobe von Schweizer Haushalten aufzeigt.

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List of abbreviations

BfS : Bundesamt für Statistik

CRB: Centre suisse d'études pour la rationalisation de la construction

eBKP-H: Baukostenplan Hochbau

ESL: Estimated service life

KM : Kaplan Mayer

OFS: Office Fédéral de la Statistique

PH: Proportional Hazard

RSL: Reference service life

SCCER-CREST: Swiss Competence Center for Research in Energy, Society, and Transition

SHEDS : Swiss Household Energy Demand Survey

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Introduction

In order to define effective energy policy instruments and to design new concepts and technologies that help the diffusion of energy-efficiency in the building stock, it is important to identify the actual renovation patterns and the relevant factors in renovation decisions. This report presents the results of an analysis of empirical lifespans of construction elements in owner-occupied and tenant-occupied residential buildings in Switzerland. Its purpose is to provide an understanding of whether and to what extent the actual replacement rates follow the values in buildings' technical norms as reported in the DUREE WP1 study. In addition, it provides information on the distribution shape of "survival" curves of building elements, i.e., the evolution of renovation probability with increasing element age. This information is not available in the lifetime values presented in DUREE WP1 report. "Element survival", which is used interchangeably with the terms "effective service life" or "observed service life" in this report, refers to the period between the installation of an element and its final replacement. Survival curves are graphical representations relating a given time span (number of years) to the share of elements in a sample that have not been replaced (i.e., they "survived") during that time span (see, section 2). Finally, this report provides additional multivariate regression analysis highlighting the main determinants of renovation behavior among a sample of Swiss households.[2]

The main analysis is conducted on data from two annual waves of an online survey of roughly 5000 households per year in the German and French speaking parts of Switzerland. Lifespans are derived from the reported 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).

A number of previous studies have investigated renovation behavior for residential buildings in Switzerland [1]–[3]. Using comprehensive surveys among single family houses [2] and multi-family buildings [3] in northern Switzerland (Aargau, Bern, Basel-Landschaft, Thurgau and Zürich), these studies elicit replacement rates for a number of building elements over fixed time windows (1986 to 2000 in the case of Jakob and Jochem [1], and 1996 to 2010 in the studies by Filippini et al. [2], [3]). Jakob et al. (2014) provide a quantitative review of these studies [4]. Similarly, combining register data on buildings with information from applications for planning permission in the canton of Zürich over the period 2000 to 2015, Rey and Brenner compute a general rate of renovation and renewal of residential buildings of 1.48% per year [5]. Notably, they focus on the general renewal rate among buildings in the canton and refrain from computing element-specific renovation rates. Similarly, Lehman et al. apply a small web survey to analyze the way in which households make replacement decisions for façades (and windows) [6]. Focusing on five cantons, Basel-Stadt, Bern, Schaffhausen, Thurgau and Zürich, they identify a number of issues why homeowners refrain from energy-efficiency façade retrofits, especially for historic buildings. They include structural factors such as timber frame construction, aesthetic factors such as brick façade, and administrative factors such as protection orders.

The present study contributes to this line of research in two ways. First, the analysis covers a large geographical scope, including all of the French- and German-speaking regions. Second, instead of eliciting replacement rates over pre-defined time intervals, the survey aims at eliciting the renovation history of buildings.[3] This allows to trace replacement rates by the age of the element, rather than the age of the entire building, hence to construct detailed life-tables and survival curves for the four categories of building elements.

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[2] These factors encompass characteristics of the dwelling such as for example its size and location on the rural-urban continuum, and the household living there, such as risk attitudes or position in the income distribution. These analyses permit to identify characteristics that are *ceteris-paribus* related with renovation behaviour, and thus provide a more comprehensive and detailed account of the covariates of renovation behaviour than the one obtainable from descriptive analyses alone. Moreover, they can provide some insights into channels affecting replacement behaviour, and thus provide valuable information for policy design.

[3] Not all previous studies effectively compute replacement rates from their survey data. Lehman et al. [6] for instance provide no such information from their web survey.

1. Methodology: Swiss Household Energy Demand Survey

1.1 Survey design

To investigate empirical survival times of building elements in Switzerland, we use data from the 2017 and 2018 waves of the Swiss Household Energy Demand Survey (SHEDS). The SHEDS is an online, rolling panel survey of about 5000 individuals living in Switzerland (excluding Ticino).[4] Since 2016 it is organized and maintained by the Swiss Competence Center for Research in Energy, Society, and Transition (SCCER-CREST) and hosted at the University of Neuchâtel (for a more detailed description, see [7]). Survey design is a collaborative effort of researchers from different backgrounds including psychology, sociology and economics. Consequently, the survey contains comprehensive information on respondents' socio-economic characteristics and psychological profiles. The full sample is representative for the Swiss population outside Ticino with respect to respondent age and gender, as well as primary regional language (i.e., German and French) and dwelling ownership.

We complement the SHEDS questionnaires in 2017 and 2018, with a "renovation module" to fulfil the specific goals of this project. This renovation module contains a set of items aiming to elicit the renovation history of the respondent's current residence. In particular, it focuses on four building elements: the windows, the heating system, the façade and the roof.[5] In particular, it focuses on three main groups of elements according to the e-BKP classification of construction costs provided by the Swiss Centre for Studies on the Rationalisation of Construction (CRB): the technical systems, the façade and the roof. Table 1 presents the list of considered building elements and its classification according to the e-BKP. This reduced list with a variable level of detail for some elements (heating system, façade, roof) was chosen to cover the main building elements replaced during energy-related renovations. In that sense, the scope is here more limited in terms of building elements than the one in DUREE WP1 study. Conversely, this study has a much higher representativeness in terms of data sample using the SHEDS with 5000 individuals living in existing buildings instead of considering a limited *de facto* sample of few tens of literature lifetimes values in WP1. Appendix 1 provides the details of the renovation module used in this project.

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[4] Ticino is excluded as the survey company charged with fielding the survey does not command a sufficiently representative base of respondents in this canton.

[5] For the 2017 wave we likewise collected information on basement and kitchen renovations. These elements were excluded in the 2018 wave and are not investigated further in this project as the WP1 data does not cover them.

Table 1: Investigated building elements classified according to the e-BKP of construction costs (CRB) and names used in the renovation module of the SHEDS

e-BKP classification of construction costs considered in DUREE WP1 database	*Name in the renovation module of the SHEDS*
D. Technical equipment	
D5. Heating system	Heating system
D5.1 Heat production	Heat production
D5.2 Heat distribution	Heat distribution
E. Facade rendering	
E2. Facade rendering against exterior	Facade
E2.2 External thermal insulation	Compact facade
E2.3 Cladding	Ventilated facade
E3. Windows, doors	
E3.1 Windows	Window
F. Roof	
F1. Roofing	Roof
F1.2 Flat roof	Flat roof
F1.3 Slanted roof	Slanted roof

In the following, we will refer to the element's name as presented in the SHEDS' renovation module (cf. Appendix 1).

The dependent variables used in this study are the survival time spans in years for the four main building elements, namely, windows, heating system, façade and roof, at the time of their last replacement. For this purpose, we consider a renovation as a *replacement*, a term we use hereafter, to refer to a major retrofit (i.e., general replacements). However, due to the structure of the survey and possible bias in survey respondents it is also likely that other types of activities not strictly corresponding to a replacement like general maintenance actions are also part of the survey results. This may include small repairs or refurbishments, such as repainting a façade. The measure of survival time is different across respondents: For some respondents it is the current element (no replacement done yet) whereas for others, it is the element that has been replaced (elements with a reported replacement). The observations in which the element has not yet reached replacement are (in econometric terms) *right-censored*. This implies that the end of the lifespan (the survival time) is not observed as it is yet unknown how long it will last.[6] That is, we focus on building elements that have been replaced (survival time reached) or original construction elements that have never been replaced. Figure 1 shows the replacement information from the SHEDS renovation module using three fictitious examples. Solid blue lines present the actual lifespan of buildings A, B, and C. That is, the respective period between the year of their construction (shown by a blue dot) to the year in which the survey was executed (marked by the orange vertical line). In our fictitious example, building B is therefore older than building A, which in turn was constructed earlier than building C. As the SHEDS module asks respondents for the age of the current place of residence, all current buildings survive at least until the year of the survey. The current elements' lifetimes are "censored from the right", hence indicated by the dashed lines passing the year of the survey. Years in which an element, e.g., a window, installed in any building was renovated are marked by a blue triangle. Thus, one window renovation occurred in building A, two in building B, and none in building C.[7]

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[6] These observations are nevertheless important because they provide information on how long an element has survived at least. For example, if a heating system in a house built in the year 2008 has not been replaced until 2018, we still know that the system survived at least 10 years.

[7] Note that while it is possible that more than two renovations of the same element have taken place since the construction of a building, information on additional, earlier renovations are not available. SHEDS collects only information on the recent renovation history, i.e. only on the last two renovations –if they occurred- of each element, and not on the entire renovation history of a building. This is done to limit the workload for respondents, and to reduce the impact of measurement error arising from long delays between the renovation and the survey years.

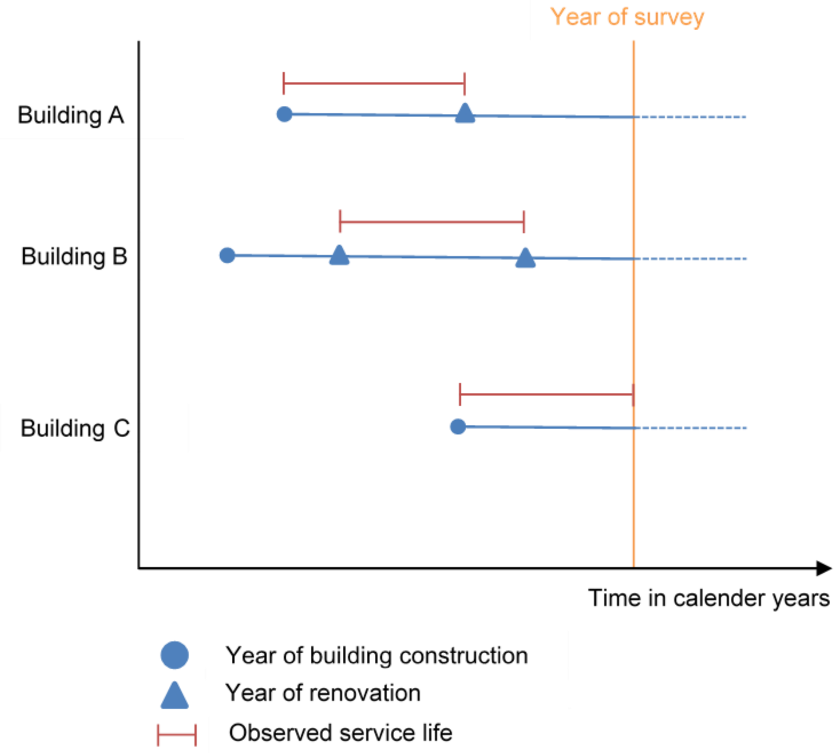

Figure 1: Hypothetical observations from SHEDS

The SHEDS renovation module aims at eliciting how old a renovated or replaced element was at the time of last renovation. In Figure 1, this information is shown by the length of the red line. To obtain this information, we follow a simple procedure. For each element we asked when (in which year) the last renovation or replacement had taken place. If no such change in the building structure was reported, the element's age is set equal to building's age and the observation is coded as right-censored. This is the case for building C from Figure 1. If a single replacement or renovation was indicated throughout the building's lifetime the element's age was identified from the building's construction year. This is the case for building A. Finally, if there are more than one replacements, we asked respondents how old the renovated or replaced element was at the time of replacement and used this information directly as the element's age. Such an example is depicted for building B.

One important consequence of the SHEDS's longitudinal nature is that a substantial share of respondents in each year are re-interviewed in consequent waves. In particular, more than two-thirds of respondents (69%) of the 2018 wave have also been interviewed in previous years. To avoid duplicating observations, renovation histories in the 2018 wave are elicited only for new respondents (N = 1'543) and those indicating that they had moved since last participating in the SHEDS (N = 373). For this reason, all respondents from the 2017 wave (N = 5'015), but only 38% of respondents of the 2018 wave (N = 1'916) provided some information on the survey's renovation section.

1.2 Response analysis and representativeness

Of the 6'931 respondents who answered (parts of) the accommodation/renovation section of the SHEDS waves of 2017 and 2018, only 5'930 (85.6%)[8] provided sufficient information to compute the element age for at least one of the four elements. The main reason for this additional loss of data is that individuals did not know or were not able to recall the year of renovation, not even approximately. As expected, such lack of information on the renovation history of the current residence is greater among

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[8] This rate drops, however, to 67.0% for the 4'296 respondents who provided valid responses to all four building elements. A further 747, 489 and 389 respondents provide valid age information for three, two and one element, respectively.

tenants. Depending on the building element, between 4% and 7% of owners reported not to know the renovation year, compared to between 22% and 38% of tenants.[9]

While SHEDS is representative of the entire Swiss population (outside Ticino) with respect to the basic socio-demographic characteristics detailed in the preceding section [8], the survey's unit of analysis is the household rather than the building of residence. SHEDS is not a-priori designed to be representative of the Swiss building stock. To assess the degree of divergence between the national building stock and the one covered by SHEDS, we compared our data to construction and housing statistics from the Swiss Federal Office of Statistics (BfS/OFS) [9]. This publication contains basic information on the structure, type and construction period of residential buildings in Switzerland, with data from the last available year stemming from 2016. We focused on comparing construction period and rough categorical distinction of the type of building (single-family house vs. multi-apartment buildings).

Figure 2 plots the share of buildings by construction period for BfS/OFS data from 2016 (blue bars), the SHEDS data from 2017 and 2018 (red and green bars). Red bars give the fraction relying on data from all participants who provided some information on the accommodation section, while green bars are based on the final sample. Aside from differences in year to which the two data sources refer, another difference between them arises from the way in which construction periods are defined. Whereas SHEDS data collects construction decennials as the period from the decennial's first to its last year (e.g., from 1990 to 1999, including both limits), the decennial definition in BfS/OFS data is shifted forward by one year, such that the construction period corresponding to the above example ranges from 1991 to 2000. Therefore, information for each bar does not refer to identical periods. However, given the large overlap of these two period definitions, we believe that valid conclusions can be drawn concerning the representativeness of SHEDS data with respect to building construction cohorts. For this reason, and to increase the clarity of the graph, we have opted to use axis labels as defined in the official building and construction statistics.

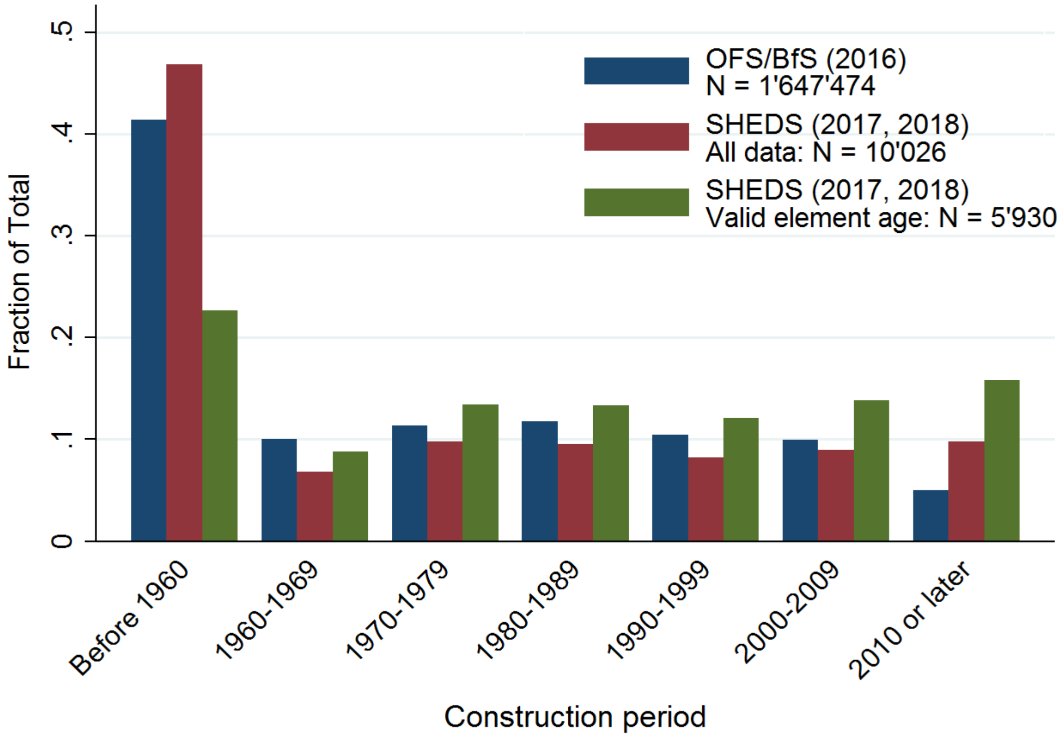

Figure 2: Distribution of construction periods of residential buildings in the SHEDS and in the Swiss population

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[9] In detail the share of owners (resp. tenants) providing no valid information on element replacement and age are 4.2% (22.2%) for windows, 4.9% (33.1%) for the heating system, 5.8% (31.2%) for the façade, and 7.2% (37.9%) for the roof.

Figure 2 shows that there are certain differences in the age distribution of buildings between the SHEDS survey and the building stock in Switzerland. In particular, the distribution in the final sample differs considerably, especially with respect to the two tails of the distribution. While buildings constructed before 1960 are significantly underrepresented, buildings constructed in later years tend to be overrepresented, particularly those constructed since 2010. As the congruence between official statistics and the sample distribution is much larger for the complete SHEDS data, survey design itself is unlikely to explain the observed differences in distributions. Aside from the above-mentioned slight differences, this result rather points to a relationship between construction period and the respondent’s ability to retrieve information on the renovation history. That is, individuals living in more recently constructed buildings are likely to recall whether and when a building element has been renovated or overhauled, partly because they have lived in the building since its construction. While we have intended to reduce this recall problem by focusing on the last renovation cycle rather than the building’s entire renovation history, we recognize that this overrepresentation of new buildings should be considered with caution, as it may introduce a selection bias. Whether this is likely to affect our findings depends entirely on whether renovation rates change systematically with construction period. While previous research has generally found such changes in Switzerland, the direction of change is still a matter of debate. For instance, Filippini et al. [3] and Jakob and Jochem [1] using household surveys document lower annual renovation rates for more recently constructed buildings, whereas Meyer et al. [10] using data from a real estate management agency find that replacement cycles are shorter, and thus renovation rates higher, among more recently constructed buildings.

The SHEDS sample is not necessarily representative of the stock of residential buildings in Switzerland. Figure 3 plots the relative frequency of single and multi-family houses as derived from SHEDS and BfS/OFS data. It shows that while about 57% of residential buildings in Switzerland are single family houses, only 35% (all data) to 39% (final sample) of SHEDS respondents report to live in such a building. This difference arises largely due to survey design representing Swiss residents rather than Swiss buildings. As a result, the distribution of building types in the SHEDS is much closer to the distribution of residents (second bar from the left) than to the building types in Switzerland (first bar from the left). According to official building statistics between 27.5% and 31% of Swiss residents live in single family houses.[10]

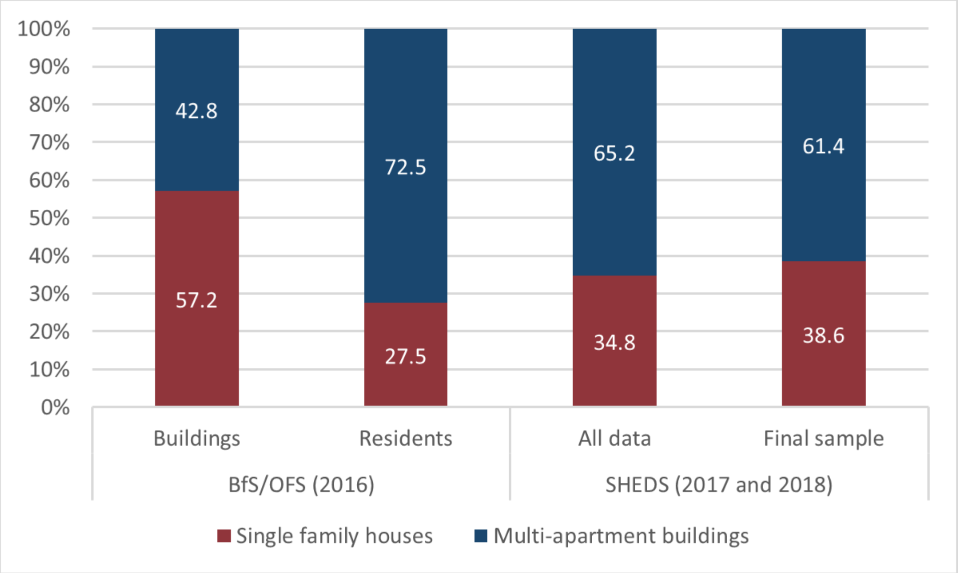

Figure 3: Distribution of residential building types (single family houses vs multi-apartment buildings) in the SHEDS and in the Swiss population

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[10] Notably, BfS/OFS data distinguish between four types of buildings: single family houses, multi-family houses, residential buildings with additional use, and buildings with partial residential use. Since such differences are not observable in SHEDS data, we have opted to group the latter three categories into one comprehensive other. This leads to an underestimation of households residing in homes containing only a single apartment or residential space. 31% of the Swiss population live in such homes (BfS/OFS, 2018, p. 11) [32].

Results from Figure 2 and Figure 3 suggest that our final sample is not a representative sample of the Swiss residential building stock. To obtain an idea in how far these differences affect the estimated survival probabilities and replacement rates, the descriptive and inferential statistics presented in the following sections are estimated with and without applying a weighting scheme that compensates for the sampling-related deviations from the building population distribution. In accordance with standard survey methodology e.g., [11], we calculate these final design weights by first creating two independent weighting factors for the cohort (period of construction) and for the building type (single or multi-family house). These two weighting factors are then multiplied.[11]

A more subtle issue that could lead to systematic bias in estimated survival probabilities and replacement rates is self-selection through unobservable characteristics [12] [13], a general problem of online surveys such as the SHEDS. In particular, respondents completing the survey could come from a part of the population more interested in energy efficiency issues. This may be an advantage in as much as one can assume that those individuals are probably well informed about the energy-related structure of their dwelling of residence, and thus its renovation history. As a consequence, measurement error may be smaller than in the general population. However, we cannot exclude that those individuals are also living in more energy-efficient and thus more recently constructed or more rapidly renovated buildings. As a result, average observed service life may be shorter in the SHEDS than in the Swiss building population, such that the length of empirically identified replacement cycles may be underestimated (renovation rates overestimated). On the other hand, reported renovation history might rely on respondents' recollection hence an under-reporting of less recent renovations, and an upward potential bias in the length of replacement spells.

1.3 Outlier definition

A disadvantage of working with retrospective data is that they are potentially subject to errors of recall. That is, memory tends to decay as the distance to an event increases [14]. As a consequence, information on renovations occurring more recently is likely to be more accurate than information on similar events happening several decades ago.[12] This problem is likely to be further exacerbated by the fact that a building's current inhabitants may have been living elsewhere at the time of the last renovation, and thus might be forced to rely on third-party information, such as documentation or anecdotes, when reporting on the renovation history.[13] We therefore cannot exclude that some renovations go unreported in the data, and that particularly among old, censored observations average element age is over-estimated. To account for this possibility, we exclude observations reporting building element age exceeding a certain threshold.

For simplicity, we define outliers for each building element as observations reporting that the element in question has not been renovated in more than 100 years. We exclude these outlier observations from both descriptive statistics and survival estimations. The choice of such a threshold is also motivated by the assumption that long survival times could be either quite specific to rare buildings or simply indicative of misreporting by respondents. This assumption is supported by the fact that the longest uncensored

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[11] In detail, individual weight, w_c, for each construction cohort c is computed by standardizing the fraction of buildings in the SHEDS constructed throughout that period, n_c, by the fraction in the population of Swiss buildings, N_c, such that $w_c = n_c/N_c$. An identical strategy is applied to construct building type weights, w_b. Final design weights, w_f, are then obtained by multiplying the two weights: $w_f = w_c \times w_b$.

[12] Whether this is indeed the case is debatable, as psychological research has also found that rare events that are highly salient (i.e., highly valued or feared) are remembered well even over long time horizons [33], [34]. Given that renovations are rare, financially strenuous and often stressful, one could assume that they qualify as events with high salience. One indication supporting this hypothesis is that among respondents reporting a renovation, we find no evidence that the decade in which the renovation happened predicts whether the respondent knows the exact year of renovation or not. Yet, if memory decay would play an important role, one would expect lower shares of respondents to provide an exact date among renovations happening earlier, e.g. in the 1970s compared to the 2000s. However, using the SHEDS data it is impossible to evaluate whether earlier renovations are more likely to go unreported. To the best of our knowledge, no research has systematically investigated the effects of memory on the accuracy of self-reported renovation history date. Therefore we cannot exclude that recall systematically affects the SHEDS renovation history data.

[13] This is the case for 17% (heating system) to 25% (roof) of owners, and 36% (heating system) to 45% (windows) of tenants.

survival periods across elements was found to be just under 100 years.[14] As shown in section 3, results remain largely unaffected when shifting this threshold by up to 50 years in either direction.

Table 2 reports the number and share of respondents that are lost due to this definition of outliers. Shares of excluded observations range from 1.9% for heating systems (owners) to 7.2% for roofs (tenants). We experimented with other outlier definitions including shorter and longer thresholds, as well as Tukey's inter-quartile rule [12]. However, results, both descriptive and inferential, are very similar to the ones given below. We therefore present results based on this simple heuristic outlier definition.

Table 2: Observations lost due to restricting survival times to less or equal to 100 years

	Absolute numbers			Shares		
	Total	Owner	Tenant	Total	Owner	Tenant
Window	217	169	48	3.880%	1.906%	5.498%
Heating system	178	45	133	3.562%	1.881%	5.106%
Façade	275	84	191	5.283%	3.560%	6.878%
Roof	251	64	187	5.010%	2.641%	7.228%

Additionally, depending on the element, a further 22 (façade, ≈ 0.4%) to 33 (windows, ≈ 0.6%) observations were removed as the reported age of the building element exceeded the age of the building.[15] Although this may be theoretically possible – for instance, when installing old, reused windows into a new building – a vast majority of these values (roughly 95% for all elements) arise for observations that rely on mid-point estimates of either building age or element age or both, and are therefore likely to arise due to data limitations. We believe that the remaining responses are likely to indicate a problem of misreporting or misunderstanding.

As detailed above, there are substantial uncertainties concerning the renovation history of the dwelling of residence among tenants in the SHEDS. In an effort to obtain a more robust picture of renovation behavior in this type of buildings, we have also tried to collect renovation data from the accounting data of a large real estate management agency active in the French-speaking part of Switzerland. Unfortunately, the period of observation for this data was limited to the interval between the year 2000 and the year 2015, as prior to 2000 consistent machine-readable information was not accessible. As a consequence there were a number of strong data-related problems that effectively precluded the use of this data set for the analysis of element survival.[16]

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[14] In detail, these maximal survival times are: 93 years among windows, 94 years for heating systems, 99 years for façades and 99 years for roofs.

[15] In greater detail, this affects 33 (0.62%) of remaining observations for windows, 25 (0.52%) for the heating system, 22 (0.45%) for the façade, and 23 (0.48%) for the roof.

[16] First, renovations were not always recorded consistently in the accounting data. For a substantial number of buildings, it was impossible to exclude that renovations happened, despite the absence of corresponding information in the accounting books. Second, due to the limited period of observation, we were unable to exclude that renovations in the building stock took place prior to 2000. Moreover, we could not observe more than one renovation of the same element in any building. Therefore, constructing survival curves would have required making heavy, and to some extent random assumptions concerning either the occurrence of renovations outside the period of observation or on the distribution of element survival. In auxiliary trials using these data, we obtained survival curves that closely reflect prior assumptions, such that we could not draw valid conclusions on the effective empirical survival distribution. We therefore decided to abstain from using this data for further analysis.

2 Descriptive statistics

2.1 Methodological approach

In this study, descriptive statistics are based on the Kaplan Meier (KM) estimator of survival probabilities [15]. The estimator $\hat{S}(t)$, denotes the probability of an element to survive t years after installation. In its product-limit expression, the estimator can be specified as:

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

where $t_{(i)}$ is the rank-ordered survival time ranging from 1 to T years, where T is the maximum survival threshold defined in section 1.3. n_i is the number of elements that had not been renovated at the beginning of year i, and r_i is the number of observed replacements or renovations in that year. Thus, the probability of an element to survive a certain number of years $t_{(i)}$ depends on the replacement rate in that year and the probability of surviving up to that year.

To illustrate this estimation procedure, consider the following hypothetical example with eight observations depicted in Figure 4. Red lines give the length of the observed service life (i.e., the age at replacement or simply: survival) for a given element in each of the eight buildings, A to H. For each building the element's service life starts at installation $t = 0$. Cases whose service life ends with a red triangle are the ones for whom renovations are observed (A, B, D, G, and H). Others are right-censored, meaning no renovation is observed up to the survey (C, E, and F). Observed service life, t_i, can differ across buildings.

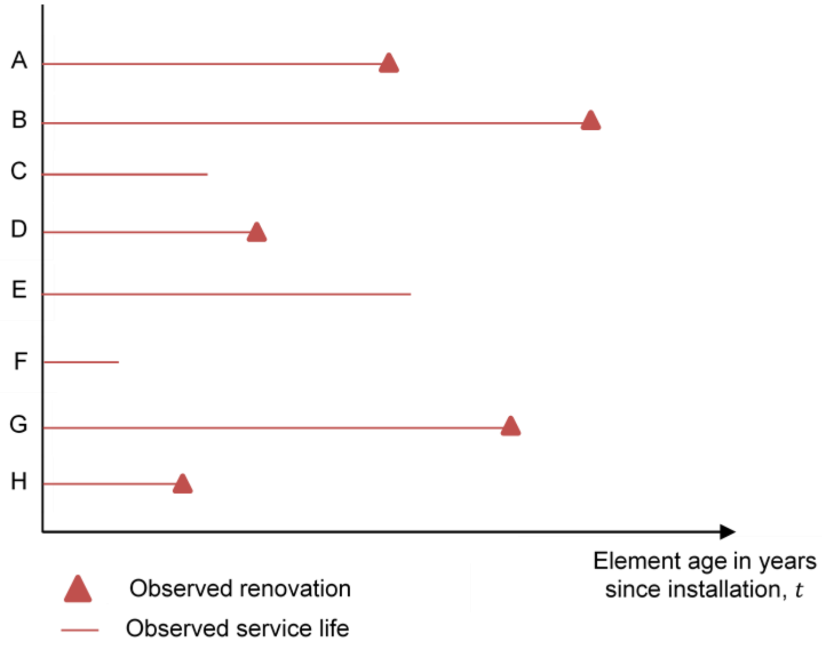

Figure 4: Service life lengths in a hypothetical sample

Assuming that observed service life for a given element in buildings A, B, C, D, E, F, G, and H is 30, 40, 12, 18, 28, 7, 33, and 11 years, respectively, observations can be sorted according to these values. They are given in column 1 of Table 3. Column 2 of this table indicates whether the end of the survival period was terminated by an observed renovation (indicated by a value of 1) or due to right-censoring (indicated by 0). Column 3 gives the number of buildings in the hypothetical sample that at the corresponding survival time (column 1) can still experience a renovation of the element. That is all those that have not already experienced a renovation or were lost due to right-censoring. In statistical parlance, these observations are still "at risk". For example, the shortest observed survival time is 7 years. Thus, between the year of installation and 7 years later, all eight elements in the sample are observed, and consequently all of them are at risk for being renovated. At year $t_i = 7$, observation F is lost due to right-censoring. Hence, the number of elements at risk reduces to 7, because after that year there are only 7 observations left for which we can observe survival periods longer than 7 years. The second shortest observed survival period is 11 years, as at year $t_i = 11$ a further observation from the sample is lost due to renovation. This again reduces the number of elements at risk to 6, as for only 6 out of the 8 observations from the hypothetical example observed service life values greater than 11 can be observed. Eventually, the last observation is lost after 40 years due to renovation. That is, in our hypothetical sample, no element survives longer than 40 years.

Table 3: Life table in a hypothetical sample

Survival time	Observed renovations	Number of elements at risk of renovation	Survival probability
0	0	8	1
7	0	7	1
11	1	6	0.85
12	0	5	0.85
18	1	4	0.68
28	0	3	0.68
30	1	2	0.46
33	1	1	0.23
40	1	0	0

Applying equation (1) to these numbers, one can compute the conditional survival probability for each observed service life. Up to year $t_i = 7$, no renovation in any building is observed, such that survival probability up to this year is $\hat{S}(0) = \hat{S}(1) = \hat{S}(2) = \hat{S}(3) = \hat{S}(4) = \hat{S}(5) = \hat{S}(6) = 1$. In year $t_i = 7$ one observation is lost to right-censoring, which reduces the number of observations at risk, but is not counted as renovation because the element is known to survive longer than can be observed, yet it remains unmeasured by how much. Consequently, the survival rate remains unaffected, just until year $t_i = 10$ ($\hat{S}(7) = \hat{S}(8) = \hat{S}(9) = \hat{S}(10) = 1$). At the beginning of year $t_i = 11$, there are thus 7 elements at risk out of which one element is effectively replaced. As such, conditional survival probability in year 11 is $\hat{S}(11) = \hat{S}(10) * \frac{6}{7} = 1 * 0.85 = 0.85$. Thus, conditional survival probabilities adjust every time a renovation occurs. Computations for every (observed) survival time are given in the fourth column of Table 3. A table linking age with survival probability, such as Table 3, is known as "life table".

Given the large sample and long observation period of up to 100 years, we summarise information from the empirical life tables using two alternative strategies. For one, we give key quantiles of the conditional survival probability distribution – also known as the "survivor function" - such as the median, the first and third quartiles. These provide information on the length of the period after which a fixed share of sample elements have been replaced. The p^{th} percentile of survival time distribution is given by:

$$\hat{t}_p = \min\left\{t : \hat{S}(t) \leq \frac{p}{100}\right\} \qquad (2)$$

In the hypothetical sample, for instance, it takes 30 years for half of the elements to have been replaced, That is, the median of the survival time distribution is 30 years or $\hat{t}_{50} = 30$. To detail the evolution of element survival with increasing age more thoroughly we additionally display the information from the life tables in graphical form, using survival curves, i.e. by plotting survival probability against the length of survival time for each element investigated in the study. Figure 5 gives such a survival curve for the hypothetical sample.

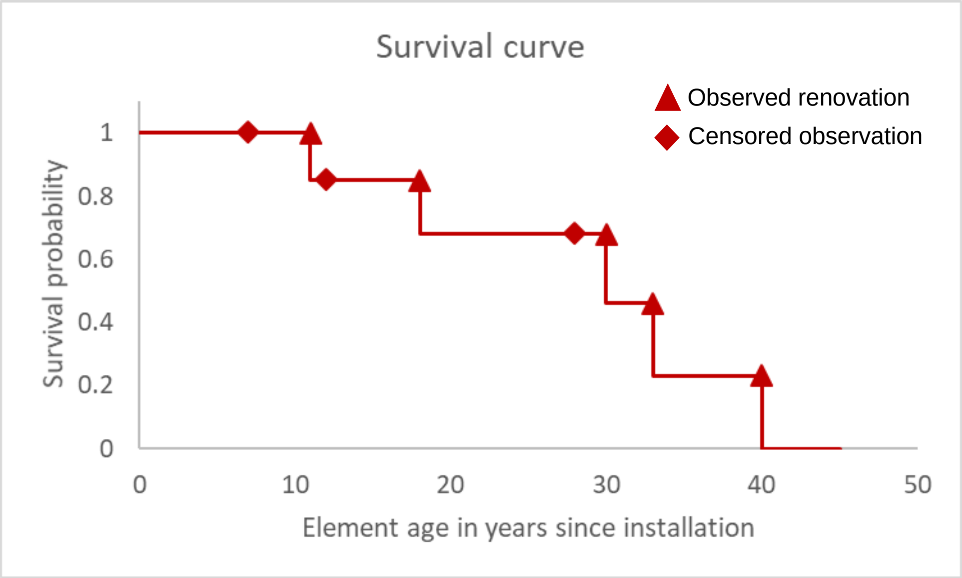

Figure 5: Survival curve for the hypothetical example

2.2 Life tables

Table 4 provides information on the first quartile ($\hat{t}_{25}$), the median ($\hat{t}_{50}$) and the third quartile ($\hat{t}_{75}$) of the survival time distribution for the two samples. For the SHEDS sample values are also given separately for owners and tenants. For instance, $\hat{t}_{50}$ for windows represents the lifespan during which 50% of existing windows are replaced, and similarly, $\hat{t}_{75}$ for roofs is the lifespan during which 75% of the roof elements is replaced. The table also provides basic sample information on the four building elements for each group.

Table 4: Descriptive survival statistics (SHEDS 2017 and 2018)

	Survival time (in years)			Total observ-ations	Observed renovations	Element Years at risk	Annual renovation rate
	25%	50%	75%				
Panel A: SHEDS, entire sample							
Window	22 [22, 23]	34 [33, 35]	50 [48, 50]	5255	2530	123490	0.0205 [0.0199, 0.0211]
Heating system	20 [20, 20]	30 [30, 31]	47 [45, 49]	4720	2275	101380	0.0224 [0.0216,0.0232]
Façade	28 [27, 29]	44 [42, 47]	76 [70, 82]	4821	1683	124090	0.0136 [0.0131, 0.0140]
Roof	32 [32, 35]	56 [52, 57]	81 [78, 84]	4647	1292	122346	0.0114 [0.0101, 0.0110]
Panel B: SHEDS, owner-occupied dwellings							
Window	26 [25, 27]	35 [33, 35]	48 [46, 50]	2413	1073	56759	0.0189 [0.0182, 0.0196]
Heating system	20 [20, 20]	28 [27, 29]	40 [38, 41]	2291	1170	47345	0.0247 [0.0239, 0.0259]
Façade	29 [27, 30]	42 [42, 47]	74 [70, 82]	2287	777	58624	0.0133 [0.0125, 0.0141]
Roof	37 [32, 37]	55 [50, 57]	80 [70, 83]	2297	622	60542	0.0106 [0.0097, 0.0109]

	Survival time (in years)			Total observ-ations	Observed renovations	Element Years at risk	Annual renovation rate
	25%	50%	75%				
Panel C: SHEDS, tenant-occupied dwellings							
Window	17 [20, 22]	32 [32, 35]	50 [49, 52]	2842	1457	66731	0.0218 [0.0209, 0.0228]
Heating system	17 [19, 20]	32 [32, 35]	55 [50, 61]	2429	1105	54035	0.0204 [0.0193, 0.0219]
Façade	27 [25, 28]	45 [42, 48]	80 [68, 89]	2534	906	65466	0.0138 [0.0130, 0.0146]
Roof	30 [30, 32]	55 [53, 59]	82 [80, 91]	2350	670	61804	0.0108 [0.0100, 0.0116]

Note: 95% confidence intervals in brackets. NA = not available (insufficient data for an estimate).

The estimated survival times in the two sub-samples of the SHEDS data seem largely congruent, indicated for instance by very similar annual average renovation rates (cf. the last column of Table 4). Results for the entire sample suggest, for instance, that after 33 to 35 years 50% of windows are replaced. Similarly, we can deduce that 25% of heating systems are replaced before they reach an age of 20 years, or that 25% of roofs are not renovated for over 81 years. The statistic "Element years at risk" gives the sum of observed survival durations for all observations. For example, the sum of window survival durations among owner-occupied homes in the SHEDS sample is 56'759 years, meaning that among the 2'413 homes in this sample average (observable) window survival is about 23.5 years. Finally, by dividing the number of renovations by the years at risk, we obtain the average annual replacement rate.[17] These values range between 1.14% for roofs and 2.50% for heating systems. There is considerable variation in survival probabilities and thus replacement hazards across the building elements. Some elements such as windows and heating systems are replaced at a much higher rate than others.

2.3 Empirical survival curves

2.3.1 SHEDS 2017 and 2018

To obtain a more comprehensive overview of the empirical survival time of different building elements, Figure 6 plots the Kaplan Meier survival probabilities and corresponding 95% confidence intervals for all four building elements over their lifespans. The survival probability is a conditional probability representing the likelihood of replacement should the element have "survived" up to a given age. This conditional probability lends itself well to estimate the rate of replacement or the renovation rate.

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 to 20 years. For instance, values from the survival functions of the four elements in the owner sample suggest that in the first 10 years after installation only about 3.7% of windows, 6.7% of heating systems, 3.5% of facades, and 2.7% of roofs have been renovated. 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 those elements experiencing rapid acceleration of replacement probabilities (windows, heating systems), one can also observe an abatement in replacement probabilities over the final decades of observed survival time. Notably, this could be because only few dwellings remain with non-renovated old elements.

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[17] It can be interpreted as a "weighted" average in the broadest sense with weights reflecting the period of observation (i.e., survival time) for each element in the sample.

To highlight differences between owners and tenants, we present the survival curves separately. The left panel gives the survival curves for owner-occupied buildings, while the right panel presents the corresponding survival curves for tenant-occupied buildings.

The differences between the two groups suggest that owner-occupied buildings are subject to renovation after shorter lifespans especially in the windows and heating systems. In the case of owner-occupied buildings, the renovation rate increases with the element's age after 15-20 years and before 40-50 years for windows and heating systems. This evolution of element survival is slightly more expressed among owner-occupied homes, for which survival curves tend to be steeper than among tenant-occupied buildings. For instance, as can also be seen from Table 4, 75% of heating systems have been renovated in owner-occupied dwellings after about 40 years, whereas it takes 55 years to reach the same value among tenant-occupied homes. This implies that the probability of keeping an equipment in owner-occupied buildings diminishes to zero faster as the equipment gets older. However, if an element survives without major renovation after a long period (e.g. 50 years for heating system and windows), the survival rate diminishes but at a slower rate. While this observation is also true for tenant-occupied buildings, the slightly more linear survival curves also suggest that renovation rates among this sub-population vary less dramatically.

Some caution is warranted when comparing tenant and owner groups. As stated above, non-response is much more prevalent among tenants than among owners. While this may be little surprising considering the fact that dwelling owners are more likely to have reliable information on the renovation history of their building of residence, it is an indication that the sub-sample of tenants retained from SHEDS may not be random. Thus, it could be those tenants that for various reasons (personal interest, recent renovation, etc.) are particularly well-informed about the renovation history of their dwelling. It could also be the case that those respondents are more willing to make use of heuristic approximations or rules-of-thumb when providing information on replacement year and age. This latter proposition is to some extent supported by the fact that the share of tenants whose answers are based on mid-points rather than exact values of the element's age is considerably higher than the corresponding share among owners. For instance, for 42.7% of tenants but only 13.7% of owners window age is computed using mid-point information.[18] Another indication for problematic response patterns among reporting tenants, is that heaping at 'particular round' numbers is much more pronounced among this group than among owners.[19] For instance, roughly one third of the tenants reports that their dwelling of residence was built in a year that is an integer multiple of 10, compared to 15% of owners. Thus, it seems that tenants are more likely to lack of detailed information on the renovation history. They tend to rely on heuristic approximations to provide answers throughout the renovation module.

SHEDS households report a number of very early replacements. Between 3 % (windows) and 5 % (roof) of all renovations are reported to occur within the first two years after installation. We assume that these replacements are due to a failure of the element's construction material or faulty initial installations. Such cases may be of limited relevance for judging the service life of a "normally" installed element of sufficient quality. Nevertheless, they represent an empirical evidence about renovation needs, since some elements will fail earlier in reality. As such they provide important information for realistically modeling the replacement distribution of building elements, and thus to predict monetary and energy-related life-cycle costs. We have therefore kept these observations.

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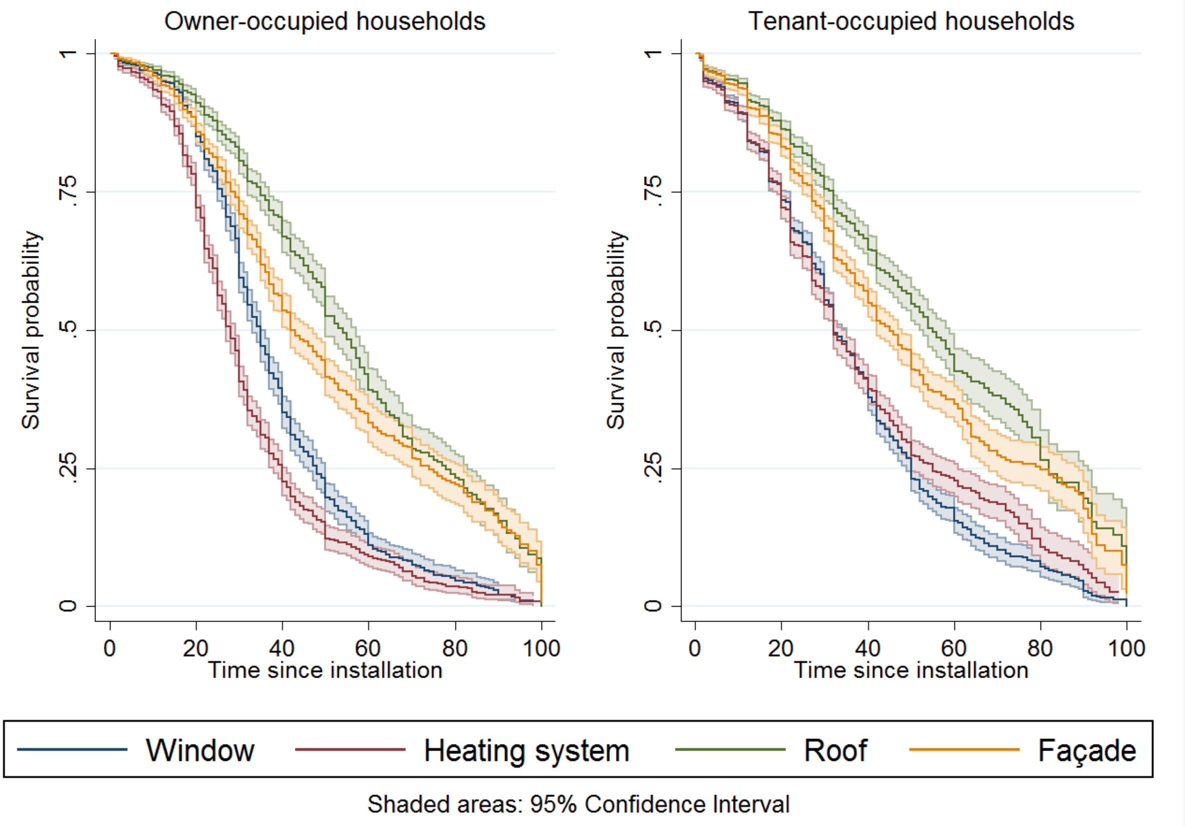
[18] For the remaining elements these shares are among tenants (resp. owners): 41.4% (14.9%) for heating systems, 38.9% (12.5%) for façades, and 37.2% (11.5%) for roofs.

[19] Heaping refers to the phenomenon that reported years have non-smooth distributions with peaks at multiples of ten years.



Shaded areas: 95% Confidence Interval

Figure 6: KM Survival Curves for the four building elements (SHEDS 2017 and 2018)

This pattern in replacement rates can likewise be observed when using survival functions to compute average renovation probabilities. For this purpose, we rely on a simple approach, which consists of calculating unconditional replacement rates by averaging annual replacement probabilities over a given age interval:[20]

$$R_j^{uncond.} = \frac{1}{\Delta t}\sum_{t_{(i)}=j}^{j+\Delta t}\left(\hat{S}\left(t_{(i)}-1\right)-\hat{S}\left(t_{(i)}\right)\right) \tag{3}$$

with the relevant interval spanning a fixed age range of length Δt from starting with the year-of-age j. We choose starting points of different age intervals, such that these intervals are non-overlapping and set $\Delta t = 10$.[21] That is, we compute annual averaged replacement rates over consecutive 10-year intervals.

Figure 4 plots these unconditional rates over consecutive, non-overlapping 10-year intervals in the owner-sample. It shows that across all elements annual average replacement rates tend to follow an inverted parabola with the highest replacement rates occurring sometime in the period between 20 and 50 years after installation. Notably this peak is element-dependent with renovation rates for windows and heating systems reaching the highest value in the decade between 20 and 30 years after

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[20] Using a slight derivation of this measure by conditioning replacement rates on initial survival, i.e. computing conditional replacement rates of the form: $R_j^{cond.} = \frac{1}{\Delta t}\sum_{t_{(i)}=j}^{j+\Delta t}\left(\frac{\hat{S}(t_{(i)}-1)-\hat{S}(t_{(i)})}{\hat{S}(t_{(i)}-1)}\right)$, yields similar differences in replacement patterns across elements. However, instead of approaching zero, as for the unconditional measure, replacement rates stabilize at about 2% per year for all elements throughout the latter age cohorts. This simply suggests that a fixed share of the elements surviving beyond a certain lifespan is replaced every year.

[21] Therefore, $j \in \{1,11,21,31,41,51,61,71,81,91\}$.

installation, whereas highest annual renovation rates for façades occur about 10 years later, and peak renovation rates of roofs are again shifted by about 10 years. Moreover, the parabola pattern is less pronounced for façades and roofs suggesting that renovation is more uniformly spread out for these two elements.

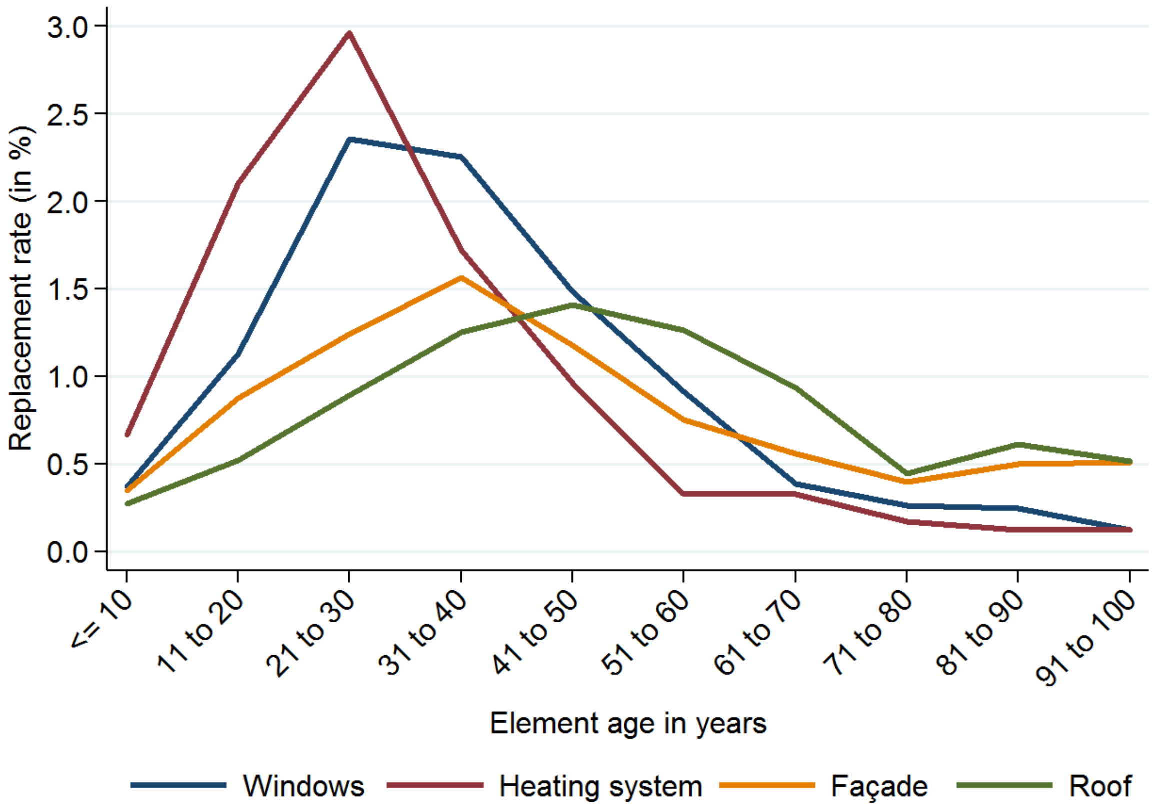

Figure 7: Average annual replacement rates by age groups (SHEDS 2017 and 2018)

2.3.2 Types and subgroups of building elements (SHEDS 2018)

For three of the four elements collected during the 2018 wave of SHEDS we have additionally obtained information on relevant characteristics of the replaced element, which allows us to slightly deepen the analysis of replacement behaviour among a sub-section of our sample (N = 1'916).

In particular, these additional questions asked for:

- Heating system: Whether the heat production (boiler or furnace), heat distribution & diffusion (tubing and radiators) were separately or simultaneously replaced and about the type of the heating fuel used before and after renovation.
- Facade: Whether the current and replaced facade was compact (i.e., using an external thermal insulation including a rendering) or ventilated (i.e., a ventilated cladding of external walls, including thermal insulation and frames[22].
- Roof: Whether the current and replaced roof was inclined or flat.

A substantial number of respondents did not provide valid information on these questionnaire items. For instance, about 30% of owners and 60% of tenants could not provide information on the current type of the façade of their building of residence. Similarly, of those who reported that the façade had been

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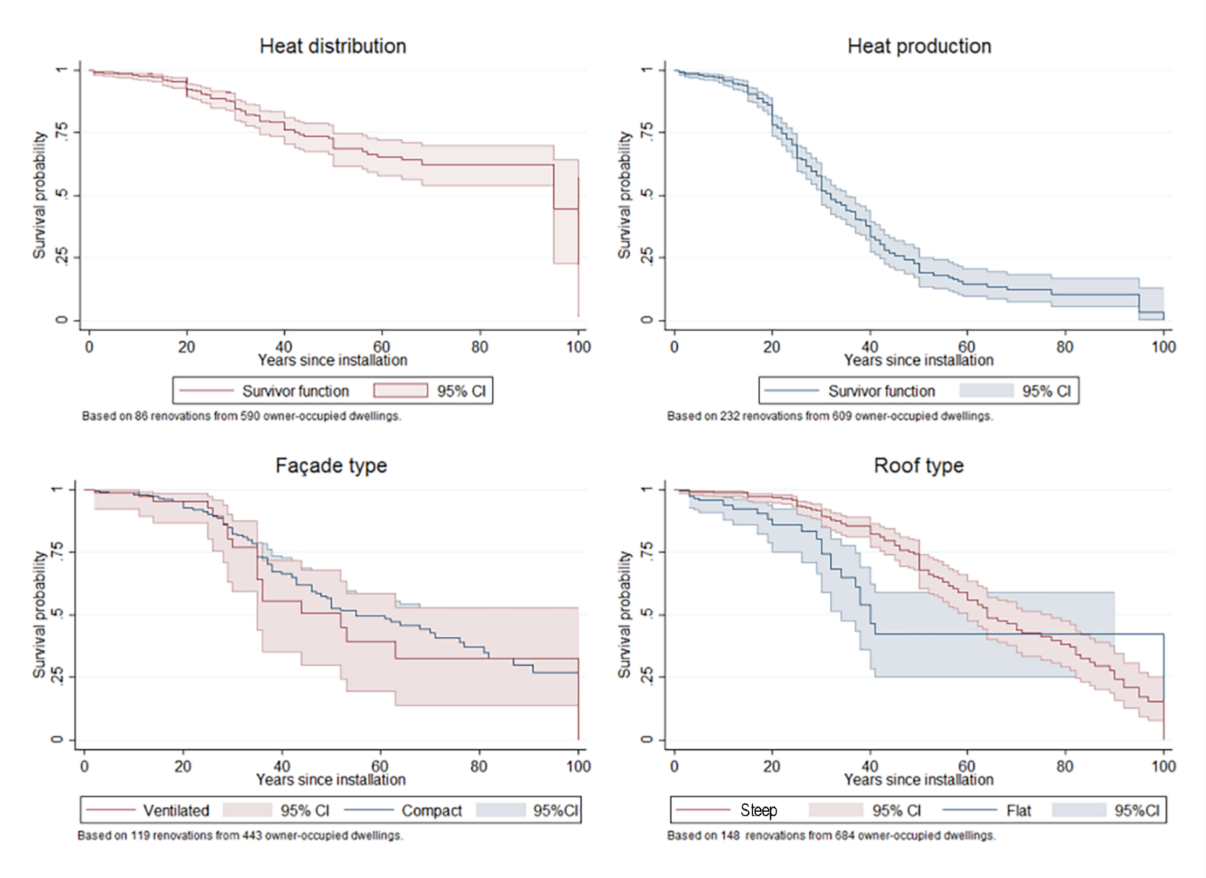
[22] It was also asked whether the current façade was only repainted (or only rendered) see in Appendix 1, question accom9e3_2) to distinguish from a replacement of the insulation.

replaced (19% of owners and 11% of tenants) roughly the same percentage reported not to remember the type of the replaced façade. For this reason, information on element substructures derives from a very limited sample and should be considered with caution.

Figure 8 plots the Kaplan Meier survival curves for each type for the elements heating system, roof and façade using information from owner-occupied buildings (the number of households and reported renovations are given below each plot).


Heat distribution

Based on 86 renovations from 590 owner-occupied dwellings.

Heat production

Based on 232 renovations from 609 owner-occupied dwellings.

Façade type

Based on 119 renovations from 443 owner-occupied dwellings.

Roof type

Based on 148 renovations from 684 owner-occupied dwellings.

Figure 8: KM Survival Curves for sub-structures of building elements (SHEDS, 2018)

Except for the facade, KM curves show that survival is not identical across types. For example, boiler and furnaces are replaced considerably faster than the distribution system (tubing and radiators). The difference is substantial with median survival time of heating distribution elements exceeding that of heating production elements by about a factor three ($\hat{t}_{50}^{heat\ production} = 32$ and $\hat{t}_{50}^{heat\ distribution} = 95$). This suggests that the survival values reported for the heating system in section 2.3 are likely to correspond to the heating production unit, rather than the heating distribution system. Similarly, flat roofs experience more frequent replacements than inclined roofs, with median survival times of 40 years for flat roofs and of 64 years for steep roofs.

While replacement rates for the two different façade types also differ, with median survival time reaching 55 years for compact façades and 50 years for ventilated façades, differences are statistically not significant. In fact, slight differences in the survival function are completely contained within the 95% confidence interval of ventilated façades. Thus, we find no evidence for a systematic difference in replacement patterns across the two façade types. However, given the comparatively high rate of item non-response, we cannot exclude that some of the respondents who answered the question do not fully understand the difference between the two types of façades.

2.3.3 Parallel renovations of multiple elements

A considerable number of SHEDS' respondents provide the exact years of renovation. It is therefore possible to investigate the frequency of joint renovation works. That is, how often renovations of different elements are executed simultaneously (or at least within the same year).

Table 5 gives the number of respondents by ownership type who report exact years of renovation for any possible combination of the four building elements, occurring within the same year or in the duration of two consecutive years. In total, there were 1'514 owners and 1'422 tenants who provided the exact year of renovation for at least one of the elements, and 400 owners and 300 tenants who gave exact years of renovation for the four building elements. The difference arises because some respondents have not performed more than one renovation, or because the respondents did not remember the exact year of renovation. That is, Table 5 should not be read as an information on the number of SHEDS' respondents who renovated several elements throughout the service life of their home. Instead, it gives the number of respondents who renovated several elements and provided exact years when these renovations occurred. For instance, of the 400 owner-occupiers who reported exact years of renovations for the four building elements, 85 report that all these renovations occurred in the same year. This is 21.3% of those reporting exact years for the four elements, and 5.6% of those providing the exact year for at least one renovation. Numbers also suggest that parallel renovations do not seem to be unusual in Switzerland. For instance, of the 622 owner-occupiers who report a roof renovation (see Table 4 page 99), 360 (57.9%) report at least one other renovation happening in the same year. 85 respondents (13.7%) also renovate the three other elements in the same year. Moreover, given that we only count parallel renovations for which we observe the exact year of renovation, these values are likely to underestimate the true prevalence of such joint exercises. Notably, compared to other possible combinations, simultaneous renovations of the four elements are relatively common, being the most frequent combination among tenants and the first or second most frequent combination among owners.

We also observe that some combinations tend to occur more frequently than others. In particular, we find that combinations including a renovation of the heating system occur less often. For instance, the combination windows, façade, roof occurs three times as often as the alternative combinations of three elements including the heating system. As windows, façade and roof are part of the building envelope, this is likely to reflect the structural dependencies in a building.

Table 5: Counts of joint renovations

Combination				Number of respondents reporting renovations of these elements in the same year		Number of respondents reporting renovations of these elements in the same year or two adjacent years	
Windows	Heating system	Façade	Roof	Owner	Tenant	Owner	Tenant
x	x	x	x	85	140	93	149
x	x	x		20	34	32	41
x	x		x	19	20	29	25
x		x	x	60	74	70	79
	x	x	x	21	10	26	13
x	x			83	65	144	82
x		x		72	114	82	122
x			x	39	18	47	19
	x	x		35	23	43	24
	x		x	12	15	31	25
		x	x	72	52	81	57

3 Comparing renovation rates to previous studies

The results from the preceding analyses can – to some degree – be compared to previous findings on retrofit decisions among households and home owners in Switzerland [1]–[3]. Similar to the SHEDS, most of these studies rely on web or paper based surveys in order to estimate annual renovation rates for a set of building elements. However, they rely on a slightly different statistical approach. It consists of first obtaining information on renovation behaviour over pre-defined periods, and then deriving annual renovation rates by averaging the share of renovated buildings in the entire sample over the length of the observation period. Jakob et al. (2014) provide a comprehensive review and synthesis of these results [4]. While we cannot directly compare survival curves to these findings, it is possible to analyse similarities and differences in the implied average annual replacement rates between these studies and the current one.

We proceed in two complementary steps. First, we simply draw on the implied average annual replacement rates derived from the basic life-tables. Second, we can mimic the analytical approach taken by the earlier literature and compute average annual replacement rates among our survey sample within fixed time intervals. In particular, we follow Jakob et al. [4] and compute average annual replacement rates over the 10-year interval between 2001 to 2010 for buildings constructed prior to 1991. Moreover, as they estimate replacement rates for single-family and multi-family homes separately, we likewise follow this strategy in an effort to increase comparability.[23] Nevertheless, considerable differences between this previous research and the current study remain. First, all previous analyses are restricted to a small number of cantons in the northern part of the country, whereas SHEDS covers the entire country except Ticino. Second, unlike the previous literature, the SHEDS data does not allow to differentiate readily between energy-efficient and general maintenance retrofit rates.[24] Moreover, these studies likewise adjust for partial retrofits, e.g. cases where only some but not all windows are replaced – a fact that we cannot account for in the SHEDS data. Jakob et al. report that between 5% (façades in multi-family houses) and 60% (windows in multi-family houses) of all observed renovations are effectively partially executed [4].

Table 6 gives annual average replacement rates as derived from the SHEDS data, as well as the summarized results from the previous literature as provided in Jakob et al. [4]. Results are provided separately for single-family and multi-family houses. Moreover, to increase comparability between results from the previous literature and the ones obtained from SHEDS, we consider only renovations occurring between 2001 to 2010 in buildings constructed prior to 1991 for frequency-based estimations. No such data restrictions are applied to survival models. Both exclude observations that report that an element has not been renovated in over 100 years.

When comparing the current results to previous findings, one has to bear in mind that SHEDS explicitly asks for the year in which the last renovation has occurred (and eventually the age of the replaced element). This is problematic in as much as observing multiple renovations that may have occurred in the decade between 2001 and 2010 is limited by this way of eliciting renovation dates. For instance, if a household reports a renovation for the year 2015 and claims that the replaced element was 8 years at the time of replacement, it is impossible to reconstruct from the data whether a further renovation has

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[23] Since the study of Ray and Brenner (2016) does not provide element-specific retrofit rates, these findings are not explicitly considered for the current comparison.

[24] We have tried to account for this difference by asking SHEDS respondents for the main reason for executing a renovation (see Appendix 1, question accom9d). However, response rate to this question was low. Only between 32% (roof) and 48% (heating system) of those who reported a renovation also provided an answer to this question. Moreover, of those who responded, a vast majority gave more than one main reason for the execution of a renovation, often conflating energy-related and non-energy-related reasons. Only a small fraction of households reported that renovations were executed only for aesthetic considerations or general maintenance requirements. Among those responding to the question, this fraction ranges between 8% for windows and 49% for façades. This highlights the fact that decisions over renovations are rarely driven by a single cause. However, it also suggests that we would lose a sizeable portion of the uncensored sub-sample when focusing only on respondents providing a valid answer on the motivational question. Excluding households who only provide non-energy-related reasons for a renovation (aesthetic or general maintenance) yields results that are very similar to the ones presented in this report. See, for instance, results presented in Table 10 to Table 13 in the Appendix. However, these results rely on the assumption that all households not responding to the motivational question have performed renovations primarily for energy-related reasons.

taken place between 2001 and 2007. In this sense, frequency-based estimates from SHEDS are likely to underestimate replacement activity.

Moreover, both current and previous estimates are derived from samples rather than the entire population of interest. They are thus subject to random sampling error. For instance, with an average sample size of about 700 owner-occupied single family buildings constructed after 1989, the standard error for an annual renovation rate of 1% in the frequency-based estimations is about 0.03%. This translates well to the estimates reported by Filippini et al. [3], using a much smaller sample size than the one available from SHEDS.

Table 6: Replacement rates from the current and from previous studies ([1] to [4]).

Estimation method	Frequency-based				Survival	
Source	Previous literature		SHEDS		SHEDS	
Dwelling type	SFH	MFH	SFH	MFH	SFH	MFH
Windows	2.1%	3.0%	0.6%	0.7%	1.9%	1.8%
	(1.1%)	(0.5%)	[0.4%,0.7%]	[0.5%,1.1%]	[1.8%,2.0%]	[1.7%,2.0%]
Heating system	0.8%	1.2%	1.2%	1.3%	2.5%	2.3%
	(n.a.)	(n.a.)	[1.0%,1.4%]	[1.0%,1.8%]	[2.4%,2.6%]	[2.1%,2.5%]
Façade	0.6%	0.7%	0.4%	0.8%	1.2%	1.6%
	(1.8%)	(1.6%)	[0.3%,0.6%]	[0.5%,1.2%]	[1.2%,1.3%]	[1.4%,1.8%]
Roof	1.2%	1.5%	0.3%	0.9%	0.9%	1.2%
	(0.5%)	(0.4%)	[0.2%,0.4%]	[0.6%,1.4%]	[0.9%,1.0%]	[1.1%,1.4%]

Note: For the previous literature, two types of results are given. The rate of energy-efficiency improvements as the upper value, and the rate of general maintenance works in brackets. For SHEDS findings, squared brackets give the 95% confidence interval, which is based on a simple estimate using the asymptotic variance of the log-transformed rate for frequency-based estimates [16], and on the bootstrap using 250 draws for survival estimates. Frequency-based estimations are computed for all renovations occurring between the years 2001 and 2010 in homes constructed before 1990. Survival estimates are not subject to data restrictions.

Thus, taking account of the fact that point estimates from both current and previous studies are subject to uncertainty, a number of observations should be noted. First, we observe that different estimation techniques tend to yield very different replacement rates. On average, frequency-based replacement rates are significantly smaller than survival-based ones. For several reasons, this is not very surprising. For one, both types of estimates cover different observation periods. While frequency-based estimations consider only renovations occurring between 2001 and 2010, survival-based estimations do not restrict the observational data. Moreover, frequency-based renovation rates and life-table-based renovation rates are conceptually different. Whereas the latter give replacement probabilities at any element age given that an element has not been replaced before, frequency-based renovation rates simply provide unconditional replacement probabilities. That is, frequency-based rates are estimated by standardizing observed renovations by all buildings, life-table-based renovations rates are estimated by standardizing observed renovations by the sub-set of buildings that are still at risk. Finally, frequency-based estimations cannot account for renovations that happen in years adjacent to the observation period, such that some under-estimation from this method is to be expected.

A second important observation from Table 6 is that frequency-based estimates from the SHEDS data tend to be smaller than the renovation rates identified in the previous literature, particularly for windows and roofs. This becomes even more apparent when considering that total replacement rates in this literature is the sum of energy-related replacements and general maintenance renovations (in brackets). Thus, estimates from SHEDS may indeed be subject to misreporting due to the long cut-off threshold of 100 years introduced in section 1.3. This threshold implies that censored survival values can reach up to 100 years. It is likely that some households have experienced but not reported a renovation e.g., due to memory loss effects or because they are only aware of renovations after they have purchased the building or move in the building. In that case, they are treated as if they have not renovated major building elements. These latter households may therefore inflate the number of non-renovating households downward biasing the estimated average replacement rates in survival and frequency-based estimations. While this problem is less prevalent for other characteristics of the survival distribution, such as the median, the average rates given in Table 6 are likely to be affected by this choice.[25]

To obtain an idea of how strongly, annual average replacement rates given in Table 4 and Table 6 are subject to such bias, we have experimented different outlier thresholds. Figure 9 plots changes in average replacement rates related to changes in the cut-off value. Results suggest that average replacement rates are sensitive to changes in this cut-off level only when substantially reducing the threshold. Using 30 instead of 100 years as a threshold for excluding observations roughly doubles average replacement rates for the frequency-based estimations, and increases survival-based values by 10% (windows) to 40% (façade). However, this strong sensitivity is confined to comparatively small threshold values. Using a threshold of 50 instead of 100 years increases renovation rates by only 10% (survival estimations) to 20% (frequency-based estimations). Given that, setting very low thresholds effectively excludes a considerable number of reported renovations of older elements, observing higher replacement rates in more restrictive samples is not surprising.[26] This is partially due to the fact that the combination of requiring buildings to be constructed before 1991 and elements being no older than 30 years, reduces the relevant construction period for buildings to the years between 1971 and 1990, and thus substantially decreases the number of observations.

Moreover, as the variance of the estimator decreases over-proportionally with the number of observed renovations,[27] confidence intervals in samples with more restrictive cut-off values are much larger. As a consequence, the estimate for the annual average replacement rate using the 100-year threshold is contained within the 95% confidence interval of the estimate relying on the 30-year threshold for most elements in both single-family and multi-family homes. That is, while differences appear sizeable, they are not statistically significant.

As replacement rates tend to stabilize quickly, with little differences in estimates with thresholds ranging from 50 to 150 years, results also suggest that the outlier definition detailed in section 1.3 is likely to have limited effects on the results given in Table 6 (or Table 4).

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[25] Yet, results from these exercises do not change substantially when shifting the observation window for the frequency based estimation by 5 years in either way (i.e. to the periods 1996 to 2005 or 2006 to 2015).

[26] Notably, using a threshold of 30 years instead of 100 years implies a loss of at least a quarter of reported renovations of each element. In multi-family homes, this affects 37% of reported window renovations, 24% of heating system renovations, 33% of façade renovations, and 36% of roof renovations. Among single-family homes, we lose 48% of reported window renovations, 29% of heating system renovations, 50% of façade renovations, and 60% of reported roof renovations. This suggests that a considerable number of SHEDS respondents recall renovations that have happened at considerably distant times in the past, calling into question whether memory effects indeed play a major role in recalling renovation events.

[27] As the observed average annual replacement rate is effectively an incidence rate, i.e. the rate of new events occurring in a population at risk (or: the number of renovations by number of buildings and years of observation), its variance can under certain assumptions be consistently estimated using the inverse number of observed events [16]. As a consequence, changes in the observed number of events change the variance (of the log-transformed rate) in an inverse quadratic manner.

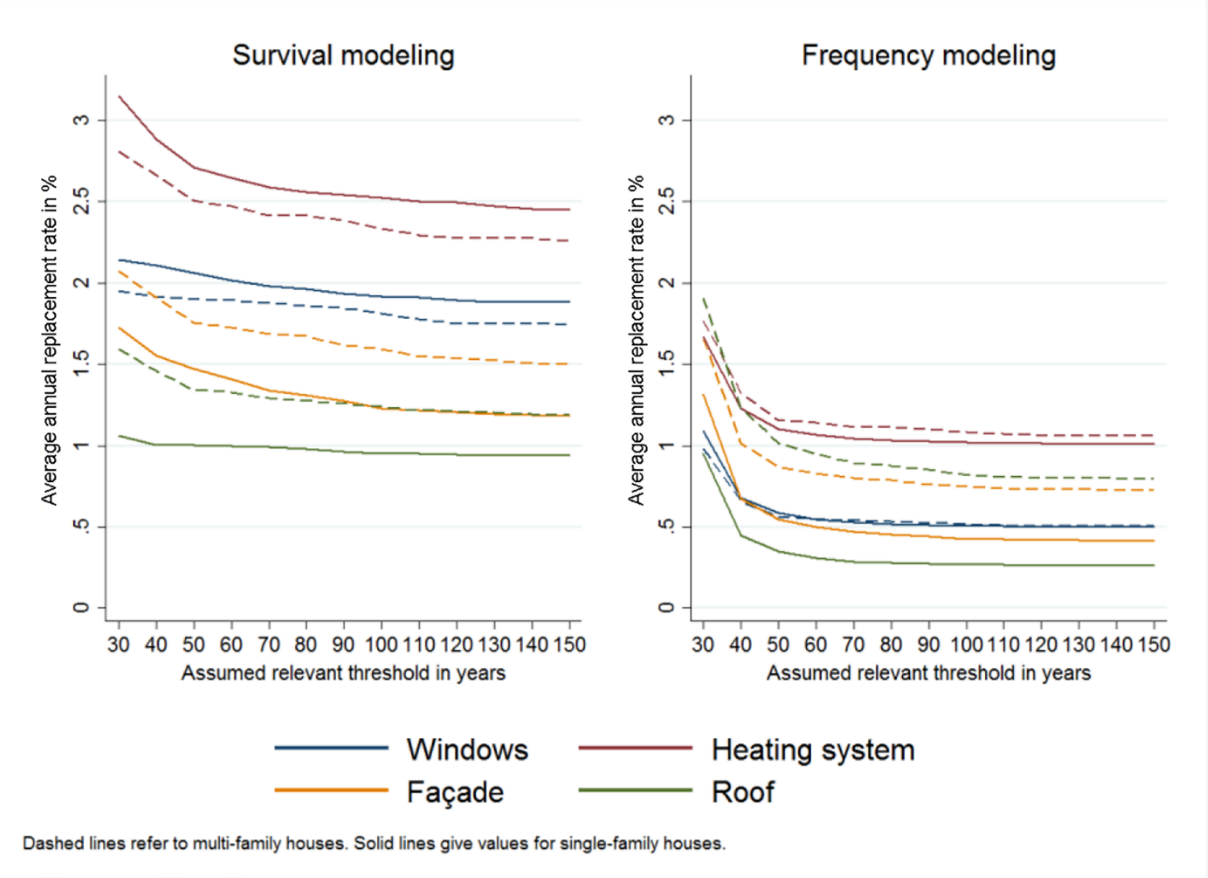

Figure 9: Sensitivity of annual average renovations rates with respect to chosen threshold

Last but not least, it should be stressed that the results in the previous section (Figure 7) show that replacement rates are not constant but change systematically over the life-cycle of an element. In this sense, average annual replacement rates 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. This result constitutes a further understanding of renovation rates of building elements compared to the previous literature.

4 Comparing empirical replacement to information from literature values

In this section we contrast "literature-based" against empirically observable replacement behaviour. By "literature-based", we mean all service life values collected from the literature in WP1.[28] The aim of this exercise is to obtain an overview of how well actual renovation decisions follow the literature recommendations (and respectively check if the values reported in these literature sources are on line with the actual renovation decisions).

4.1 Constructing survival curves from literature values

To be able to make such comparisons, we draw on results from the WP1 report in two complementary ways. In a fist attempt, we focus on information from Switzerland as codified in the "Bases for the Estimation of Life-cycle Costs" provided by the Swiss Centre for Studies on the Rationalisation of Construction (CRB). It provides information for the reference service life (RSL), defined as the period between the installation and replacement of a building component assuming that a set of reference conditions are fulfilled [17]. These conditions concern the characteristics of the element, such as its quality or the type of material from which it is made [18]. To account for such differences in greater detail, values are provided for a range of plausible RSLs. Table 7 gives average, maximum and minimum reference service life from the CRB for the main building elements used in this work package.

Table 7: Reference service life values from CRB for the building elements

Building element	Period of use		
	Minimum	Average	Maximum
Heating system	30	45	60
Heat production	15	20	25
Heat distribution and emission	40	60	80
Facade	20	35	80
Rendering	10	25	35
Compact facade	30	35	45
Ventilated facade	30	40	80
Window	25	35	45
Roof	20	35	100
Flat roof	15	25	40
Slanted roof	25	40	100

Notes: [a] Values were computed bottom-up using information on element substructures available from the CRB source [17]. For further details on CRB service lives data, see the DUREE WP1 study.

To obtain a prediction for the expected lifetime of a specific element (called estimated service life (ESL)), different analytical and stochastic methods (or the combinations of both) have been developed [19]. The most common analytic method, also included in the ISO Standard 15686 [20], [21], and thus the CRB

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[28] It was shown in the WP1 report that while service life data stem from diverse sources with values varying considerably between sources, there is no systematic relationship between the type of source (e.g., management sources such as building professional owners' manuals, life-cycle cost analysis, or environmental life cycle assessment) and the length of the reference service life. So, the global sample of service lives data of the DUREE database (developed in WP1) was considered in this study. It only takes into account the global sample excluding the additional data collection early 2019 from the IEA-EBC Annex 72 project [35]. However, the descriptive statistics of the global sample for the analysed elements in WP2 are relatively similar to the global sample including the Annex 72 service lives data (cf. comparative values in the WP1 report appendix 4).

manual, is the so-called "factor method". It estimates ESL by weighting RSL values using on-site (expected) conditions of the element for seven factors known to influence service life [18],[19].[29] For each of these seven factors, ISO standards suggest weights ranging from 0.8 for conditions that heavily accelerate element deterioration to 1.2 for conditions that greatly prolong the service life of an element. Under perfect conditions, ESL values can therefore exceed RSL values by a factor of almost 3.6, while under the worst possible conditions ESL is about 80% shorter than corresponding RSL.

In order to generate technically determined retirement and survival curves for building elements, we need to combine the information on key parameters of the technical lifetime distribution with some further assumptions. To the best of our knowledge, no research has dealt with the distributional form of replacement patterns for building elements. In this study, we follow two complementary sets of assumptions drawing on the literature investigating electronic appliance replacement [22], [23] and vehicle replacement e.g., [24], respectively.

For a first, simple approach, we assume that the reference conditions underlying the definition of the RSL values provide a sufficiently good estimate for the boundaries of variation in technical service life. We can assume that all elements lose their functionality at some time between the minimum and the maximum RSL. That is, we assume that no element is replaced before reaching the minimum reference service life[30], t_{min}^{RSL}, and no element survives beyond the maximum reference service life[31], t_{max}^{RSL}. To capture technical failure rates between these extremes, we draw on the literature on electronic appliance replacement [22] and assume that survival curves of building elements follow a similar linear function. Thus, we assume that the technical survival function, $S_{tech}(t)$, of each element is a piece-wise linear function given by:

$$S_{tech}(t) = \begin{cases} 1 & \text{if} \quad t \leq t_{min}^{RSL} \\ \alpha + \beta(t - t_{min}^{RSL}) & \text{if} \quad t_{min}^{RSL} < t \leq t_{max}^{RSL} \\ 0 & \text{if} \quad t > t_{max}^{RSL} \end{cases} \tag{3}$$

where values for α and β are chosen such that border values for t_{min}^{RSL} and t_{max}^{RSL} are attained. Figure 10 plots the resulting piecewise linear technical survival curves for the four elements based on CRB-RSL values (upper panel).

For a second approach based on CRB information, we deviate both from the assumption of the sufficiency of RSL as a prediction of technical service life and from assuming linearity of survival curves. Instead, we assume that technical lifetime is bounded by minimum and maximum expected service life, which can be derived by adjusting minimum and maximum RSL considering the worst and best-case scenarios of factor conditions.[32] In other words, both minimum and maximum element survival shift further away from the mean RSL values. Moreover, for specifying the failure rate between these points in time, we draw on the literature for vehicle replacement [24] and assume that technical survival curves of building elements follow a log-log function of the form:

$$S_{tech}(t) = 1 - e^{-e^{\left(\alpha + \beta\left(t - t_{min}^{ESL}\right)\right)}} \tag{4}$$

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[29] These factors include: (A) element's quality that accounts for the quality of materials but also potential damages occurring during transport and storage (B) design level that accounts for the integration of the element in the building structure hence its protection from erosive forces, (C) on-site implementation quality that assesses if the element has been correctly installed, (D) the internal physical environment that takes into account the erosive forces affecting the element from the inside (e.g. a window installed in a kitchen or bathroom), (E) external physical environment capturing the exposure to external corrosive forces, (F) use conditions that measures the element's usage intensity, and (G) maintenance conditions.

[30] Otherwise a satisfactorily functioning element would be replaced.

[31] Otherwise an element would be kept that is no longer able to fulfil its intended function.

[32] That is, minimum expected service life, t_{min}^{ESL}, is defined as: $t_{min}^{ESL} = t_{min}^{RSL} \times 0.8^7$, while maximum expected service life, t_{max}^{ESL}, is given by: $t_{max}^{ESL} = t_{max}^{RSL} \times 1.2^7$.

where again α and β are obtained by such that all elements are replaced sometime between t_{min}^{ESL} and t_{max}^{ESL}[33]. Figure 10 plots the corresponding log-log technical survival curves for the four elements based on CRB-ESL values. Clearly the log-log functional form appears to be closer to the observed empirical survival curves, at least in terms of smoothness.

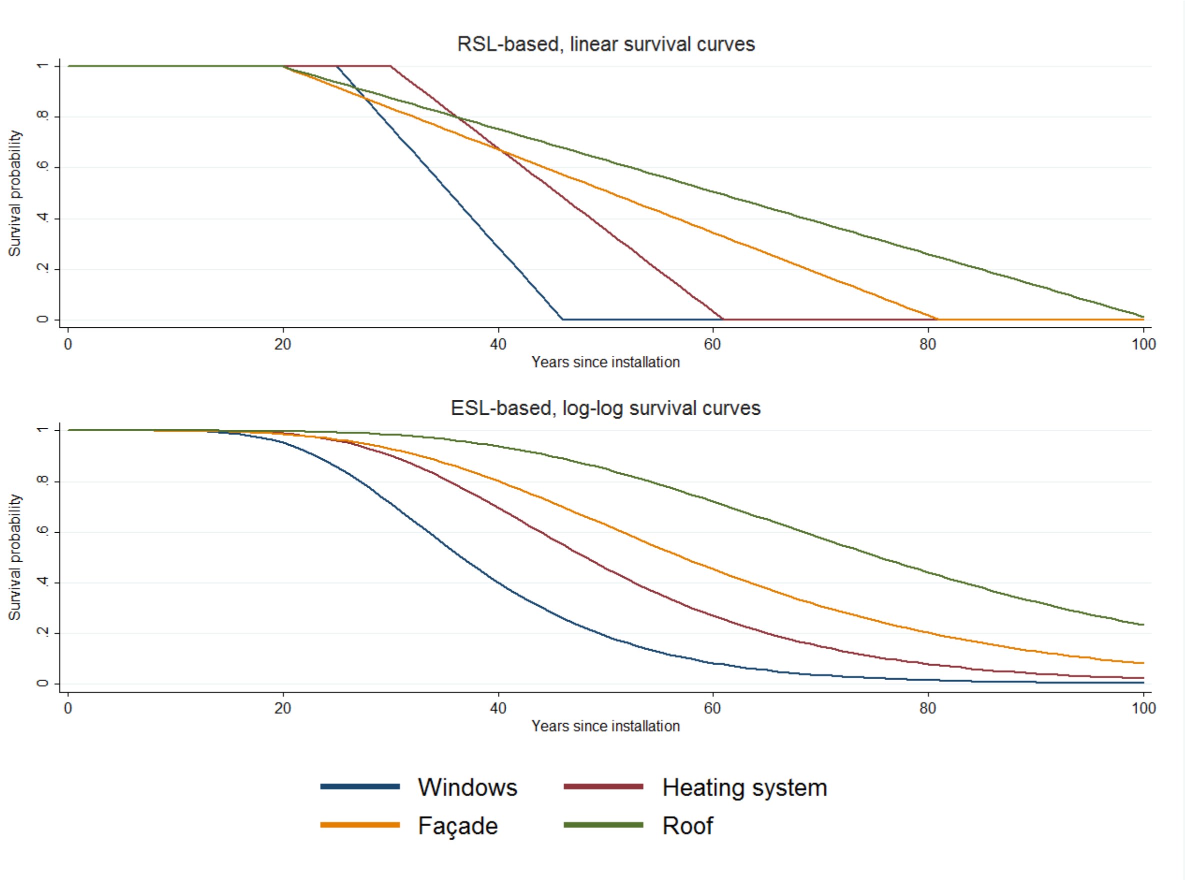

Figure 10: Technical survival curves of building elements based on CRB assumptions with reference service life (RSL) and estimated service life (ESL)

A first visual inspection suggests that despite differences according to the chosen functional form, the ordering of elements by survival length is largely congruent between literature-based and empirical survival curves. However, CRB standard suggest a slightly earlier onset of replacement for façades (i.e., façade coatings according to CRB) than for heating systems, which is the opposite in the empirical results. One reason for this divergence is that literature values actually report very different technical lifetimes depending on the type of components of the heating system i.e., the heat production or the heat distribution (see WP1). The level of details for the service lives of façade includes also the insulated compact and ventilated facades as well as the rendered or painted facades (without insulation). Consequently, a better assessment of congruence between normative and empirical information would require plotting technical survival curves for heating technology subgroups as well as plotting the types of façade coatings (see Table 7).

While CRB-based technical lifetime values are Swiss-specific and therefore provide an intuitive basis for comparisons between literature-based and empirical survival curves using Swiss datasets, such as the SHEDS, they are a comparatively poor reflection of the considerable variation in literature-based lifetime estimates presented in WP 1, even when adjusting for expected service life. Moreover, using

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[33] Note that the range of the log-log function is only defined for values on the interval $(0,1)$. Therefore, instead of assuming that a 100% elements are replaced between t_{min}^{ESL} and t_{max}^{ESL}, we allow for a margin of 0.001% of replacements beyond each threshold, when computing technical log-log survival curves.

these values forces us to make assumptions about the functional form of survival curves that may not be justified from an empirical point of view.

A second attempt for comparing literature values and empirical renovation decisions is therefore to take advantage of the entire information collected in WP 1. For this purpose, we construct "synthetic survival curves" by plotting the lifetime of each element against the fraction of literature values that predict that it survives up to this point. Note that by doing so, we mix literature values from different sources (ecological life-cycle analysis, life-cycle cost analysis, building management manuals) and different geographic origins (Switzerland, Europe, North America), as well as different values along the survival distribution (min, mean, max) specified in these literature values. As such, not all data points used to construct these curves are perfectly comparable. However, using this approach provides a ready way to capture the variation in expected lifetime of elements across sources, and thus provides some information in how far CRB data are representative of the entire literature values population. Figure 11 shows these synthetic survival functions.

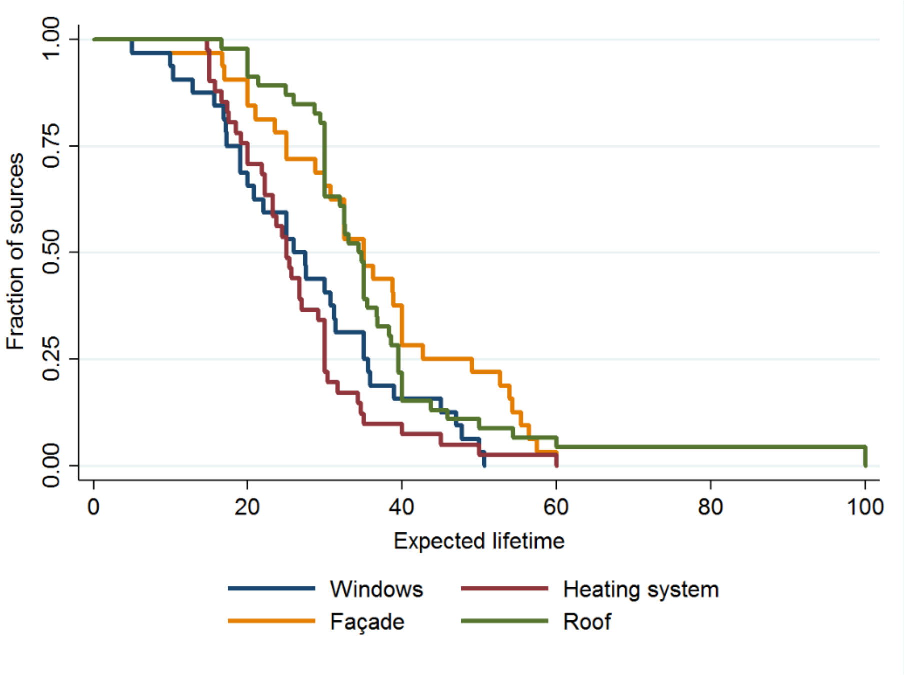

Figure 11: Synthetic survival curves of building elements based on all service lives' values collected in the literature in WP 1

While the ordering in Figure 11 slightly changes, in particular with respect to the expected lifetime of windows compared to façades, which is much closer in CRB-data than in the entire literature data, the ordering of replacement age is again very similar to empirical observations from section 2.3.

4.2 Contrasting literature-based and empirical replacement behaviour

To facilitate further comparisons of literature and empirical survival information, Figures 12 to 15 plot empirical survival curves (solid black line, 95% CI dotted black lines) against literature-based information using CRB-based technical survival curves (dashed coloured line) and synthetic survival curves (solid coloured line) for each of the four elements, respectively. Given potential reporting issues among tenants highlighted in section 2.3.1, empirical survival curves are estimated from SHEDS's owner-occupied buildings alone.

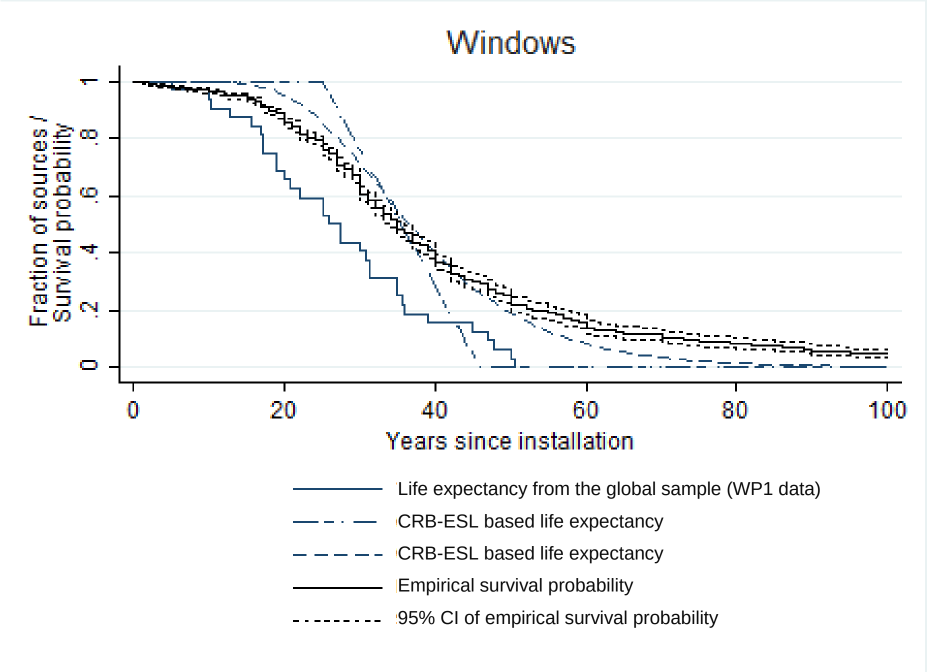

Figure 12: Empirical survival curves, CRB-based, and literature-based curves for windows (SHEDS 2017 and 2018)

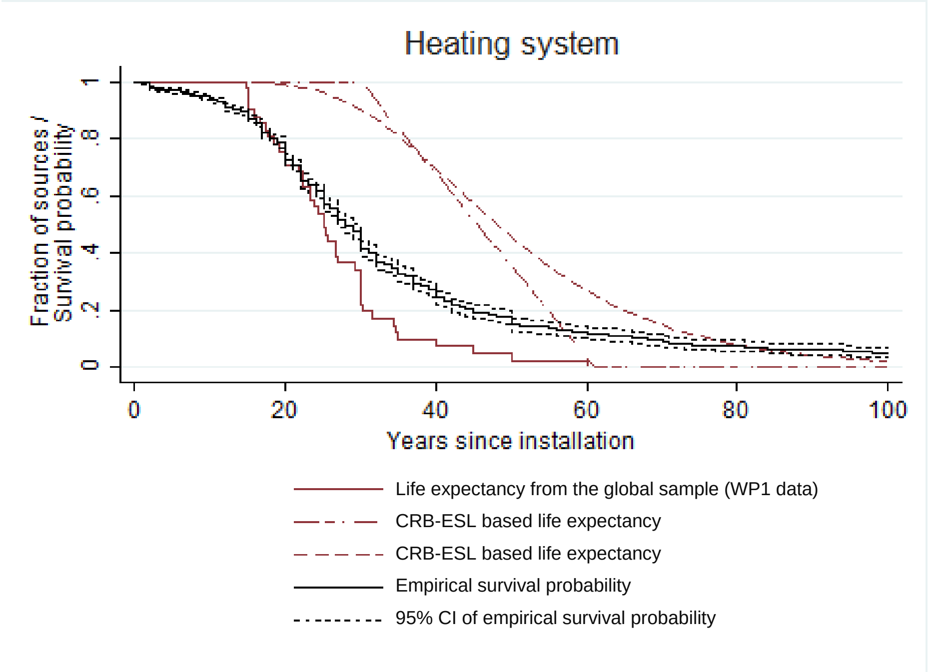

Figure 13: Empirical survival curves, CRB-based, and literature -based curves for heating systems (SHEDS 2017 and 2018)

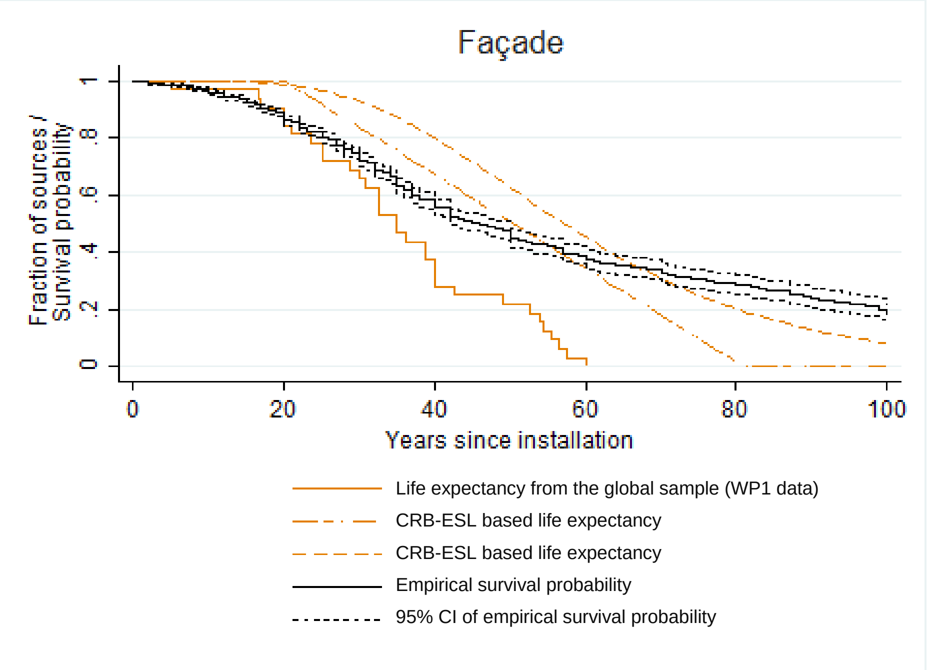

Figure 14: Empirical survival curves, CRB-based, and literature -based curves for facades (SHEDS 2017 and 2018)

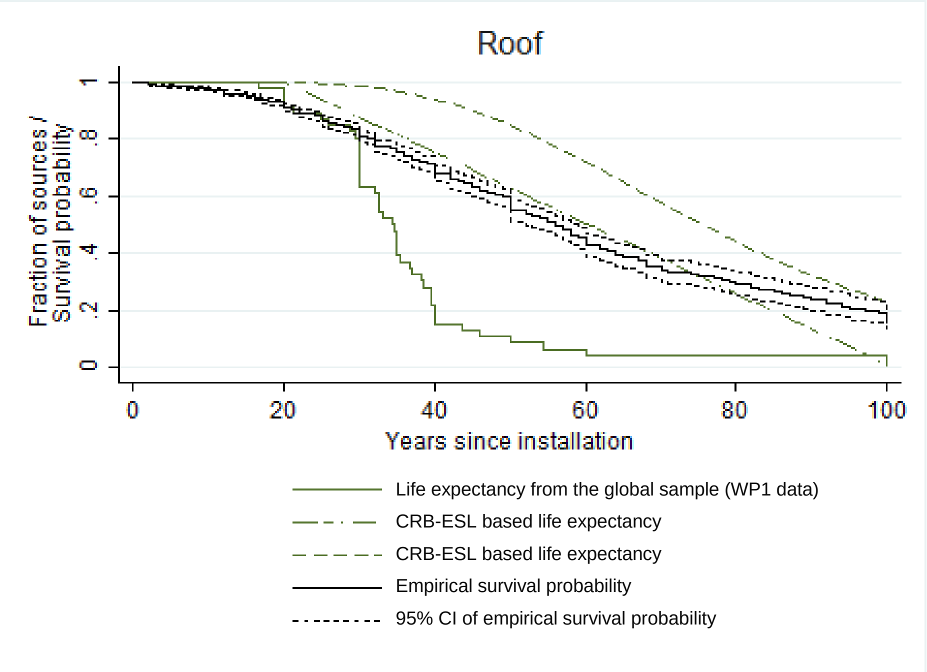

Figure 15: Empirical survival curves, CRB-based, and literature -based curves for roofs (SHEDS 2017 and 2018)

Several common patterns arise when comparing the two CRB-based survival curves against the empirical curves obtained from the SHEDS. First, the results suggest that both ways of depicting CRB-based survival information yield comparatively similar survival curves. While some deviations clearly exist – in particular with respect to the timing of the first and the last replacement – it suggests that assumptions about the functional form of survival curves based on CRB standard make no major difference in terms of constructed survival curves. On the other hand, using information from the entire set of international literature values (including the CRB values) tends to yield "synthetic" survival curves that yield systematically higher replacement risks. Specifically, for roofs, heating systems (and windows), the international values yield considerably shorter survival predictions than CRB values. It shows that CRB values tend to provide survival curves that are more conservative, in the sense of predicting longer element survival than the remaining literature values.

Substantial and systematic deviations can also be observed between literature-based and empirical element replacement. In particular, literature sources appear to under-estimate 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, although it is more pronounced among linear survival curves constructed from RSL information. This is partly due to the very restrictive assumption underlying the construction of the linear survival curves. It also clearly shows that the assumption of linearity, as applied for instance in the literature on electronic appliance replacements [18], is not adequate for describing replacement patterns of building elements. When judged over the entire period of observation, survival predictions based on the "synthetic survival curves" tend to fare worse than either CRB-based survival curve, although they better capture empirical replacement behaviour in the first 10 to 20 years. Specifically, "synthetic survival curves" tend to heavily overestimate replacement rates. A notable exception is heating systems, for which the synthetic curves appear to capture factual survival well, and much better than either version of the CRB-based survival predictions.

Notably, we have derived literature-based survival curves for elements at a high level of details according to the CRB classification of building elements (e.g., the entire heating system rather than its components) and without taking into account the fact that different technical variants of the same element may have rather different expected service lives. For example, we do not distinguish between flat and gabled roofs, despite the fact that most literature sources suggest that the latter has a substantially longer service life than the former. Therefore, the comparisons between empirical replacement behaviour and WP1 data presented in Figures 12 to 15 may be slightly misleading. For instance, the observation that CRB-based survival curves for the heating system considerably overestimate empirical heating system replacement 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 distribution tubes. To assess the effect of such mismatches between WP1 data and SHEDS data, Figures 16 to 19 plot survival curves of these sub-elements relying on information collected during the 2018 wave of SEHDS..

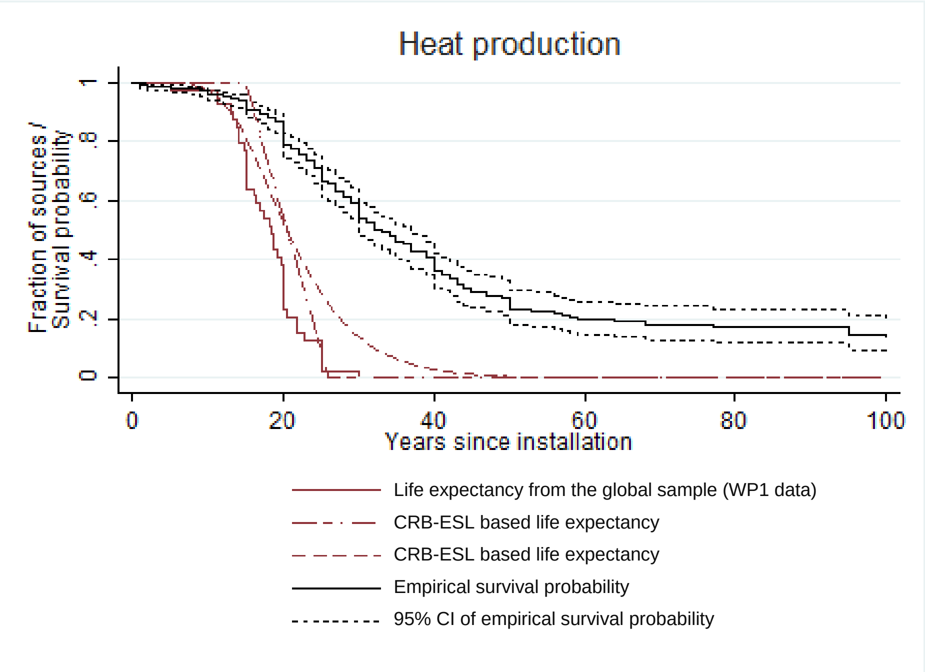

Figure 16: Empirical survival curves, CRB-based, and literature-based curves for heating production (SHEDS 2017 and 2018)

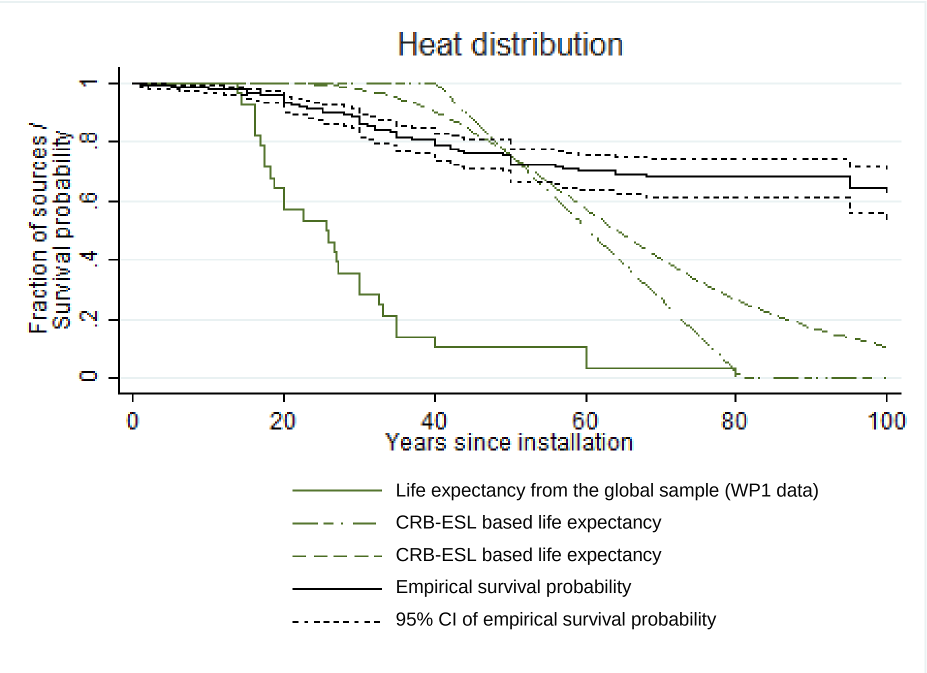

Figure 17: Empirical survival curves, CRB-based, and literature -based curves for heating distribution (SHEDS 2017 and 2018)

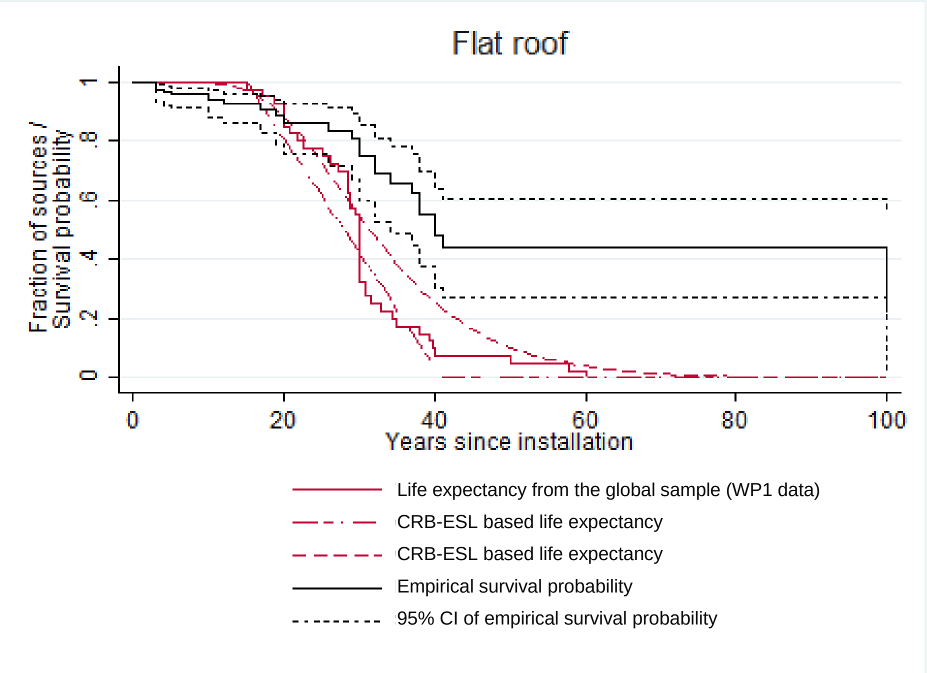

Figure 18: Empirical survival curves, CRB-based, and literature -based curves for flat roofs (SHEDS 2017 and 2018)

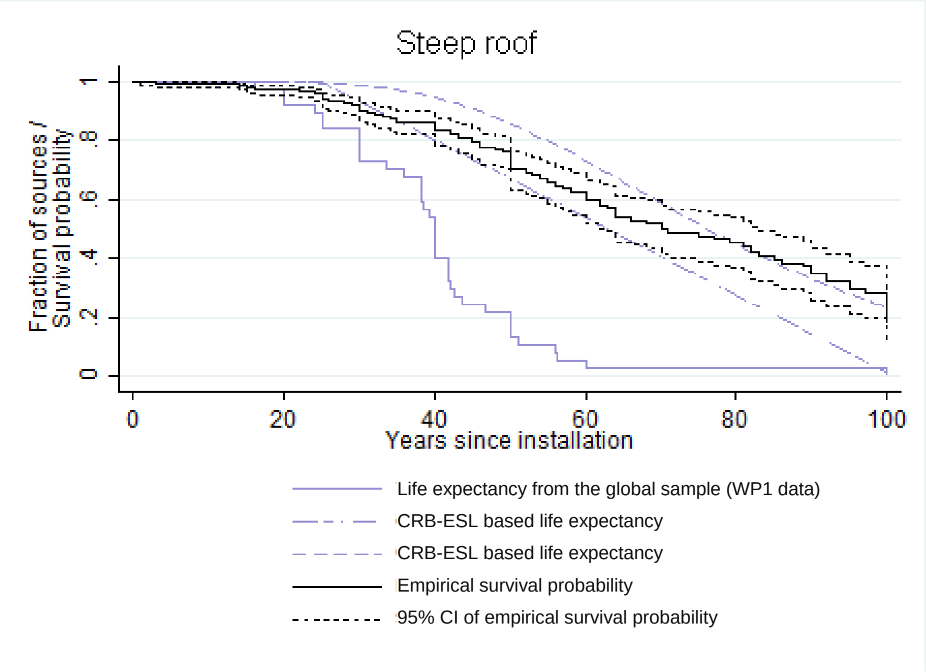

Figure 19: Empirical survival curves, CRB-based, and literature -based curves for gabled roofs (SHEDS 2017 and 2018)

In general, Figures 16 to 19 show very similar patterns of divergence between WP1 data and empirical replacement behaviour observed for the higher-order element structure.

5 Determinants of renovation timing

In this section, we use the SHEDS data to extend the preceding analysis in an effort to provide a more comprehensive understanding of the factors related to delaying renovations, beyond the differences across elements identified in the preceding sections. This is important information for the political debate and empirical evaluation of competing policy measures.
They are also useful to environmental researchers and market developers for predicting the length of time that technological innovations or the built environment need to diffuse in the building stock, and provide information on the structure of these diffusion processes. Most importantly, they allow to isolate the impact of several factors, such as the type or location of the building or individual characteristics, on the probability of replacement.

5.1 Econometric strategy and specification

To more comprehensively examine which factors determine the survival time of different building elements we make use of the semiparametric proportional hazards model introduced by Cox (1972).[34] In this framework the replacement hazard rate at time t, defined as conditional probability of replacement given that the element has survived up to that point in time,[35] is denoted as $h(t, \boldsymbol{x}, \beta)$. It can be written as:

$$h(t, \boldsymbol{x}, \beta) = h_0(t) e^{\sum_{i=1}^{k} \beta_i X_i} \tag{5}$$

where $h_0(t)$ is the baseline hazard function, which describes the change in replacement hazards as a function of survival time (i.e., how conditional replacement probabilities change with element age in general), while the exponential function $e^{\sum_{i=1}^{k} \beta_i X_i}$ characterizes systematic deviations from this hazard depending on the value of the k covariates, $X_1, \dots, X_k$. The coefficients of interest, β_1 to β_k, then describe the effect of these covariates on replacement hazards at any point in time. They can be directly translated into hazard ratios, i.e. the relative differences in replacement hazard rates between buildings with and without a characteristics encoded by X. For example, assume that a variable, say *SFH*, measures whether an element is installed in a single-family home. The variable *SFH* takes a value of one if this is true, and zero otherwise. Further assume that we estimate a model such as the one given in equation *(5)* with SFH being an element of X, and obtain a coefficient of $\beta_{SFH} = 0.1$. The implied hazard ratio is given by the exponential of this coefficient, such that $\frac{h(t, SFH=1, \beta_{SFH})}{h(t, SFH=0, \beta_{SFH})} = \exp(\beta_{SFH}) = 1.105$. This means that elements installed in single family houses have a 10.5% higher replacement hazard than elements installed in another type of building.[36] For simplicity, all coefficients in the result tables are given in exponentials (cf. Tables 10 to 13 in Appendix 2). That is, they can directly be interpreted as hazard ratios.[37]

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[34] The term "semiparametric" refers to the fact that the Cox model does not pre-specify a functional form of the underlying baseline hazard function, $h_0(t)$. It does not parameterize the functional relationship between element age and conditional survival probability. At the same time, it assumes that the effect of time-invariant variables, X_k, can be modeled in a linear additive way. That is, the Cox model combines a "non-parametric" function (first right-hand side term of equation (5), i.e. the baseline hazard function), with a perfectly parametric part (the second right-hand term of equation (5), i.e. the part modelling the effects of time-invariant variables on deviations from the baseline hazard). A hazard function, $h(t)$, describes the instantaneous potential of an event occurring per unit of time, given that the event has not happened up to that point in time, t. In our case, it gives for each year the probability that an element will be renovated in that year, given that it has not been renovated before. In contrast to the survivor function, which describes the conditional probability of *no renovation* happening, the hazard function focuses on the chances that a *renovation is executed*. In some sense, the hazard function can therefore be considered as the opposite side of the information given by the survivor function [22].

[35] More formally, this instantaneous probability of replacement can be defined as $h(t) = \lim_{\Delta t \to 0} \frac{\Pr(t < T < t + \Delta t | T > t)}{\Delta t}$ where T denotes the time to replacement.

[36] A similar translation can be made for cardinal variables such as dwelling size. In this case, the exponentiated coefficient gives the change in hazard rates associated with a change in one unit of the cardinal variable.

[37] To deal with the substantial number of tied failures in the data we rely on Efron's (1977) approximation to the exact marginal failure probability.

The attractiveness of this modelling approach derives from the fact that the baseline hazard function is a-priori unspecified, such that estimates of regression coefficients, hazard ratios and adjusted survival curves remain unaffected by deviations between the empirical and the theoretically imposed functional form of the baseline hazard. That is, unlike parametric alternatives, such as the Weibull or the Lognormal model, the functional form of the baseline hazard rate, $h_0(t)$, is not completely specified in the Cox model.[38] It can thus easily accommodate deviations of the baseline hazard from parametric forms. The advantage is that systematic shifts from the baseline hazard, associated with time-invariant variables, X_k, can be more precisely identified, although identification is less efficient than parametric alternatives (i.e., it is harder to obtain statistically significant associations). The semiparametric Cox model is therefore a comparatively "safe" choice when it is unknown which parametric specification of the baseline hazard would be appropriate [25], [26]. For this reason, it is also among the most widely used models in applied survival analysis (cf. [27]). We have likewise used alternative parametric models including Weibull, Lognormal, and Loglogistic parameterizations. All yield estimates similar to the ones presented below. Yet, a comparison of goodness-of-fit based on Akaike Information Criteria strongly favoured the Cox model for all elements and almost all specifications.

The validity of the proportional hazards (PH)[39] assumption is evaluated in two different ways. First, we tested specifications based on Schoenfeld residuals [28]. These tests do not reject the proportionality assumption for the entire models nor for any individual covariates at conventional levels of error, even when not adjusting for multiple testing. Second, we estimate fully parameterized versions of the Cox models allowing the effects of all covariates (except cantonal dummies) to vary over survival time. Models yielded overwhelmingly insignificant coefficient estimates for the time-dependent effects. Moreover, a set of ensuing Wald tests of joint significance of these effects similarly yielded no evidence for an improvement in the explanatory power of these fully parameterized models compared to that of the proportional specification. The main exception to this general observation are cantonal fixed effects, which are found to violate the PH assumption in most estimations. In order to deal with this violation, we follow a standard solution to such issues (cf. in [26]) and relax the assumption that every element in the sample faces the same baseline hazard. Instead, we assume that baseline hazards vary across cantons, such that whenever we want to control for unobservable cantonal effects, equation *(5*) is relaxed to:

$$h(t, \boldsymbol{x}, \beta) = h_{0c}(t) e^{\sum_{i=1}^{k} \beta_i x_i}, \tag{6}$$

where $h_{0c}(t)$ describes the baseline hazard in canton c.

The variables contained in the set of controls, X_k, encompass a range of (largely) time-invariant variables characterizing the building of residence and its geographical position in Switzerland. They comprise the dwelling type namely, a categorical variable in three levels (detached house or bungalow, semi-detached or terraced house, apartment block), location (city, agglomeration, and countryside), the dwelling size in square meters, and the geographical region (French Switzerland, Alps and Pre-Alps, Western Midlands, Eastern Midlands). Moreover, controls include a variable measuring whether the respondent is the owner of the residence or a tenant (used in a limited number of initial estimations),[40] the household's gross monthly income in Swiss Francs in 2017, as well as the risk attitude of the survey respondent. Income information in the SHEDS is collected in six categories ranging from less than CHF 3'000 (1) to CHF 12'000 or more (6). To account for the fact that income at the time of installation or replacement may have been different from current income, we reduce these values to three categories

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[38] For instance, the Weibull hazard model is a parametric model of the form: $h(t, \boldsymbol{x}, \beta) = pt^{p-1} e^{\sum_{i=1}^{k} \beta_i x_i}$, whose baseline hazard, pt^{p-1}, is completely defined by the unknown coefficient p and the time since installation t.

[39] The term "proportional hazard" refers to the fact that the Cox model requires that the hazard ratio is constant over time. That is, the hazard for one building is proportional to the hazard for any other building and that the constant proportionality is independent of time. To give an example, if single-family houses have a lower hazard rate than multifamily houses during the first 10 years after installation, they must also have a lower hazard rates 50 years after installation. Moreover, the ratio of the two cases takes the same constant, $exp(\beta_{SFH})$, at both times**.**

[40] In complementary estimations, we have additionally controlled for type of ownership (outright vs. cooperative). In general, estimated hazard ratios were insignificantly different from one. Similarly, likelihood ratio tests comparing models with and without this determinant did not yield evidence that its inclusion improved the explanatory power of the model significantly. Moreover, information criteria favoured models excluding this variable.

assuming that they better reflect the household’s position in the permanent income distribution. Moreover, as over 15% of respondents prefer not to give information on this item, we create a separate category for those individuals. Doing so allows to minimize data loss. Risk attitudes are derived from a simple questionnaire item, asking respondents whether they consider themselves as individuals who tend to take financial risks. Answers are given on a 5-point Likert scale ranging from 1 (not at all) to 5 (very much). Since less than 1.5% of respondents stated that they commonly take “very much” financial risk, we merged this category with the one below in order to avoid problems with numerical optimization. Finally, X_k includes a set of variables that aim to capture the entry cohorts of both the element under investigation and the building in which it was installed. That is, we allow for the possibility that replacement rates change across generations of elements and dwellings, for instance due to technological progress or legal regulations concerning the preservation of historic buildings. Building construction cohorts are defined as a nominal variable, with the aim to ensure that each cohort roughly has the same number of observations. More precisely, building and element cohorts are defined by splitting the respective distribution in the year 1990. That is, we distinguish between two cohorts such that the corresponding variable takes a value of zero if the element (resp. the building) was installed (resp. constructed) before 1990 and one otherwise. In detail, control variables are described in Table 8.

Table 8: Description of control variables (assumed to be time-invariant)

Variable	**Description**	**Codebook**
Apartment	Single family house vs apartment block	0 - Single family house 1 – Multifamily house
Income	Monthly gross income group (nominal)	1 – bottom (less than CHF 4’500) 2 – middle (CHF 4’500 to CHF 8’999) 3 – top (CHF 9’000 or more) 7 – missing income
Urban Area	Placement along urban-rural continuum	1 – city 2 – agglomeration 3 – countryside
Dwelling size	Size of living space in m^2	Continuous (in natural logarithm)
Building cohort	Construction cohort of building	0 – constructed before 1990 1 – constructed in 1990 or later
Element cohort	Installation cohort of *element*	0 – installed before 1990 1 – installed in 1990 or later
Region	Larger region in Switzerland	1 – Suisse romande 2 – Alpen und Voralpen 3 – Westmittelland 4 – Ostmittelland
Canton	Swiss cantons (except Ticino)	1 – ZH 2 – BE 3 – LU 4 – UR 5 – SZ 6 – OW 7 – NW 8 – GL 9 – ZG 10 – FR 11 – SO 12 – BS 13 – BL 14 – SH 15 – AR 16 – AI 17 – SG 18 – GR 19 – AG 20 – TG

Variable	Description	Codebook
		22 – VD 23 – VS 24 – NE 25 – GE 26 – JU
Year	Survey year	0 – survey wave 1 (2017) 1 – survey wave 2 (2018)
Risk Aversion	Risk attitudes in financial matters	1 – Risk averse 2 – Rather risk averse 3 – Risk neutral 4 – Risk seeking or rather risk seeking

5.2 Results and discussions

A concise summary of the most important findings is given in Table 9. For each element, it summarizes the direction and significance of coefficients on length of service life from a set of 10 alternative specifications. Detailed description of these specifications, as well as comprehensive estimation results for the four elements from the SHEDS data set are given in Tables 10 to 13 in Appendix 2. A positive sign implies that higher values of an attribute are related with higher replacement hazards, meaning that renovations tend to occur sooner. A negative sign means that higher values of an attribute are associated with longer observed service lives.

Table 9: Summary of Cox estimations

	Windows	Heating system	Façade	Roof
Income	+^{ns}	+**	-^{ns}	+^{ns}
Dwelling size	0	+*	+^{ns}	0
Apartment	+**	+*	+**	+**
Western Switzerland/ Midlands	-*	-*	0	0
Urban Area	-**	0	-*	+*
Risk Aversion	-*	-*	-^{ns}	+^{ns}
Element cohort	+**	+**	+**	+**
Building cohort	-*	-*	-*	-**

Legend:
+ increase the risk of replacement (i.e., decrease the service life)
- decrease the risk of replacement (i.e., increase the service life)
** significant in 50% of specifications or more
* significant in less than 50% of specifications
^{ns} coefficients with same sign across specifications, but no significant relationship
0 no consistent sign of coefficients across specifications

Despite some variation in point estimates across elements, results from Table 9 show that there are a number of common patterns that emerge from these regressions. They are presented below for each variable.

Income & dwelling size:
We find mostly positive (and significant) hazard ratios for the two indicators of financial well-being, i.e. household gross income and the size of the living space.
When taking the average across specifications, a household in the top income category has a 3.4% (windows) to 28.4% (heating system) higher replacement rate than a household in the lowest income category. An exception to this rule are façades, for which we find decreasing replacement rates with

increasing income. Yet, coefficients are not significant at generally accepted levels of significance. So we cannot exclude that there is in fact no association between household income and replacement behaviour for façade renovation.

Similar results are obtained for the relationship between dwelling size and replacement hazards, which likewise appears to be positive for a majority of elements (except for windows, for which replacement hazards appear to be unrelated to the household's size of the living area). An increase of one percent in living space (corresponding to about 1.2 m^2 at the sample mean) is associated with an increase in replacement hazards of between 6% (façade) and 13% (heating system). However, again associations are not statistically significant at commonly accepted levels of error for a majority of point estimates on window, façade and roof replacements.

Type of apartment (SFH vs. MFH):

Compared to households living in multi-family buildings, households living in single-family homes report significantly and substantially lower replacement hazards. Estimated hazard rates for single family houses range between 0.59 for façades and 0.88 for the heating system, suggesting that households living these types of houses are replacing façades at a 31% lower rate and the heating system at a 12% lower rate than otherwise comparable households living in multi-family buildings. These findings reflect earlier results on dwelling-specific differences in renovation behaviour in Switzerland. They found that renovation rates, in particular for energy-efficiency upgrades, are substantially lower in single-family homes (for a recent meta-analysis of Swiss findings, see Jakob et al. [4]).[41] One reason for this difference could be that the cost of renovation is lower for households residing in apartments as fixed costs are distributed over more parties and some elements, such as heating systems or roofs, are jointly used by all parties.

Regions and cantons:

We find limited evidence that households situated in Western Switzerland (Espace Mittelland West and Romandie) have lower replacement rates for windows and heating systems than the households in the rest of the country, while no relationship could be established for the remaining two elements (roof and façade). Notably, differences in replacement rates tend to disappear when allowing for canton-specific baseline hazard rates, suggesting that differences in rates across geographical regions may be related to cantonal regulations.

Urban location:

Dwellings standing outside urban centres tend to have higher replacement rates than comparable dwellings in the city. One possible reason for this may lie in an increased logistical effort related to renovations taking place in densely populated areas. Except for heating systems and roofs, for which we find no significant differences in renovation rates along the rural-urban continuum, buildings constructed in the agglomeration or the countryside show about 25% higher renovation rates than buildings found in city centres. One reason for this substantial and significant difference in replacement rates could be related to the fact that the number of historic buildings under preservation order is substantially higher in inner city areas, than in the agglomeration or the countryside where a majority of buildings was erected in more recent years. Lehman et al. also identify preservation orders as one of the most important barriers to energy upgrades of façades and windows [6]. Alternatively, one can imagine that demand for living space is considerably higher in inner cities, driving up prices for real estate and thus reducing owners' incentives or (financial) possibilities to renovate their property.

Risk aversion:

There is tentative evidence for an association between replacement rates and the respondent's risk attitudes, at least for windows and heating systems, with renovation rates increasing in risk tolerance in the financial domain. These results are similar to findings by Farsi [29], who also finds that risk attitudes are linked with willingness to pay for energy efficient home improvements. They underline the conclusion

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[41] Notably, previously estimated differences in replacement rates between the two types of buildings are also similar in size to the ones identified in the SHEDS. For instance, among buildings constructed after 1990, Jakob et al. (2014) find that renovation rates for energy-efficient upgrades are between 55% (basement ceiling) and 14% (façades) lower among single family homes as compared to multi-family buildings.

that policy incentives such as subsidies or tax breaks reducing the financial risks associated with energy-efficient upgrades are likely to foster their diffusion. A notable exception are renovations or replacements of roofs and facades, where higher risk tolerance has no significant impact.

Element cohort (after 1990) & building cohort (after 1990):

For all building elements, we find that both element cohort and building cohort tend to be related to replacement hazards.

First, results suggest that elements belonging to a later installation cohort (i.e. those who were installed after 1990) show substantially higher replacement hazards, with coefficient estimates ranging from 1.83 (roof) to 4.23 (heating system) times the replacement rate of elements installed in 1990 or before. This general finding remains unaffected when simultaneously controlling for an identically defined dwelling cohort (i.e., whether the building, in which the element is installed, was constructed after 1989). That is, elements belonging to a more recent cohort tend to face higher replacement risk at each stage of their service life. This finding is line with an earlier analysis by Meyer et al., who likewise report a contraction of building element life-cycles among more recently installed elements [10]. Given that, we control for the financial well-being of the household, this result indicates that – as suggested in this earlier study – either usage intensity has increased or material quality deteriorated over time.

Interestingly, we find the opposite effect for the relationship between building age and replacement hazard. Indeed, we observe that buildings constructed after 1990 generally show lower replacement hazards over their lifetime than buildings constructed in 1990 or before. This result is, however, sensitive to model specification. When both element cohort and building cohort are included, the coefficient of buildings constructed after 1990 is substantially and significantly below one. However, when the element cohort is excluded from the model, we observe a significantly lower replacement hazard for newer buildings only for one of the four elements (roof). Thus, results suggest that while replacing a roof is less likely among newer buildings, there is no robust evidence of a similar effect for heating systems, façades or windows.

The inconclusive estimates of the building cohort's effect are not surprising. The two cohort dummies are highly correlated, such that the magnitude of coefficients is likely subject to important estimation errors arising from this multi-collinearity. Yet, we note that our estimations with various cohort definitions (including different cut-off years for elements and building) point to a general tendency (even though not always statistically significant), namely that replacement cycles are shorter among more recently installed elements (and older buildings). For example, we found identical tendencies using a three-tier building cohort,[42] or when shifting the threshold of the element cohort 10 years in either direction.

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[42] That is, we split the building age distribution at the construction years 1970 and 2000, yielding the cohorts "constructed before 1970" (33% in the entire SHEDS sample), "constructed between 1970 and 1999" (35%) and "constructed after 1999" (32%).

Conclusions

The empirical analyses presented in this work package (WP2) can shed light on renovation behaviour in Switzerland’s residential building sector. They can contribute to the political debate and to the empirical assessment of renovation policy measures. Moreover, they are useful to environmental researchers and market developers for predicting the time span required for the diffusion of technological innovations for the built environment, and provide information on the structure of these diffusion processes. Finally, they provide valuable insights for comparing technically determined survival and replacement rates in building construction norms and literature sources.

Descriptive survival analysis of reported renovation behaviour reveals a number of important patterns in performing retrofit and replacement works. In the following, consistent and important patterns are emphasized and their policy implications are discussed:

- Renovation cycles vary considerably across elements. The median survival time of façades and roofs is between 1.5 and two times longer (45 to 59 years) than the medium survival time of windows and the heating system (25 to 36 years). From a global renovation perspective, this can be problematic as the building’s potential energy savings will be limited to the solely renovated elements and suboptimal renovations are likely. For instance, installing a more efficient heating system is not ideal if substantial heat loss continues through the building envelope (e.g., due to single glazed windows or not isolated external walls). This problem will be exacerbated if the reduced relative heating costs lead to an increase in the residents demand for indoor temperatures – a phenomenon, known as the rebound effect, which has likewise been found among Swiss residents [30]. One important implication for energy policy which derives from these considerations is that financial incentives for energy-efficient renovations of one building element should depend to a certain extent on the state and efficiency of the remaining elements, favouring general overhauls over partial ones. Similar policies have already been partially implemented at the cantonal level. For instance, in Valais the amount of subsidies that can be received for energy upgrades can depend, among other factors, on the change in the energy label that results from the renovation [31].
- Renovations of several elements in parallel are not uncommon in Switzerland. We find that a non-negligible number of respondents have renovated several elements at the same time. Combinations of elements from the building envelope (window, façade, roof) are more frequent than combinations of the envelope with the heating system.
- Survival curves for all elements, and in all sub-elements follow a similar sigmoid pattern with few replacements being observed for an initial period of 10 to 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. After this inflection point, replacement rates fall to a constant fraction of remaining, relatively old elements being replaced every year. This indicates that there is a tendency among certain groups of the population to delay replacements of elements long after their economic (and potentially also their technical) service life has been reached. These parts of the population therefore present a natural target group for policies incentivizing and supporting energy-efficient renovations.
- This evolution of replacement propensity with element age also highlights that assuming constant replacement rates independent of the element 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 the age of elements are between 30 and 50 years. Taking account of the age-structure of the element stock would therefore help to improve this kind of predictions.
- Comparing literature-based (i.e., the global sample of WP1 data and Swiss CRB data) with empirical survival curves, we find that, in central tendency, observable and technically predicted renovation timing coincides. That is, across all elements the period after which 50% of elements in the SHEDS have been replaced roughly corresponds to the period that would be predicted

based on various norms. This is particularly true for elements of a building's envelope, such as the windows, the façade and the roof.

- With the exception of heating systems, we likewise observe that this similarity in central tendency is higher when constructing survival curves based on literature service lives provided by the CRB for Switzerland, than when using the global sample from the WP1 study. This suggests that despite the strong international trade in products and services in the building sector, leading to a high comparability of technical product and installation standards, regional and national specificities in replacement behaviours persist. This may be due to various factors, but could also be related to differences in building traditions.
- Independent of the norm's origin, we observe that discrepancies between empirical replacement timing and ones predicted from WP1 grow when moving away from the centre of the survival distribution. That is literature data (norms and other sources), systematically under-estimate 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, although it is more pronounced among survival curves constructed from RSL information. That is, there is a considerable number of elements that are replaced well before norms would predict such a behaviour. At the same time, there is a substantial proportion of elements that remain in the initial state long after norms would predict that they have been replaced. From a policy perspective, there are two – somewhat contrasting – conclusions that can be drawn from this observation. Which one dominates depends on the primary function that norms and literature-based information are supposed fulfil in the building environment. If they are primarily there to describe the technically or environmentally optimal timing of renovation works, then the observed discrepancy between literature and empirical element survival suggests that there is a considerable number of home-owners who execute sub-optimal replacements, and shifting renovation timing among this group would yield comparatively large economic and environmental benefits. On the other hand, if the chief function of norms is to provide guidelines for the prediction and planning of replacement cycles, then the observed differences indicate that the norms and literature sources are likely to gain in predictive accuracy when accounting for them. One way to improve the predictive power of existing literature sources and especially the building norms, would therefore be to work with age-specific replacement probabilities rather than fixed replacement periods.

Results from survival regression models reveal a number of factors that are systematically associated with the replacement hazard of the four elements under investigation. These analyses are helpful for identifying potential barriers for renovation and thus provide information to judge competing policies. While there is some variation in the relationship across the different elements, there are a number of common patterns that emerge across. In the following, the main results are summarised:

- We observe 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. While this phenomenon has already been identified in previous studies [4], it is nevertheless surprising as, particularly in buildings owned by several parties, coordination costs can be conjectured to be substantial. Yet, estimation results suggest that these coordination costs are likely to be outweighed by the economies that pooling resources over multiple owners generates. It underlines the common finding that financial constraints tend to play a key role in preventing or delaying renovation works (see also below).
- There is likewise robust evidence that survival time decreases considerably along the urban-rural continuum. Dwellings situated in rural areas and the agglomeration tend to have significantly and substantially higher replacement rates than otherwise comparable buildings found in city-centres.
- 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. This interpretation is supported by results on the link between risk attitudes and renovation behaviour, showing that replacement of two out of four elements

(windows, heating system) occurs earlier in households whose respondent is more inclined towards financial risk taking. Renovating one's dwelling is essentially a risky activity whose financial benefits depend on a number of uncertain future developments, including house and energy-fuel prices. Thus, financial incentives can reduce the associated financial risks. As a note of caution, it should be stressed that point estimates of household wealth and risk attitude are not consistently significant across elements and model specifications.

- 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 [3], [10]. 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.

There are a number of limitations to the present research. In particular, relying on self-reported retrospective replacements makes our estimates vulnerable to (potentially systematic) errors of recall. While we find only limited evidence that it strongly biases our results, we cannot exclude that some bias persists. Similar analyses based on different data, ideally derived from public registers, would therefore provide an important complement to the current findings. Moreover, although we have tried to differentiate between energy-related renovations and non-energy-related refurbishments, the severely limited item response rate rendered this effort futile. Therefore, reported renovations refer to major retrofits, but potentially include minor upgrades and repairs, as well. The empirical service life investigated in this WP therefore encompasses both kinds of renovations. This is well-reflected by the fact that average replacement rates using the frequency-based method (see, section 3) fall between the renovation rates of general maintenance activities and energy-related renovations reported in the previous literature. A more detailed analysis restricting the sample to major energy-efficiency renovations would be a valuable addition to the present results, and would allow to judge to what extend smaller element refurbishments drive current findings.

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 data set 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.

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Appendix 1: section of the SHEDS survey for 2017 & 2018

SHEDS 2017 wave: Accommodation section (excluding questions on mobility)
The modifications done in the SHEDS 2018 wave are reported in **blue font**

accom_change
Within the last 12 / 24 months, has your living situation changed, i.e., have you moved or bought the accommodation you live in?
○ Yes (1)
○ No (0)

accom1
Regarding your accommodation, you are...
○ Owner (1)
○ Tenant (2)
○ Living in a cooperative (3)

accom1a
*Only displayed to "Tenants" in **accom1**.*
Your landlord is:
○ a private person (1)
○ a private company (insurance, pension fund, real estate firm, construction firm, Swisscom, SBB/CFF, ...) (2)
○ a public institution (city, canton, ...) (3)
○ Other/I don't know (-1)

accom2a
What type is your accommodation?
○ Flat in a building with less than 5 flats (2)
○ Flat in a building with 5 to 10 flats (3)
○ Flat in a building with more than 10 flats (4)
○ Detached house (5)
○ Semi-detached house (6)
○ Terraced house (7)

accom2b

Only displayed if the respondent indicated living in a flat in ***accom2a****.*

How many floors are there in your building? (Only integers, no decimals)

- ___________

accom2c

Only displayed if the respondent indicated living in a house in ***accom2a****.*

How many floors are there in your house? (Only integers, no decimals)

- ___________

accom2d

Change in SHEDS 2018: this question is not only asked to people who live in houses.

What is the type of roof on your home or the house you live in?

○ Flat roof (1)
○ Gabled roof (2)
○ I don't know/I don't remember (-1) *(new item in SHEDS 2018)*

accom2e

What is type of façade on your home or the house you live in?

○ Compact (1)
○ Ventilated (2)
○ I don't know/I don't remember (-1)

accom3

Since when do you live in your current accommodation?

○ yyyy (year if ≥ 1950) *Change in SHEDS 2018: lower bound decreased from 1970 to 1950*
○ Before 1950 (1949)
○ I do not know (-1)

accom4a1

Can you please tell us the year of construction of your building?

(This value cannot be larger than the indicated year of entry in the accommodation.)

○ Year of construction: ___________ (yyyy)
○ I do not know (-1)

accom4a2

*Only displayed if the respondent ticked "I do not know" in **accom4a1**.*

You said, you were not sure in which year your accommodation was constructed. Can you tell us an approximate time period?

○ 2010 or later (1)
○ 2005-2009 (2)
○ 2000-2004 (3)
○ 1995-1999 (4)
○ 1990-1994 (5)
○ 1985-1989 (6)
○ 1980-1984 (7)
○ 1975-1979 (8)
○ 1970-1974 (9)
○ 1965-1969 (10)
○ 1960-1964 (11)
○ Before 1960 (12)
○ I do not know (-1)

accom5

What is the size of the living area in your accommodation?

- m^2: __________

accom6

Your accommodation contains...

	0 (0)	1 (1)	2 (2)	3 (3)	4 (4)	5 or more (5)
Rooms (including kitchen)	○	○	○	○	○	○
Bathrooms, toilets	○	○	○	○	○	○
Other spaces (e.g., cellar, garage, winter garden)	○	○	○	○	○	○

accom7

Does your accommodation conform with the Minergie standard or better standards?

○ Yes (1)
○ No (0)
○ I do not know (-1)

accom8

Which of the following devices is your accommodation equipped with?

For each device 0 = no, 1 = yes.

☐ Photovoltaic solar panels (to produce electricity)
☐ Solar thermal panels (to produce hot water)
☐ Heat pump
☐ None *(this answer is exclusive)*
☐ I do not know *(this answer is exclusive)*

accom9a1

Change in SHEDS 2018: number of elements reduced from 8 to 4 (windows, heating system, façade, roof).

In which year were the following elements refurbished or renovated for the last time?

*Note that we have restricted the possible answers. Only years following the year of construction of your home are displayed. As a reminder, you said that your home was built in: yyyy (from **accom4a1** or **accom4a2**). If this is not correct, please go back to that question and enter the right year or period.*

	Year (yyyy)	There was no renovation since construction (-4)	A renovation took place but I do not know when (-3)	I do not know (-1)
Windows	dropdown list: 2018, 2017, … 1901, 1900 (= 1900 or before)	❍	❍	❍
Heating system		❍	❍	❍
Façade		❍	❍	❍
Roof		❍	❍	❍
Basement		❍	❍	❍
Kitchen		❍	❍	❍
Extension (please specify):		❍	❍	❍
Other (please specify):		❍	❍	❍

accom9a2

Change in SHEDS 2018: number of elements reduced from 8 to 4 (windows, heating system, façade, roof).

*Only displayed if the respondent ticked at least one element in the column "A renovation took place but I do not know when" in **accom9a1**.*

You said, you were not sure in which year exactly the following renovations have taken place. Can you tell us an approximate time period?

*Note that we have restricted the possible answers. Only years following the year of construction of your home are displayed. As a reminder, you said that your home was built in: yyyy (from **accom4a1** or **accom4a2**). If this is not correct, please go back to that question and enter the right year or period.*

Only elements for which the respondent indicated "A renovation took place but I do not know when" in **accom9a1** are displayed.

	2010 or later (1)	2005-2009 (2)	2000-2004 (3)	1995-1999 (4)	1990-1994 (5)	1985-1989 (6)	1980-1984 (7)	1975-1979 (8)	1970-1974 (9)	1965-1969 (10)	1960-1964 (11)	Before 1960 (12)	I do not know (-1)
Windows	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Heating system	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Façade	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Roof	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Basement	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Kitchen	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Extension	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Other	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

accom9b

Change in SHEDS 2018: this question has been removed.

Only displayed if the respondent indicated being owner in ***accom1*** *and if "no renovation took place since the construction" has been indicated for all elements (optionally for extension and other) in* ***accom9a1****.*

You said, no renovation took place in your accommodation since it was constructed. Do you plan anything related to the following elements for the next 2-3 years?

	Yes (1)	No (0)
Windows	○	○
Heating system	○	○
Façade	○	○
Roof	○	○
Basement	○	○
Kitchen	○	○
Extension	○	○
Other	○	○

accom9c1_1

Only displayed if the respondent indicated a year of renovation for Windows in ***accom9a1*** *or a range of years for Windows in* ***accom9a2****.*

You said, that the **windows** in your building have been renovated. Can you tell us how old the replaced/renovated **windows** were at the time of renovation?

Please choose "The last renovation was the only one", when there was only a single renovation done for the element.

Note that answer possibilities have again been restricted based on the construction year of the building and the reported year of renovation.

○ Age in years of renovated windows: *1 (= 1 or less), 2, …, 99, 100 (= 100 or older)*
○ The last renovation was the only one (-3)
○ I do not know (-1)

accom9c1_2

Only displayed if the respondent indicated a year of renovation for Heating system in ***accom9a1*** *or a range of years for Heating system in* ***accom9a2****.*

You said, that the **heating system** in your building have been renovated. Can you tell us how old the replaced/renovated **heating system** was at the time of renovation?

Please choose "The last renovation was the only one", when there was only a single renovation done for the element.

Note that answer possibilities have again been restricted based on the construction year of the building and the reported year of renovation.

○ Age in years of renovated heating system: *1 (= 1 or less), 2, …, 99, 100 (= 100 or older)*
○ The last renovation was the only one (-3)
○ I do not know (-1)

accom9c1_3

Only displayed if the respondent indicated a year of renovation for Façade in ***accom9a1*** *or a range of years for Façade in* ***accom9a2****.*

You said, that the **façade** in your building has been renovated. Can you tell us how old the replaced/renovated **façade** was at the time of renovation?

Please choose "The last renovation was the only one", when there was only a single renovation done for the element.

Note that answer possibilities have again been restricted based on the construction year of the building and the reported year of renovation.

○ Age in years of renovated façade: *1 (= 1 or less), 2, …, 99, 100 (= 100 or older)*
○ The last renovation was the only one (-3)
○ I do not know (-1)

accom9c1_4

Only displayed if the respondent indicated a year of renovation for Roof in ***accom9a1*** *or a range of years for Roof in* ***accom9a2****.*

You said, that the **roof** on your building has been renovated. Can you tell us how old the replaced/renovated **roof** was at the time of renovation?

Please choose "The last renovation was the only one", when there was only a single renovation done for the element.

Note that answer possibilities have again been restricted based on the construction year of the building and the reported year of renovation.

○ Age in years of renovated roof: *1 (= 1 or less), 2, …, 99, 100 (= 100 or older)*
○ The last renovation was the only one (-3)
○ I do not know (-1)

accom9c2

Change in SHEDS 2018: this question has been removed.

Only displayed if the respondent ticked at least one item in the column "I do not know the age of the old equipment when it was replaced" in ***accom9c1****.*

You said, you were not sure how old the replaced equipment was at the last renovation. Can you tell us an approximate age?

Only items for which the respondent ticked "I do not know the age of the old equipment when it was replaced" in ***accom9c1*** *are displayed.*

	0-4 years (1)	5-9 years (2)	10-14 years (3)	15 -19 years (4)	20-24 years (5)	25-29 years (6)	30-34 years (7)	35-39 years (8)	40-44 years (9)	45-49 years (10)	50 years or older (11)	I do not know (-1)
Windows	○	○	○	○	○	○	○	○	○	○	○	○
Heating system	○	○	○	○	○	○	○	○	○	○	○	○
Façade	○	○	○	○	○	○	○	○	○	○	○	○
Roof	○	○	○	○	○	○	○	○	○	○	○	○
Basement	○	○	○	○	○	○	○	○	○	○	○	○
Kitchen	○	○	○	○	○	○	○	○	○	○	○	○
Extension	○	○	○	○	○	○	○	○	○	○	○	○
Other	○	○	○	○	○	○	○	○	○	○	○	○

accom9d

Only displayed if the respondent indicated a year of renovation for at least one element in ***accom9a1*** *or a range of years for at least one element in* ***accom9a2****.*

You have reported that the following element(s) were renovated. Can you please tell us the main reason for their last renovation or overhaul?

Multiple answers possible.

Only elements for which the respondent did not select "There was no renovation since construction" in ***accom9a1*** *are displayed.*

	Saving Energy	Reducing energy costs	Rise in CO2 tax	Benefitting from subsidies	Improve comfort	Aesthetics	Equipment was outdated	General maintenance	Other	I don't know (new item in SHEDS 2018)
Windows	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Heating system	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Façade	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Roof	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

accom9e2_1

Only displayed if the respondent indicated a year of renovation for Heating system in ***accom9a1*** *or a range of years for Heating system in* ***accom9a2****.*

Can you tell us, which parts of the heating system were changed?

○ Boiler/Furnace (1)
○ Tubing and/or radiators (2)
○ Both (3)
○ Something else/I don't know/I don't remember (-1)

accom9e2_2

Only displayed if the respondent selected "Boiler/Furnace" or "Both" in ***accom9e2_1****.*

You said that the boiler or furnace has been changed. Can you please tell us, what energy source the replaced system relied on for ... ?

	Oil (1)	Gas (2)	Electricity (3)	Wood (4)	Heat pump (5)	Solar (6)	District heating (7)	Other (8)	I do not know (-1)
heating	○	○	○	○	○	○	○	○	○
warm water	○	○	○	○	○	○	○	○	○

accom9e3_1

Only displayed if the respondent indicated a year of renovation for Façade in ***accom9a1*** *or a range of years for Façade in* ***accom9a2****.*

Can you tell us, of which type the replaced or renovated façade was?

○ Compact (1)
○ Ventilated (2)
○ I don't know/I don't remember (-1)

accom9e3_2

Only displayed if the respondent indicated a year of renovation for Façade in ***accom9a1*** *or a range of years for Façade in* ***accom9a2****.*

More concretely, was the façade repainted, repaired or replaced?

Please choose the most relevant answer.

○ Repainted (1)
○ Repaired (2)
○ Replaced (3)
○ I don't know/ I don't remember (-1)

accom9e4_1

Only displayed if the respondent indicated a year of renovation for Façade in ***accom9a1*** *or a range of years for Façade in* ***accom9a2****.*

You said, that the roof had been renovated in your home. Can you please tell us, the type of the replaced or renovated roof.

○ Flat roof (1)
○ Gabled roof (2)
○ I don't know/I don't remember (-1)

Appendix 2: Detailed results from the survival estimations

This section presents detailed results from survival regressions using the SHEDS data. Estimations follow the same strategy for each element. That is, for each the first column gives an estimation using the full sample. Ensuing columns then present estimations for the sample of owners using different specifications and sample restrictions. More precisely, column (2) gives results from a specification identical to the one in column (1), while column (3) gives point estimates including canton-specific baseline hazards. To demonstrate the robustness of these findings with respect to the chosen outlier threshold, column (4) gives results for a sample excluding all observations with survival times exceeding 50 years, and column (5) gives results excluding all buildings constructed prior to 1960 as SHEDS is particularly unrepresentative for this building cohort.

Columns (6) to (8) present results when additionally controlling for risk attitudes and entry cohort dummies of element and building. Cohort dummies identify elements/buildings that were installed/constructed after 1990 (or before), and thus additionally permit to judge whether replacement rates change systematically over the life cycle of building and element. Finally, the remaining columns (9) and (10) give the findings for a set of estimations aiming to evaluate the robustness of the preceding findings with respect to influential observations and main reasons for renovation or replacement. For example, from an energy policy perspective, refurbishments that are merely for aesthetic reasons such as repainting the façade are less relevant than more fundamental changes in the building envelope such as changing the insulation layer. For this reason, column (9) excludes all (censored) observations stating that the reason for the reported renovation was mainly aesthetical or due to general maintenance. Finally, column (10) excludes all observations that are identified as influential points based on the fact that excluding them exerts a substantial influence on the value of any of the estimated coefficients. In particular, an observation was classified as influential if differenced beta values for this observation were in the top or bottom percentile of the differenced-beta distribution.[43]

It is important to note that point estimates in all models are given as hazard ratios rather than coefficients. For deriving t-statistics from point estimates and standard errors, it is therefore important to remember that statistical tests must be interpreted against the Null: $H_0\colon \beta_k = 1$ rather than against zero, which is the more common value of the Null hypothesis in regression analysis.

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[43] The basic idea of this exercise is to evaluate the leverage of each observation by comparing the coefficient $\hat{\boldsymbol{\beta}}_{\boldsymbol{k}}$ based on all observations with an estimate $\hat{\boldsymbol{\beta}}_{\boldsymbol{k}}^{\boldsymbol{i}}$ obtained by excluding observation i. If $\hat{\boldsymbol{\beta}}_{\boldsymbol{k}} - \hat{\boldsymbol{\beta}}_{\boldsymbol{k}}^{\boldsymbol{i}}$ is close to zero, the individual observation i has little influence on the estimate. Inversely, the larger the difference in estimated coefficients the more influential a single observation on the estimated coefficients. Following Cleves et al. [27], we do not estimate $n+1$ models but approximate the distribution of differenced betas based on efficient score residuals.

Table 10: Cox estimation results for windows

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners^{a}	Owners^{b}
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Size of living space (log m^{2})	0.9097*	0.9551	1.0020	1.0053	0.9689	0.9892	1.0065	1.0703	0.9318	1.0178
	(0.0444)	(0.0700)	(0.0785)	(0.0759)	(0.0882)	(0.0771)	(0.0791)	(0.0866)	(0.0761)	(0.0698)
Monthly household income group in year of interview (ref.: Bottom)										
Middle	1.0170	0.9811	0.9991	1.0391	1.1523	0.9907	0.9922	0.9554	0.9450	0.9723
	(0.0642)	(0.1105)	(0.1192)	(0.1301)	(0.1865)	(0.1198)	(0.1193)	(0.1147)	(0.1161)	(0.1017)
Top	0.9904	1.0253	1.0437	1.0894	1.2250	0.9892	1.0335	0.9537	0.9814	0.9700
	(0.0664)	(0.1107)	(0.1216)	(0.1329)	(0.1990)	(0.1190)	(0.1219)	(0.1147)	(0.1132)	(0.1001)
Missing income	0.9836	0.9759	0.9828	1.0834	1.2367	0.9389	0.9811	0.9199	0.9357	0.9351
	(0.0802)	(0.1241)	(0.1329)	(0.1558)	(0.2290)	(0.1293)	(0.1338)	(0.1284)	(0.1327)	(0.1191)
House type (ref.: Multi-family house)										
Single family house	1.0011	0.8602*	0.8015***	0.9019	0.8274*	0.8417**	0.7921***	0.7755***	0.8593	0.7428***
	(0.0499)	(0.0695)	(0.0650)	(0.0780)	(0.0857)	(0.0695)	(0.0645)	(0.0643)	(0.0806)	(0.0564)
Region (ref.: Ostmittelland)										
Suisse romande	0.7604***	0.8253**	1.1453	0.8285**	0.7915*	1.1683	1.1360	1.1401	0.7317***	0.7285***
	(0.0502)	(0.0763)	(0.2916)	(0.0771)	(0.0947)	(0.2983)	(0.2917)	(0.3095)	(0.0758)	(0.0670)
Alpen und Voralpen	0.9056*	0.9233	0.8778	0.8684	0.9399	0.8545	0.8735	0.9384	0.8716	0.8466*
	(0.0543)	(0.0854)	(0.1969)	(0.0837)	(0.1081)	(0.1894)	(0.1966)	(0.2235)	(0.0885)	(0.0755)
Westmittelland	0.8622***	0.8387**	1.0233	0.8364*	0.7876**	1.0047	1.0238	1.0649	0.8265**	0.6539***
	(0.0488)	(0.0716)	(0.1782)	(0.0765)	(0.0915)	(0.1749)	(0.1790)	(0.2055)	(0.0803)	(0.0593)
Urbanity (ref.: City)										
Agglomeration	1.0826	1.2191***	1.2650***	1.1577*	1.2937**	1.2289**	1.2711***	1.3218***	1.2042**	1.3430***
	(0.0540)	(0.0919)	(0.1050)	(0.0950)	(0.1354)	(0.1013)	(0.1050)	(0.1066)	(0.1056)	(0.1099)
Countryside	1.0205	1.2280**	1.2808***	1.1577*	1.1664	1.2301**	1.2882***	1.2735***	1.2094**	1.4639***
	(0.0568)	(0.1005)	(0.1123)	(0.1022)	(0.1412)	(0.1084)	(0.1124)	(0.1134)	(0.1109)	(0.1251)
Risk attitudes (ref.: Risk averse)										
Rather risk averse						1.0847	1.0512	1.1164		
						(0.0895)	(0.0870)	(0.0913)		
Risk neutral						1.1191	1.1041	1.1536*		
						(0.0947)	(0.0932)	(0.0967)		
Risk seeking or rather risk Seeking						1.0833	1.0768	1.0362		
						(0.1284)	(0.1296)	(0.1254)		

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners[a]	Owners[b]
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Window cohort (ref.: installed in 1990 or before)										
installed after 1990						3.3061***		19.7042***		
						(0.3815)		(2.4278)		
Building cohort (ref.: built 1990 or earlier)										
built after 1990							0.8070	0.0743***		
							(0.1134)	(0.0119)		
Survey year (ref.: 2017)										
2018	0.7477***	0.8055***	0.7927***	0.8517**	0.8525*	0.7902***	0.7944***	0.7736***	0.8418**	0.7486***
	(0.0350)	(0.0552)	(0.0554)	(0.0601)	(0.0751)	(0.0551)	(0.0561)	(0.0539)	(0.0621)	(0.0530)
Stratified by canton	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of subjects	4568	2167	2167	2017	1708	2167	2167	2167	1951	2006
No. of renovations	2335	1026	1026	893	584	1026	1026	1026	810	910
Years at risk	121487	55975	55975	45867	36309	55975	55975	55975	48590	47921

*** p<0.01, ** p<0.05, * p<0.1

Table 11: Cox estimation results for heating systems

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners[a]	Owners[b]
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Size of living space (log m^2)	1.1559***	1.1109	1.1308*	1.1207*	1.2334**	1.0951	1.1221*	1.1073	1.1109	1.1423*
	(0.0569)	(0.0735)	(0.0764)	(0.0771)	(0.1089)	(0.0745)	(0.0757)	(0.0771)	(0.0804)	(0.0872)
Monthly household income group in year of interview (ref.: Bottom)										
Middle	1.0143	1.1286	1.1458	1.1584	1.1490	1.1182	1.1417	1.0258	1.1456	1.2961**
	(0.0668)	(0.1188)	(0.1304)	(0.1372)	(0.1615)	(0.1307)	(0.1291)	(0.1162)	(0.1297)	(0.1514)
Top	1.1082	1.2620**	1.3117**	1.3287**	1.4098**	1.1634	1.2636**	1.1381	1.2527*	1.4291***
	(0.0818)	(0.1407)	(0.1556)	(0.1653)	(0.2063)	(0.1414)	(0.1495)	(0.1358)	(0.1480)	(0.1685)
Missing income	1.0312	1.3179**	1.3636**	1.4398***	1.4595**	1.2316	1.3313**	1.1912	1.3137**	1.6775***
	(0.0935)	(0.1671)	(0.1834)	(0.1908)	(0.2375)	(0.1684)	(0.1780)	(0.1614)	(0.1777)	(0.2160)
House type (ref.: Multi-family house)										
Single family house	1.1149**	0.9112	0.8160***	0.8936	0.8587	0.9192	0.8331**	0.8687*	0.9781	0.8338**
	(0.0583)	(0.0709)	(0.0627)	(0.0713)	(0.0862)	(0.0723)	(0.0651)	(0.0686)	(0.0860)	(0.0638)
Region (ref.: Ostmittelland)										
Suisse romande	0.8523**	0.8646*	1.1199	0.8912	0.8451	1.0862	1.1250	1.1862	0.8606	0.8032**
	(0.0551)	(0.0734)	(0.3352)	(0.0836)	(0.0959)	(0.3383)	(0.3396)	(0.3616)	(0.0808)	(0.0788)
Alpen und Voralpen	1.0535	1.0297	0.9697	1.0148	1.0260	0.9070	0.9598	1.0139	1.0325	1.0725
	(0.0636)	(0.0871)	(0.2436)	(0.0895)	(0.1088)	(0.2427)	(0.2420)	(0.2776)	(0.0950)	(0.0967)
Westmittelland	1.0068	0.9816	0.9225	1.0190	0.9917	0.9259	0.9254	0.9838	0.9784	0.9730
	(0.0630)	(0.0837)	(0.1868)	(0.0845)	(0.1097)	(0.2014)	(0.1896)	(0.2176)	(0.0930)	(0.0867)
Urbanity (ref.: City)										
Agglomeration	1.0261	1.0731	1.1039	0.9645	0.9807	1.0047	1.0896	1.0786	0.9803	1.0323
	(0.0568)	(0.0832)	(0.0897)	(0.0763)	(0.0980)	(0.0810)	(0.0895)	(0.0886)	(0.0829)	(0.0843)
Countryside	1.0346	1.0410	1.0378	0.9304	0.8763	0.9728	1.0294	1.0521	0.9863	1.0298
	(0.0615)	(0.0870)	(0.0941)	(0.0776)	(0.0973)	(0.0879)	(0.0939)	(0.0969)	(0.0899)	(0.0877)
Risk attitudes (ref.: Risk averse)										
Rather risk averse						1.1321	1.0805	1.1231		
						(0.0956)	(0.0906)	(0.0939)		
Risk neutral						1.1438	1.1296	1.1382		
						(0.1001)	(0.0983)	(0.1011)		
Risk seeking or rather risk Seeking						1.2781**	1.2088	1.2328*		
						(0.1498)	(0.1424)	(0.1465)		

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners[a]	Owners[b]
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Window cohort (ref.: installed in 1990 or before)										
installed after 1990						4.2376***		10.5860***		
						(0.3699)		(1.0788)		
Building cohort (ref.: built 1990 or earlier)										
built after 1990							1.2830**	0.2280***		
							(0.1360)	(0.0278)		
Survey year (ref.: 2017)										
2018	0.5969***	0.7461***	0.7304***	0.7364***	0.6369***	0.7264***	0.7370***	0.7028***	0.7915***	0.6411***
	(0.0312)	(0.0529)	(0.0527)	(0.0526)	(0.0579)	(0.0529)	(0.0534)	(0.0491)	(0.0606)	(0.0481)
Stratified by canton	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of subjects	4027	2024	2024	1941	1584	2024	2024	2024	1816	1857
No. of renovations	2074	1104	1104	1039	682	1104	1104	1104	896	1004
Years at risk	99494	46559	46559	40849	31272	46559	46559	46559	41300	39042

*** p<0.01, ** p<0.05, * p<0.1

Table 12: Cox estimation results for façades

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners[a]	Owners[b]
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Size of living space (log m^2)	1.0614	1.0817	1.0466	1.1126	1.1362	1.0032	1.0323	0.9884	1.0535	1.1013
	(0.0684)	(0.0972)	(0.0944)	(0.1092)	(0.1410)	(0.0876)	(0.0924)	(0.0842)	(0.1216)	(0.1032)
Monthly household income group in year of interview (ref.: Bottom)										
Middle	0.8903	0.9118	0.9487	0.9028	0.9673	0.9592	0.9447	1.0658	0.8744	0.8889
	(0.0691)	(0.1208)	(0.1298)	(0.1249)	(0.1714)	(0.1320)	(0.1300)	(0.1433)	(0.1576)	(0.1024)
Top	0.8356**	0.9459	0.9687	0.9952	1.0119	0.9173	0.9467	1.0089	0.8913	0.9418
	(0.0737)	(0.1282)	(0.1345)	(0.1419)	(0.1859)	(0.1281)	(0.1324)	(0.1373)	(0.1694)	(0.1167)
Missing income	0.9068	0.9839	1.0348	0.9754	1.0433	0.9787	1.0083	1.0849	0.8586	0.8602
	(0.0884)	(0.1497)	(0.1620)	(0.1615)	(0.2201)	(0.1551)	(0.1589)	(0.1667)	(0.1906)	(0.1247)
House type (ref.: Multi-family house)										
Single family house	0.8593***	0.5827***	0.5823***	0.6828***	0.6098***	0.6390***	0.6002***	0.6303***	0.5315***	0.4726***
	(0.0501)	(0.0534)	(0.0538)	(0.0706)	(0.0735)	(0.0595)	(0.0554)	(0.0588)	(0.0721)	(0.0462)
Region (ref.: Ostmittelland)										
Suisse romande	0.8456**	1.0109	1.3721	1.0067	0.9596	1.4118	1.3711	1.5638	0.7534	0.9714
	(0.0659)	(0.1140)	(0.4762)	(0.1203)	(0.1340)	(0.4888)	(0.4757)	(0.5577)	(0.1383)	(0.1095)
Alpen und Voralpen	0.8964	1.0446	1.0301	0.8905	0.9312	1.0144	1.0154	0.9900	1.1895	0.9897
	(0.0683)	(0.1151)	(0.3310)	(0.1030)	(0.1250)	(0.3336)	(0.3292)	(0.3242)	(0.1811)	(0.1109)
Westmittelland	0.8484**	0.9068	1.3303	0.9126	0.8842	1.3217	1.3252	1.3237	1.0096	0.7679**
	(0.0644)	(0.0901)	(0.3073)	(0.0968)	(0.1121)	(0.3089)	(0.3071)	(0.3158)	(0.1466)	(0.0832)
Urbanity (ref.: City)										
Agglomeration	1.0709	1.2823***	1.3382***	0.9802	1.1133	1.2461**	1.3065***	1.3049***	1.1402	1.5699***
	(0.0701)	(0.1235)	(0.1318)	(0.0980)	(0.1327)	(0.1229)	(0.1285)	(0.1278)	(0.1655)	(0.1513)
Countryside	1.0218	1.2523**	1.3309***	0.9853	0.9709	1.2489**	1.3078**	1.2376*	1.3558**	1.3876***
	(0.0724)	(0.1273)	(0.1465)	(0.1094)	(0.1362)	(0.1370)	(0.1440)	(0.1362)	(0.1934)	(0.1474)
Risk attitudes (ref.: Risk averse)										
Rather risk averse						1.0008	0.9995	0.9498		
						(0.1038)	(0.1027)	(0.0983)		
Risk neutral						1.0496	1.0602	0.9945		
						(0.1124)	(0.1135)	(0.1038)		
Risk seeking or rather risk Seeking						1.0456	1.0365	1.0556		
						(0.1392)	(0.1371)	(0.1408)		

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners[a]	Owners[b]
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Window cohort (ref.: installed in 1990 or before)										
installed after 1990						3.4598***		25.0596***		
						(0.4355)		(4.1942)		
Building cohort (ref.: built 1990 or earlier)										
built after 1990							1.5430***	0.0977***		
							(0.1980)	(0.0172)		
Survey year (ref.: 2017)										
2018	0.5407***	0.5665***	0.5893***	0.6159***	0.5633***	0.5955***	0.5907***	0.6150***	0.9803	0.4677***
	(0.0336)	(0.0509)	(0.0530)	(0.0564)	(0.0652)	(0.0540)	(0.0532)	(0.0556)	(0.1066)	(0.0440)
Stratified by canton	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of subjects	4206	2054	2054	1818	1629	2054	2054	2054	1661	1874
No. of renovations	1564	744	744	619	430	744	744	744	351	643
Years at risk	122366	57939	57939	41263	35064	57939	57939	57939	45639	49378

*** p<0.01, ** p<0.05, * p<0.1

Table 13: Cox estimation results for roofs

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners[a]	Owners[b]
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Size of living space (log m^2)	1.0679	1.0117	0.9825	1.0248	1.0678	0.9720	0.9897	1.0071	0.9821	1.0948
	(0.0754)	(0.0936)	(0.0943)	(0.1037)	(0.1434)	(0.0943)	(0.0957)	(0.0969)	(0.1015)	(0.1297)
Monthly household income group in year of interview (ref.: Bottom)										
Middle	0.9542	0.9077	0.9593	0.8754	1.0013	0.9702	0.9722	0.9370	0.9076	0.9804
	(0.0889)	(0.1403)	(0.1494)	(0.1610)	(0.2212)	(0.1519)	(0.1509)	(0.1434)	(0.1694)	(0.1476)
Top	0.9742	1.0413	1.1209	1.0657	1.2153	1.1174	1.1527	1.0720	1.1100	1.1745
	(0.0982)	(0.1482)	(0.1655)	(0.1958)	(0.2701)	(0.1649)	(0.1682)	(0.1529)	(0.1956)	(0.1786)
Missing income	1.0218	0.9380	1.0131	0.9252	0.9570	1.0009	1.0220	0.9734	0.9971	0.7999
	(0.1164)	(0.1640)	(0.1869)	(0.1974)	(0.2484)	(0.1853)	(0.1879)	(0.1781)	(0.2134)	(0.1492)
House type (ref.: Multi-family house)										
Single family house	0.8021***	0.6693***	0.5991***	0.6540***	0.4689***	0.6207***	0.5891***	0.6043***	0.7665*	0.5408***
	(0.0554)	(0.0727)	(0.0655)	(0.0786)	(0.0675)	(0.0683)	(0.0645)	(0.0647)	(0.1086)	(0.0616)
Region (ref.: Ostmittelland)										
Suisse romande	0.9130	1.0935	1.6389	1.2181	1.1322	1.5829	1.6153	1.3879	0.8017	1.0598
	(0.0786)	(0.1243)	(0.6222)	(0.1618)	(0.1961)	(0.6120)	(0.6184)	(0.5396)	(0.1116)	(0.1381)
Alpen und Voralpen	0.9315	0.9868	0.5479*	1.0409	1.1335	0.5108**	0.5286**	0.4993**	0.9250	0.9843
	(0.0786)	(0.1218)	(0.1693)	(0.1519)	(0.2002)	(0.1622)	(0.1656)	(0.1630)	(0.1317)	(0.1316)
Westmittelland	0.9791	0.9680	0.7960	1.1791	1.2394	0.7762	0.7834	0.7815	0.9192	0.9121
	(0.0807)	(0.1121)	(0.2043)	(0.1521)	(0.2211)	(0.2050)	(0.2027)	(0.2100)	(0.1234)	(0.1077)
Urbanity (ref.: City)										
Agglomeration	1.0079	0.9848	0.9469	0.7239***	0.8257	0.9303	0.9591	1.0084	0.9070	0.9692
	(0.0737)	(0.1048)	(0.1059)	(0.0861)	(0.1232)	(0.1052)	(0.1075)	(0.1156)	(0.1134)	(0.1146)
Countryside	0.9603	0.9126	0.9209	0.6480***	0.6054***	0.9090	0.9333	0.9860	0.9634	0.7985*
	(0.0738)	(0.0997)	(0.1060)	(0.0859)	(0.1110)	(0.1053)	(0.1081)	(0.1156)	(0.1262)	(0.1000)
Risk attitudes (ref.: Risk averse)										
Rather risk averse						0.8715	0.8665	0.8133*		
						(0.0954)	(0.0945)	(0.0903)		
Risk neutral						0.9401	0.9375	0.9325		
						(0.1153)	(0.1152)	(0.1136)		
Risk seeking or rather risk Seeking						0.9282	0.9275	0.8951		
						(0.1489)	(0.1494)	(0.1441)		

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sample	All	Owners	Owners	Owners	Owners	Owners	Owners	Owners	Owners[a]	Owners[b]
Max. survival time (years)		100	100	50	58	100	100	100	100	100
Window cohort (ref.: installed in 1990 or before)										
installed after 1990						1.8310^{***}		26.7773^{***}		
						(0.2798)		(5.8826)		
Building cohort (ref.: built 1990 or earlier)										
built after 1990							0.6741^{**}	0.0367^{***}		
							(0.1308)	(0.0099)		
Survey year (ref.: 2017)										
2018	0.5425	0.5475^{***}	0.5255^{***}	0.5377^{***}	0.4726^{***}	0.5280^{***}	0.5284^{***}	0.5633^{***}	0.6859^{***}	0.3728^{***}
	(0.0353)	(0.0522)	(0.0514)	(0.0638)	(0.0740)	(0.0515)	(0.0518)	(0.0553)	(0.0739)	(0.0406)
Stratified by canton	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of subjects	4043	2061	2061	1802	1628	2061	2061	2061	1869	1878
No. of renovations	1183	586	586	432	258	586	586	586	394	470
Years at risk	120650	59869	59869	41983	36024	59869	59869	59869	53100	51242

*** p<0.01, ** p<0.05, * p<0.1

Appendix 3: Descriptive results for subgroups of elements

Table 14: Descriptive survival statistics for sub-structures and types of elements (SHEDS 2018)

	Survival time (in years)			Total observ-ations	Observed renovations	Years at risk	Annual renovation rate
	25%	50%	75%				
Panel E: Owner-occupied dwellings							
Heating production	22 [20, 24]	32 [30, 35]	47 [42, 53]	609	232	12566	0.0185
Heating distribution	43 [35, 50]	95 [95, NA]	100 [95, NA]	509	86	15583	0.0055
Compact façade	35 [33, 38]	55 [48, 76]	100 [81, NA]	345	100	10607	0.0094
Ventilated façade	35 [28, 36]	52 [35, NA]	100 [52, NA]	98	19	2057	0.0092
Flat roof	30 [26, 37]	40 [34, NA]	100 [41, NA]	180	26	2561	0.0102
Gabled roof	49 [43, 50]	64 [60, 77]	90 [82, NA]	504	122	16396	0.0074

Note: 95% confidence intervals are in brackets. NA = not available (insufficient data for an estimate).

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DUREE Project

WP 3: Uncertainty and sensitivity analysis of service lives in building LCA & LCC

Final report

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Summary

There is a substantial variability among the different data sources used, with regard to the lifetimes of building elements. This fact can lead to inaccurate estimations when performing building related assessments (such as LCA, LCC, etc.). The DUREE project aims at gathering the lifetime values observed in the Swiss and International literature, as well as assessing the effect of this variability on the LCA and LCC analyses, in order to propose best practice recommendations. The current WP3 report presents the uncertainty and sensitivity analyses of the literature-based and empirical lifetimes of the building elements and technical systems derived from the DUREE WP1 and WP2 studies. This methodology is applied to building case studies (new & existing ones), which represent different types of residential buildings of the Swiss building stock. Monte Carlo simulations are performed to evaluate the uncertainty of the lifetimes on the output results, i.e. LCA (greenhouse gas emissions and other indicators) and LCC (Swiss Francs). Finally, a sensitivity analysis follows in order to identify the relative importance of the elements lifetimes' uncertainty on the variability of the LCA and LCC outputs. The results show that the LCA and LCC uncertainty can be significantly influenced by the service lifetime variability of the wall coatings and interior coverings, as well as by that of the building.

Résumé

Il existe une grande variabilité entre les différentes sources de données utilisées en ce qui concerne la durée de vie des éléments du bâtiment, ce qui peut conduire à des estimations inexactes lors de l'évaluation liée au bâtiment (par exemple, écobilan et analyse des coûts sur le cycle de vie respectivement). Le projet DUREE vise à rassembler les valeurs de durée de vie observées dans la littérature suisse et internationale, ainsi qu'à évaluer l'effet de cette variabilité sur les analyses écobilan et analyse des coûts sur le cycle de vie, afin de proposer des recommandations pour la pratique. Le présent rapport du GT3 présente les analyses d'incertitude et de sensibilité des durées de vie empiriques et documentées des éléments de construction et des systèmes techniques dérivés des études DUREE WP1 et WP2. Cette méthodologie est appliquée aux études de cas de construction (nouvelles et existantes), qui représentent différents types de bâtiments résidentiels du parc immobilier suisse. Des simulations de Monte Carlo sont effectuées pour évaluer l'incertitude des durées de vie sur les résultats de l‘écobilan (émissions de gaz à effet de serre et autres indicateurs) et de l’analyse des coûts du cycle de vie (francs suisses). Enfin, une analyse de sensibilité est effectuée afin d'identifier l'importance relative de l'incertitude des durées de vie sur la variabilité des résultats de l’écobilan et de l’analyse des coûts sur le cycle de vie. Les résultats montrent que l’incertitude peut être considérablement influencée par la variabilité de la durée de vie des façades et des aménagements intérieurs, ainsi que de celle du bâtiment.

Zusammenfassung

Zwischen den verschiedenen verwendeten Datenquellen besteht eine erhebliche Variabilität hinsichtlich der Lebensdauer der Bauteile, die zu Fehleinschätzungen bei der Durchführung gebäudebezogener Bewertungen (z.B. Wirtschafts- oder Umweltbewertung, Ökobilanz bzw. LCC) führen kann. Das DUREE-Projekt zielt darauf ab, die in der schweizerischen und internationalen Literatur beobachteten Lebensdauerwerte zu sammeln und die Auswirkungen dieser Variabilität auf die LCA- und LCC-Analysen zu bewerten, um Empfehlungen für die Praxis abzugeben. Dieser WP3-Bericht stellt die Unsicherheits- und Sensitivitätsanalysen der literaturbasierten und empirischen Lebensdauer der Bauelemente und technischen Systeme aus DUREE WP1- und WP2-Studien vor. Diese Methodik wird auf Gebäudefallstudien (neu & bestehend) angewendet, die verschiedene Arten von Wohngebäuden aus dem schweizerischen Gebäudebestand darstellen. Monte-Carlo-Simulationen werden durchgeführt, um die Unsicherheit der Lebenszeiten auf die Produktionsergebnisse der LCA (Treibhausgasemissionen und andere Indikatoren) & LCC (Schweizer Franken) zu bewerten.

Schließlich folgt eine Sensitivitätsanalyse, um die relative Bedeutung der Unsicherheit der Lebenszeiten für die Variabilität des LCA- und LCC-Ergebnisses zu ermitteln. Die Ergebnisse zeigen, dass die Unsicherheit der LCA und LCC beträchtlich ausgewirkt werden kann, von der Variabilität der Lebensdauer der Wandbeschichtungen und Innenverkleidungen, sowie dieser der Gebäudelebensdauer.

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List of abbreviations

DB: database

eCCC-Bât: Code des Coûts de construction Bâtiment

eBKP: Baukostenpläne

eBKP-H: Baukostenpläne Hochbau

BITS: Building Integrated Technical System

CRB: Centre Suisse d'études pour la rationalisation de la construction

FSO : Federal Statistical Office

GHG: GreenHouse Gases

GHGe: GreenHouse Gas emissions

LCA: Life Cycle Assessment

LCC: Life Cycle Cost

LCCA: Life Cycle Cost Analysis

LOD: Level of Details

NPV: Net Present Value

NRE: primary Non-Renewable Energy

UBP: Umweltbelastungspunkten (ecopoints)

PDF: Probability Density Function

SHEDS : Swiss Household Energy Demand Survey

SIA: Société Suisse des Ingénieurs et Architectes

SP: Série de Prix

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Introduction

In the context of designing sustainable buildings, the life cycle assessment has been proven an efficient method to evaluate the deriving environmental impacts of buildings. According to the SN EN 15978:2011 [1], the building LCA consists of the production and construction stage (A1-A3 and A4-A5, respectively), the exploitation stage with the maintenance, replacement, operational energy, water use and other processes (B1-B7) and the disposal at the end of life (C1-C4). Each LCA stage comprises different parameters, which are defined based on measurements, individual expertise or assumptions, derived by generally accepted conventions. Since a building LCA is calculated over a long period of time, i.e., 60 years, one important parameter is the replacement of the building elements and their associated service life. It can contribute significantly to the LCA [2] with a share of up to 36% on the building LCA (expressed in GHG emissions) for a multifamily house.

Errors and uncertainties are inevitably introduced in LCA and LCC analyses and they derive from different sources. Being able to quantify the uncertainty, related to the GHG emissions and economic costs of buildings could improve the designer's control over its environmental and economic impact and hence, increase their reliability. As far as the LCA is concerned, Huijbregts attributes the possible errors to parameter uncertainties, model uncertainties, and uncertainties due to choices [3]. This is the case for the LCC analysis, as well. Based on Huijbregts' classification, the DUREE WP1 reported the parameter uncertainty (and variability) of the theoretical service lives for different building elements, while the DUREE WP2 reported those of the empirical service lives, based on the Swiss Household Energy Demand Survey (SHEDS) [4]. The current WP3 quantifies the impact of the theoretical and empirical uncertainty (and variability) on the LCA and LCC output and identifies the building elements whose variability causes the highest uncertainty on the LCA and LCC analyses on building case studies. Figure 1 presents an overview of this approach.

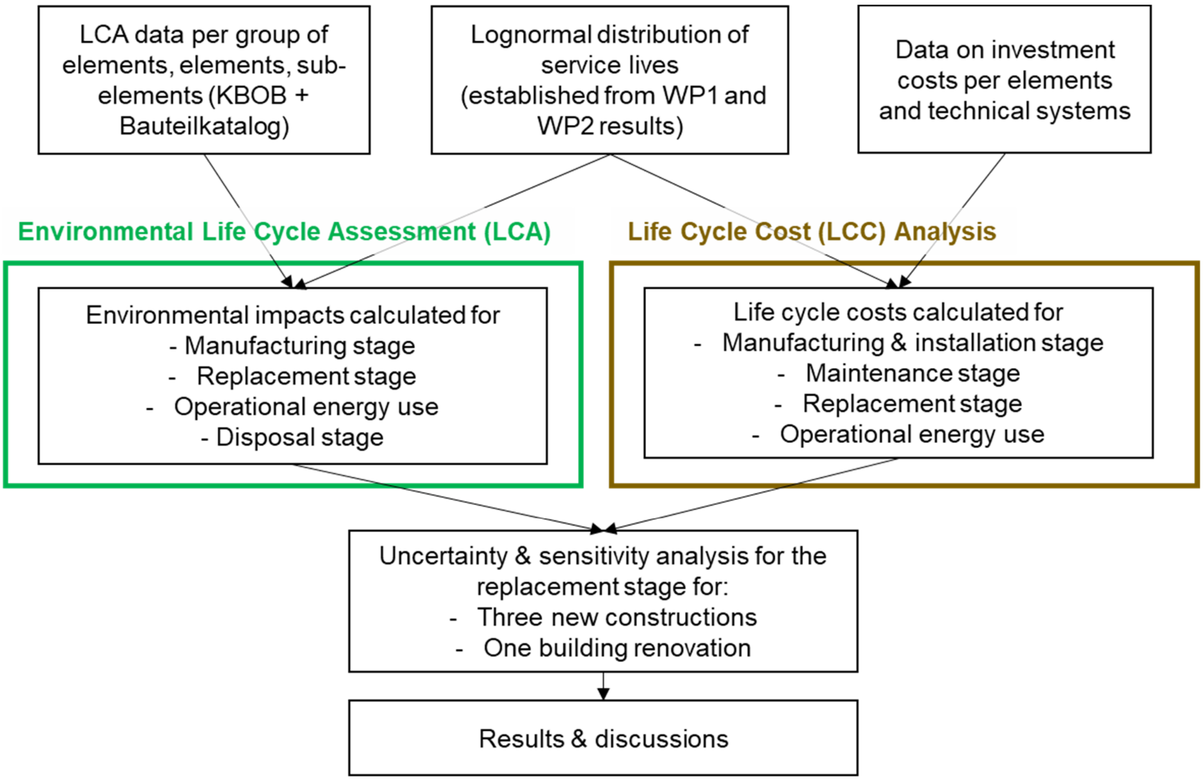

Figure 1: Overview of the approach used in the DUREE WP3 study

1 Methodology and input data

1.1 Analysed building case studies

LCA and LCC analysis are conducted for both new constructions and building renovations. Consequently, the uncertainty of the service lives of the building elements influence both construction types, for all the planning stages of the design procedure of a project (i.e., during early design as well as during the detailed design). The environmental and economic costs of the building renovation can more significantly affect the decisions of the final investment, than for new constructions, since the former is characterised by long payback periods [5], that could exceed the service life of the renovated building.

1.1.1 New constructions

The chosen case studies present different energy surface areas (in order to cover SFH and MFH), energy and ecological performances (SIA 380/1, Minergie-ECO, Minergie-P), structural systems (concrete structure vs. wooden structure) and technical systems (heat pump and district heating). They are located in the canton of Zürich. Table 1 presents the characteristics of the new constructed residential buildings. They have been already used in a preliminary study, investigating the uncertainty of materials' service lives [6].

Table 1: Characteristics of the three new constructed SFH and MFH buildings

General information	**B1**	**B2**	**B3**
Construction type	Medium weight	Light weight	Massive
Materials for the structure	Wood & concrete	Wood & masonry	Concrete & masonry
Type of facade	Compact & ventilated	Compact & ventilated	Compact
Type of roof	Sloping roof	Flat roof	Sloping roof
Energy reference area	350	374	622
Energy standard	Minergie-ECO	Minergie-P	SIA 380/1
Accommodation units	2	3	4
Basement	Yes	No	Yes
Number of floors	3	3	2
Heating & ventilation systems			
Heating device	District heating	Geothermal heat pump	Geothermal heat pump
Energy source	Wood chips	Electricity	Electricity
Solar panels	No	Yes	Yes
Annual energy demand (MJ/m^{2}y)			
Heating	106	70	169
Domestic Hot Water (DHW)	75	21	121
Ventilation	24	3	-

1.1.2 Energy-related building renovation

The building renovation case study, concerns an energy – related renovation [7] that is reported in the eRen project [8]. It is a multifamily house (MFH), built in 1972, and located in the canton of Vaud. . The renovation scenario consists of externally insulating the façade walls (U_{ren}=0.15 W/m^{2}K) and the slab of the attic (U_{ren}=0.15 W/m^{2}K), internally insulating the elements against non – heated spaces (U_{ren}=0.28 W/m^{2}K), installing more performing windows (U_g=0.7 W/m^{2}K, U_f=1.1 W/m^{2}K) and replacing the oil boiler with a heat pump. An overview of the renovation scenario is presented in Table 2.

Table 2: Characteristics of the building renovation case study

General information	**B4** *(existing building, before renovation)*	**B4** *(renovation scenario)*
Materials for the structure	Concrete	Concrete
Type of facade	Compact - Masonry	Compact - External insulation
Type of roof	Sloping wooden roof	Insulation of the attic
Windows	Double glazing – PVC frame	Tripe glazing – wood frame
Energy reference area	1446	1490
Accommodation units	15	15
Basement	Yes	Yes
Number of floors	4	4
Heating & ventilation systems		
Heating device	Oil boiler	Heat pump
Energy source	Electricity	Electricity
Solar panels	No	No
Annual energy demand (MJ/m^{2}y)		
Heating	328	138.3
DHW	56	56

1.2 Life Cycle Assessment model

The building LCA corresponds to the analysis of the building's environmental impacts over its lifetime. The ISO 14040 and 14044 standards define the LCA as: "[the] compilation and evaluation of the inputs, outputs and the potential impacts of a product system throughout its life cycle" [9], [10]. In our case the product system corresponds to the building itself. The general LCA is based on a four-step analysis. The first step, scope definition and system boundaries, defines the general purpose of the LCA. The second step defines the input and output flows, which are needed to provide a certain amount of product, system or energy use. Finally, during the third step the environmental impacts of the analysed product system are calculated. Below (sections 1.2.1 to 1.2.3) is presented the general model applicable to new constructions. The particularity of the LCA rules for building renovation are presented in section 1.2.4.

1.2.1 System boundaries

The life cycle domains and phases of materials and building integrated technical systems (BITS) are defined according to SIA 2032 [11] and SIA 2040 [12]. The basic life cycle domains are the Construction and that of the Operational energy use. Table 3 shows the different life cycle domains and the corresponding phases taken into account, in the present study. No other environmental impacts were considered in this approach (e.g. maintenance, or environmental impact due to mobility of the users, as stated in SIA 2040).

Table 3: Life cycle stages of a material; in green the included stages for the "construction" domain and in orange the "operational energy use" according to SIA 2032 and SIA 2040

According to SIA 2032 & 2040	Manufacturing	Transport	Installation	Maintenance	Replacement	Operational energy use	Disposal
Construction	X				X		X
Operational energy use						X	

(X = calculated in the LCA according to the SIA technical books)

More precisely the two analysed domains include the following life cycle phases:

- The Construction domain includes:
    - The manufacturing phase. It is the stage that gathers the extraction of raw materials, the production of the building product and the release of the finished product to the building;
    - The replacement phase. During this phase, the building serviceability is guaranteed, by the replacement of building elements that no longer serve their purpose. The frequency of the replacement of a building element is further described in Section 2;
    - The disposal phase. This phase covers the dismantling of the building materials in landfilling, incineration and recycling.
- The Operational energy use domain includes the heating demand, the domestic hot water, the ventilation and electricity, in order to cover the user needs.

1.2.2 Environmental indicators

The LCA of the case studies was evaluated, by using three environmental indicators. The inventory analysis and the environmental impacts of the materials used are grouped together and were calculated based on the technical recommendation KBOB [13]. The indicators used are:

- The greenhouse gas (GHG) emissions expressed in kg CO_2-eq
- The primary non-renewable energy (NRE) expressed in kWh or MJ
- The total environmental impact calculated expressed in UBP points [14]

1.2.3 Calculation model

The total LCA of the building is calculated, using Eq. 1,

$$LCA_{tot} = LCA_{Manufacturing} + LCA_{replacement} + LCA_{disposal} + LCA_{Operational\ Energy} \tag{1}$$

As already stated, the environmental impact of the materials and technical systems ($LCA_{Manufacturing}$ and $LCA_{disposal}$) were calculated, using the *KBOB* DB [13]. The environmental impact of the operational energy is based on heating demand calculations according to SIA 380/1:2009 [15], the default efficiency factor for heating and DHW from SIA 2040 [12] and the KBOB DB for the environmental impact of the energy carrier.

As far as the LCA of the replacement stage is concerned, it was calculated, using Eq. 2,

$$LCA_{replacement} = \left(LCA_{Manufacturing} + LCA_{Disposal}\right) * k \tag{2}$$

where,

k is the replacement rate that occurs during the reference study period of the building. It is calculated for a given element type, as a fractitional number according to SIA 2032 [16] as shown in Eq. 3,

$$k = \frac{RSP}{SL} - 1 \tag{3}$$

where

RSP	is the reference study period of the building according to SN EN 15978 [1] (years);
SL	service life of the material (years).

The functional unit of the LCA is to provide the needed thermal comfort for the user, as defined by the SIA 380/1 standard, during a building reference study period (RSP) of 60 years (baseline scenario according to SIA 2040), per square meter of energy reference area (ERA[1]). The reference unit of the LCA result is expressed per unit of LCA indicator, m^2_{ERA} and year.

1.2.4 Specific rules for the LCA of building renovation

The LCA of an energy-related building renovation takes only into account the new investments during the renovation of the building. Hence, all initial investments (e.g. construction of the building structure) and future replacements of the non-renovated building elements are considered already amortized and are not included in the LCA of the renovation scenario. This rule is in line with the technical book SIA 2040 [17]. Indeed, as the renovation LCA is mainly used in a comparative way[2], their influences remain the same whatever the renovation scenario is. The LCA for the renovation scenario is calculated for the same functional unit, as for new construction, using a RSP of 60 years, as stated in [7]. Furthermore, the GHG emissions LCA indicator is assessed, while the deterministic calculations using the service lives from SIA 2032 and CRB are not reported.

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[1] The energy reference area takes into account all the surfaces that need to be heated or cooled inside the building and it constitutes the reference surface for expressing the heating demand of a building, according to SIA 380/1.

[2] Comparison among the renovation alternatives or comparison of the building LCA to the target or indicative value, defined in SIA 2040.

1.3 Life Cycle Cost model

1.3.1 System boundaries

The system boundaries for the LCC analysis are adjusted to the LCC inherent characteristics. Table 4 presents the life cycle domains and phases taken into account.

Table 4: Life cycle stages of a building; in green the included stages for the "construction" domain and in orange the "operational energy use" adapted from the CRB costs' calculation

	Manufacturing	Transport	Installation	Maintenance	Replacement	Operational energy use	Disposal
Construction	X		X	X	X		neglected
Operational energy use						X	

(X = calculated in the LCC analysis)

More precisely the two analysed domains include the following life cycle phases:

- The Construction domain includes:
    - The manufacturing and installation phase, which takes into account the investment costs of the building elements and technical systems;
    - The maintenance phase, which includes all the constant periodical costs for preserving the material in service;
    - The replacement phase. During this phase, the building serviceability is guaranteed, by the replacement of the building elements that no longer serve their purpose. The frequency of the replacement of a building element is further described in Section 2;
    - The disposal phase, which covers the dismantling of the building materials in landfilling, incineration and recycling. Unlike the LCA, the disposal stage is assumed negligible and is not considered in the scope of the LCC in this study.
- The Operational energy use phase includes the costs related to the heating demand, domestic hot water, ventilation and electricity, in order to cover the user needs.

1.3.2 Calculation model

The calculation model comprises all the costs throughout the lifetime of a building. They are presented schematically in Figure 2 and with mathematical terms, in Eq. 4.

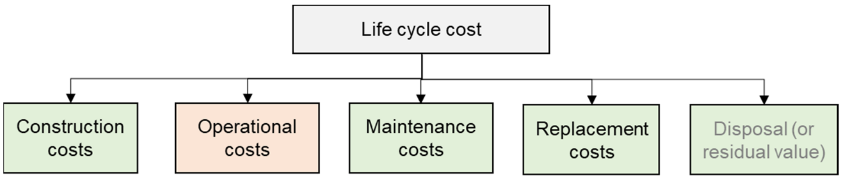

Figure 2: Costs over the building life span (adapted from CRB general framework), disposal costs not taken into account.

$$LCC = Cost_{Manufacturing} + Cost_{maintenance} + Cost_{replacement} + Cost_{operational\ energy} \tag{4}$$

The methodology used for the calculation of the LCC is based on the CRB approach [18], which provides an adjustment of the ISO standards, i.e. ISO 15 685-5 [19] and SN 506 511 [20] and defines the rules and principles concerning the LCC method for Swiss dwellings. It is based on the Net Present Value methodology, according to which all the future costs are calculated as net present values. The future costs are calculated taking into account the inflation and they are brought back to year zero, using the nominal discount rate. The LCC is then calculated, by adding all the discounted costs (or the NPVs), in the year zero, as presented in Equation 5.

$$LCC = Cost_{Manufacturing} + \sum_{1}^{n} \frac{C_{maintenance} * (1+a)^{n}}{(1+d)^{n}} + \sum_{m} \frac{C_{Manufacturing} * (1+a)^{m}}{(1+d)^{m}} + \sum_{1}^{n} \frac{C_{operational} * (1+a)^{n}}{(1+d)^{n}} \qquad (5)$$

Where

a	is the inflation rate, 2%;
d	is the nominal discount rate, 5.5%;
n	is the reference service life, RSP;
m	is the year at which the replacement occurs, linked to the service life.

The initial costs ($Cost_{Manufacturing}$) occur only once, i.e. in the year zero and they are estimated according to the Série de prix indicatifs (SP 2015) [21], a cost database which provides indicatives values for the investment costs (including the labour costs) of different materials used in construction. The LCC is supposed to be conducted during a preliminary study, according to SIA 108 [22]. Hence, an uncertainty of 25% on the investment costs was also considered, according to SIA 108 [22] to take into account the variability of the costs depending on the region, type of building and year of construction.

As far as the maintenance and the operational energy costs are concerned, they take place every year, unlike the investment costs. The maintenance costs are calculated as a percentage of the construction costs for every element type, as shown in Table 5, according to CRB recommendations. The energy costs were considered as stable, with energy price escalation rate equal to zero, since the three past years variations less than 1% were reported in the canton of Zurich [23]. The electricity price is chosen to be 0.21[CHF/kWh] according to [24] for Zürich, which represents a mean value for the electricity supply, during the whole day. As far as the energy from district heating is concerned, it is chosen to be 0.156 [CHF/kWh] for Zürich, according to [25]. It should be noted, that the energy costs do not vary significantly throughout the Swiss territory and consequently the same costs are used for the renovation case study (located in Vaud). Concerning the replacement costs, they occur at discrete years, during the reference service period (RSP), according to their attributed service lifetime.

The LCC results are expressed in Swiss Francs, per year of the building RSP (60 years) and m^2_{ERA}. The same RSP as for the LCA is chosen, in order to have a consistency, between the LCA and LCC and proceed to potential comparisons.

Table 5: Index of maintenance costs (%) for all the element types, according to CRB.

eCCC-Bât code and designation	Index of maintenance costs (%)
C. Structural system (incl. C1, C2, C3, C4)	0.10%
D. Technical systems	1.35%
D1. Electrical installations	1.25%
D5. Heat production installation	0.90%
D7. Ventilation and air conditioning systems	2.10%
D8. Water, gas and compressed air distribution (incl. sanitary equipment)	0.70%
E: Wall coatings (incl. E1, E2, E3)	0.10%
F. Roofs (incl. F1, F2, F3)	0.10%
G. Interior layouts & renderings (incl. G1, G2, G3, G4, G5)	0.10%

1.4 Decomposition of building elements for fixing the service lives

The Swiss building element classification scheme, for cost estimation, eCCC-Bât in French, (or eBKP-H, in German) is used to classify the building elements. The classification of the eCCC-Bât nomenclature has already been used for the service lives database in the DUREE WP1 section. Figure 3 presents the general description of the building into different decompositions[3]. Each building element consists of several building components, which have different functions and belong to different construction categories. The classification system attributes to the individual building components a specific code from eCCC-Bât. This allows organising the database with different levels of details and associating a service life to the corresponding level. In this study, two levels of details are considered.

In the first level of analysis, the service life is attributed to the construction categories defined according to the eCCC-Bât main groups of elements:

- C: Structure (all load-bearing parts) with a fixed service life at 60 years (as discussed in 1.2.3)
- D: Technical equipment
- E Envelope (vertical façade)
- F: Envelope (roof covering)
- G: Interior (non-load-bearing walls and interior finishing)

The second level of analysis takes into account lower levels of the group of elements. For example, the building component “exterior wall above ground” from Figure 3 is divided in three different layers (internal layer – structural element – external layer):

- E2.2 exterior wall finishing
- C2.1B exterior wall
- G3 interior wall finishing

For this second analysis, the service life is attributed to each one of the three layers, which corresponds to the second level of details (e.g. G3) or the third level of details (e.g. E3.1), according to the DUREE database developed in WP1[4]. However, it should be noted that the combination of these two levels of details (e.g. G2 and E3.1), derives from two limiting criteria:

- First, representative renovation practices are considered in order to avoid misleading service lives definition. For example, in practice, if the rendering (e.g., E2.2b) and the external insulation (e.g. E2.2a) are replaced at the same time, we do not distinguish the two components over their service lives, even if the level of details of the DUREE DB would allow doing so.

- Second, possible lack of service lives data leads to a limited sample size in the DUREE WP1 database, for very detailed elements (e.g. air-to-water heat pump). This lack of data may prevent from defining accurately a statistical distribution. In that case, the service life is, thus, defined at the upper level of details (e.g. D5.2, heat producer).

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[3] In this figure, the technical systems are represented as layers, in accordance to their GHG emissions, primary NRE or total environmental impacts expressed per square meter of the ERA, given in the KBOB database.

[4] Further levels of details are possible, if the two limiting criteria are not met.

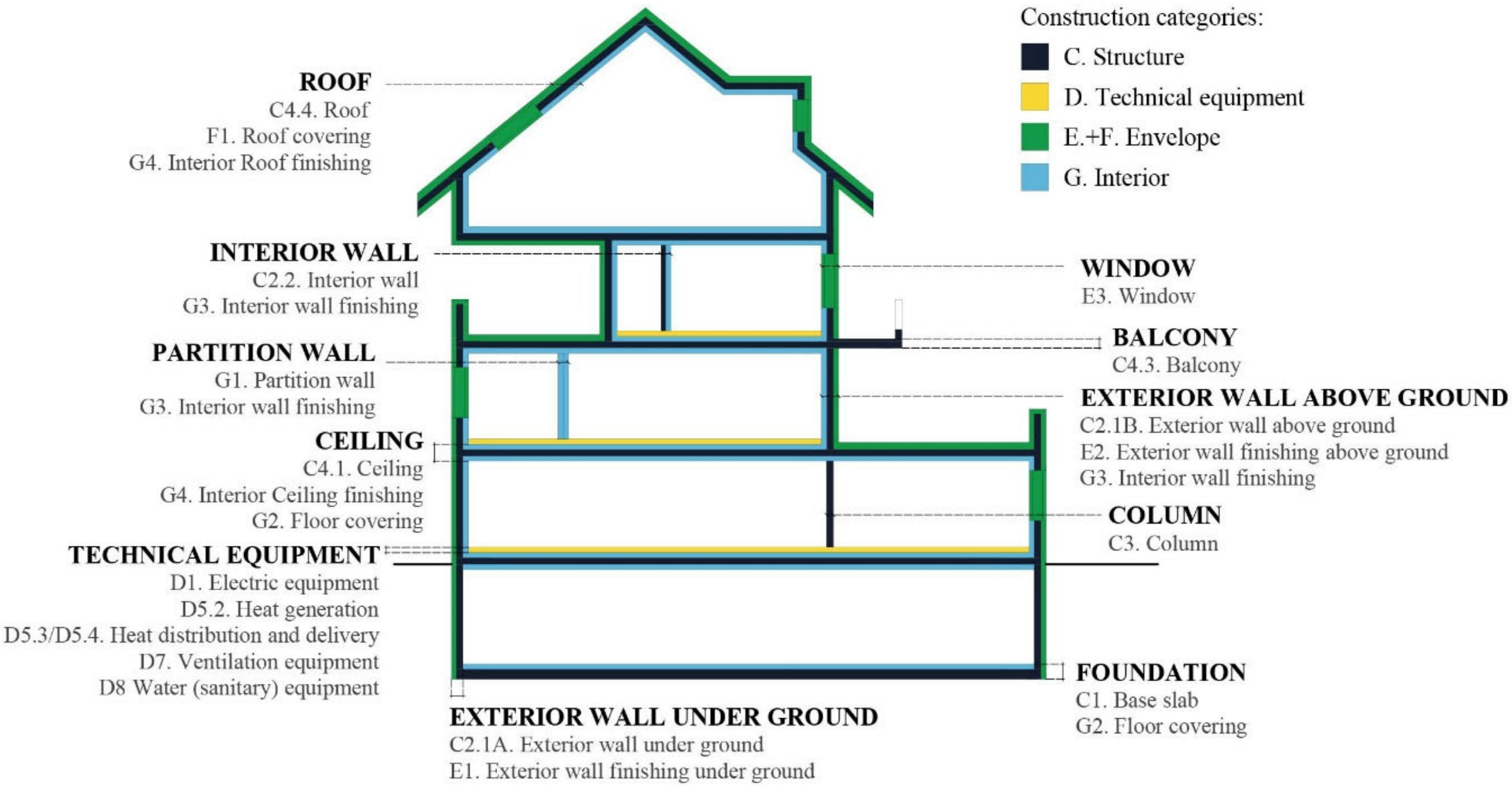

Figure 3: General description of the building, building elements, building components and construction categories according to [26]

Table 6 presents the eCCC-Bât element types[5], according to which the service lives are attributed, for the analysed case studies. As already mentioned, the second level of analysis is a combination of the second and third level of details of the eCCC-Bât classification.

Table 6: eCCC-Bât codes and the corresponding names of the element types included in the case studies

	Building LCA & LCC		
eCCC-Bât element types considered in the WP3 study	New construction case study		Energy-related building renovation
	First analysis	Second analysis	
⬛ **C. Structure**	fixed at 60 years	fixed at 60 years	not included
🟨 **D. Technical equipment**	X		
D1. Electrical installations		X	
D5. Heating system			
D5.2 Heat production		X	X
D5.2d Solar thermal collectors		X	
D5.3 Heat distribution		X	
D5.4 Heat emission		X	
D7. Ventilation and AC systems		X	
D8. Sanitary equipment		X	
🟩 **E. Facade rendering**	X		
E2. Facade rendering against exterior			
E2.2 Compact facade		X	X
E2.3 Ventilated facade		X	
E3. Windows, doors			
E3.1 Windows		X	X
🟦 **F. Roof**	X		
F1. Covering			
F1.2 Flat roof		X	
F1.3 Slanted roof		X	X
🟦 **G. Interior**	X		
G1. Internal partitions		X	
G2. Flooring		X	
G3. Wall coverings		X	X
G4. Ceiling coverings		X	X
Total number of service lives' values	***4***	***16***	***6***

---

[5] The term "element type" refers to all the CRB terms, as well as the terms introduced in Figure 3, i.e., main groups, group of elements, elements or sub-elements, building element and construction element.

2 Uncertainty and sensitivity analyses

The present study takes into account the uncertainty of the element types service life (input of the model) (i.e. D1, F1, E2, G), in the LCA and LCC analyses (output – response of the model). All the other uncertainties related to the parameters of these reference models e.g. uncertainty of the operational energy use of the building and the LCA and LCC analyses were not within the scope of this study. By doing so, the relative importance of the service lives' uncertainties was solely evaluated, taking into consideration that a small uncertainty on the total LCA result (output), derives from an insignificant influence of the service life (input).

One way to identify the error propagation, due to the uncertainty of the input on the output, is to use the Monte Carlo method within a probabilistic framework. In this analysis, the probability density function (PDF) of the input parameters (service life of the different type of elements) is estimated and samples are drawn *N* times from the estimated distributions. The model output (LCA) is then computed, which includes a set of *N* values [27]. Once the uncertainty analysis is conducted, a sensitivity analysis can be performed, in order to examine which of the input parameters (service life of the different element types, i.e. D1, E2, F1, etc.) influence more the uncertainty of the output, i.e. the LCA and LCC. Figure 4 presents a general framework for the uncertainty and sensitivity analysis applied to the calculation of building operational energy and the related LCA & LCC[6], as proposed in [28].

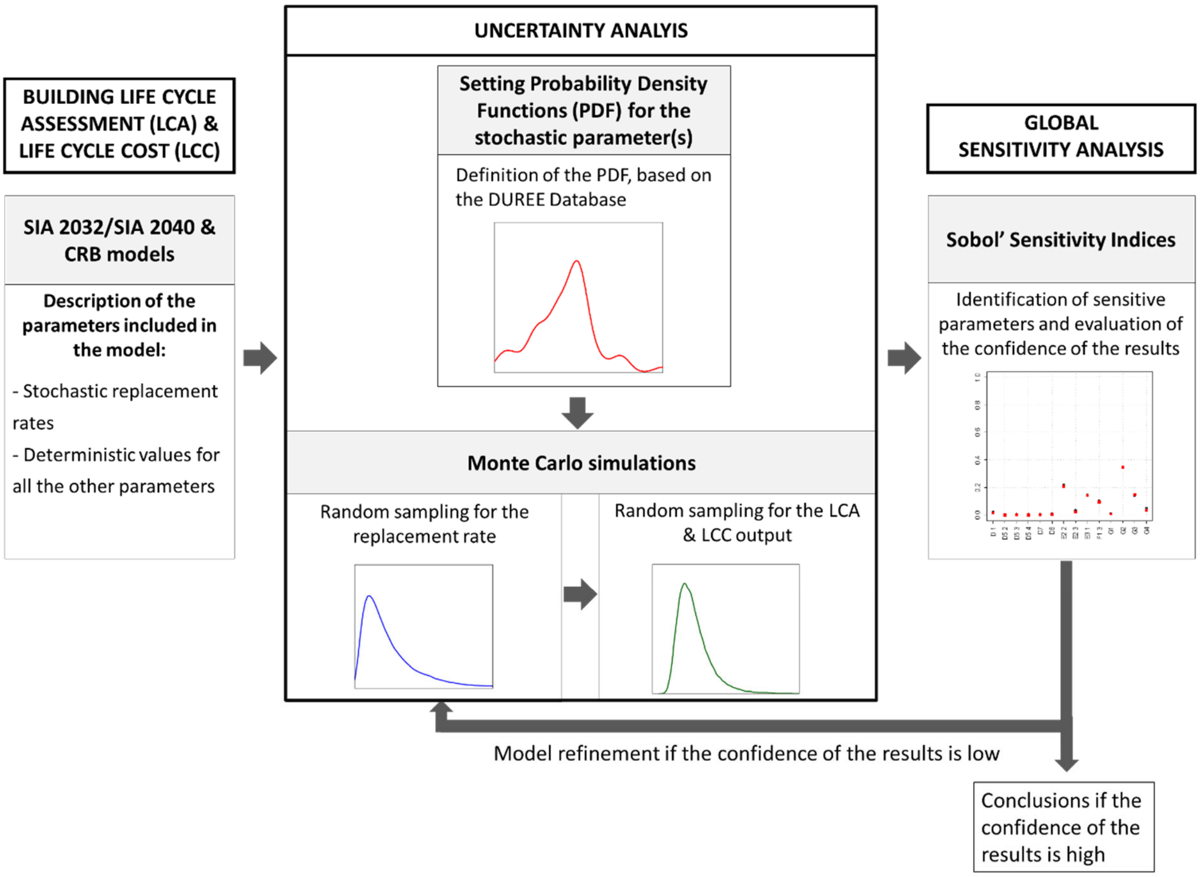

Figure 4: Probabilistic framework for the uncertainty & sensitivity analysis used in DUREE

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[6] The probabilistic framework presented in Figure 4 can be applied to the parameters for the calculation of the heating demand, according to the SIA 380/1 standard or other parameters of the LCA & LCCA. Examples of such studies include the analysis of the performance gap of the heating consumption in a new building (Padey et al 2018 [51], UserGap SFOE project) and the robust renovation scenarios in Galimshina et al 2019 [52], funded by the Swiss National Foundation (SNF).

2.1 Uncertainty analysis

The service lives data of the DUREE database[7] are used, as the input data for the identification of the distribution of the service life, for the element types and the two levels of analysis. In the literature, the lifetime data are often modelled, using a lognormal distribution or a Weibull distribution [29], [30]. Input service lives (or replacement rates) data constitute independent positive random quantities, for which the use of the lognormal process is well justified, [31], since according to the central limit theorem in the log domain, an infinite number of positive random values would approach the lognormal distribution [32]. Thus, the lognormal distribution was chosen to model the replacement rates of the element types.

In order to assess the goodness of fit of the lognormal distribution, two statistical methods are tested for all the element types of the DUREE database using the statistical software R [33]. In the beginning, the graphical method is computed, i.e. the Q-Q and P-P plots, which compares the theoretical and empirical distributions. Figure 5 presents the P-P and Q-Q plots for the replacement rate of the D.7 element type (ventilation system). The two plots show that the two distributions are linearly related and that their points lie approximately on the line $y = x$. Similar results are observed for the other elements as well. In addition, the p-value, according to the Anderson – Darling Test was calculated [34], for all the element types. The results, which are presented in Appendix 1, confirmed the initial hypothesis of the lognormal distribution, (p-value > 0.05). Thus, the PDFs of all the element types were defined, using a lognormal distribution. The same procedure is applied in order to define the distribution of the service lives, from the Swiss Household Energy Demand Survey (SHEDS) that are reported in WP2. The goodness of fit and the parameters of the lognormal distribution for the WP1 and WP2 data are presented in Appendices 1 and 2.

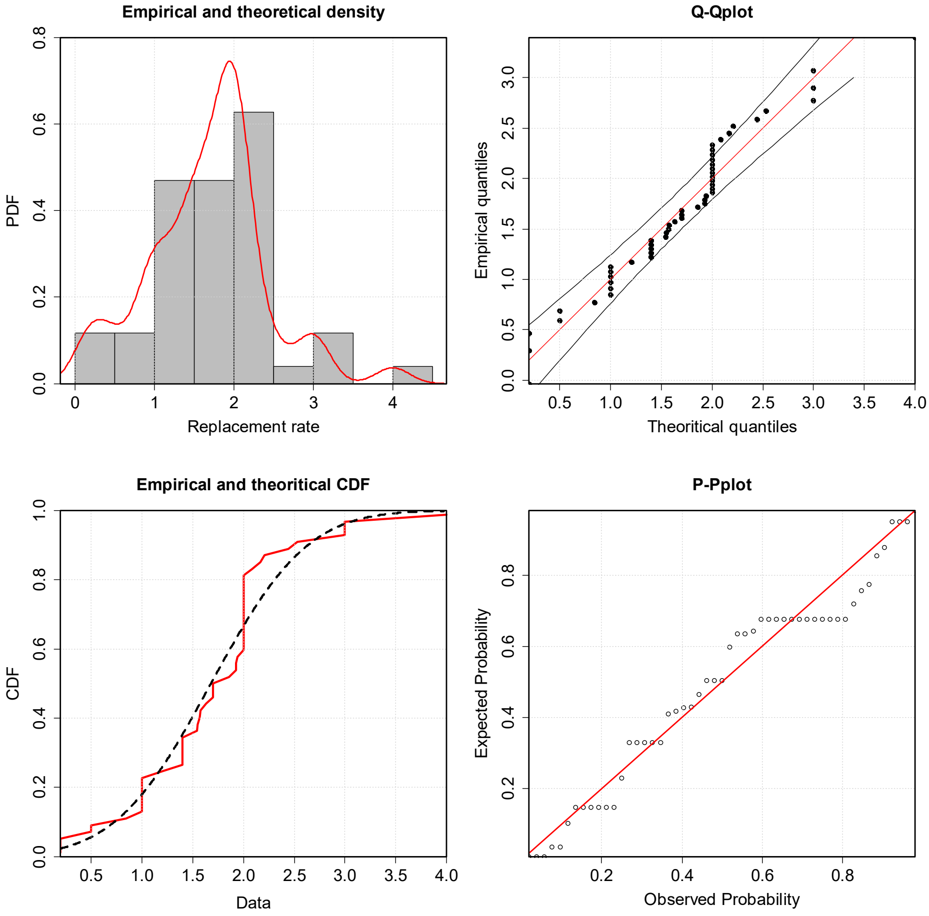

Figure 5: Example of goodness of fit for the D.7 category (ventilation system)

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[7] All service life data of the DUREE database is used. It takes into account LCA, LCC and management data sources from both the Swiss and International literature.

It should be noted that, it was decided to avoid fixing a maximum number of replacements, e.g. five times during the reference service life, a scenario that would correspond better to the majority of the replacement cases in reality. The reason for this decision lies on the nature of the probabilistic approach. The fact that the probabilistic approach is able to explore the whole domain of the possible cases and associate probabilities to show their repetitiveness, describes better the uncertain reality, i.e. a defective material, its defective application, or its misuse during its lifetime, etc.

After the identification of the input distribution, 40’000 Monte Carlo simulations are computed, in order to achieve convergence. The replacement rate is calculated using a fractional mode. Based on these simulations, the Probability Density Functions (PDF) of the LCA and LCC indicators are calculated. In addition, deterministic replacement rates from SIA 2032 and CRB (min – mean – max) were used to calculate the deterministic LCA and compare the results with the most probable value (the mode) of the probabilistic LCA. The Monte Carlo simulation are calculated, using the statistical software R [33].

2.2 Sensitivity analysis

The last step of the study includes the identification of the parameters (i.e., element types) whose uncertainty most influences the output (LCA), by applying a sensitivity analysis. Usual sensitivity analysis in LCA and in LCC include the one-at-a-time variation of parameters. Each parameter of the model is varied separately and its influence on the output is analysed. By doing so, it is not possible to identify which input parameter most affects the output when all parameters are varied simultaneously. Thus, a variance-based Global Sensitivity Analysis (GSA) is chosen. This method has not been used frequently in the LCA domain and its relevance was recently discussed in [35].

The variance-based GSA decomposes the variance of the model (LCA) into fractions, which can be attributed to inputs, i.e. the element types [36]. More specifically, the Sobol’ decomposition method is applied. The Sobol’ Indices are calculated for the different input parameters, which are assumed to be independent. The first order index that represents the main effect, i.e., the influence of individual parameters (Eq.6) is calculated, as well as the total index effect (Eq.7), which takes additionally into account possible interactions among the input parameters. Thus, the shares of the input parameters (unique contribution S_i or joint contribution with other parameters S_{Ti}) on the variance, are computed. These shares explain, thereby, the parameters that contribute the most to the overall variance. The Sobol’ Indices are calculated using the statistical software R [33].

$$S_i = \frac{Var[E(Y|X_i)]}{Var[Y]} \tag{6}$$

$$S_{T_i} = \frac{E_{X_{\sim i}}\left[Var_{X_i}(Y|X_{\sim i})\right]}{Var[Y]} = 1 - \frac{Var_{X_{\sim i}}\left[E_{X_i}(Y|X_{\sim i})\right]}{Var[Y]} \tag{7}$$

3 Results

This section presents the LCA & LCC results for the new constructions and the energy-related renovation case study. In the beginning, the GHG emissions are presented for the two levels of analysis and the three new construction case studies. The study continues with the primary NRE and the UBP indicators, as well as with the LCC analysis, for the second level of analysis and the B1 case study. Finally, the LCA and LCC of the energy-related case study follows. LCA & LCC of new constructions

3.1.1 First level of analysis – GHG emissions

The current analysis is presented for the GHG emissions indicator and applied to the three case studies. Taking into account the different stages of the environmental assessment of a building, the service lives are attributed to the main category (D, E, F, and G), according to the eCCC-Bât classification, and the DUREE database. Figure 6 presents the PDF for the GHG emissions (expressed in kg $CO_{2\text{-eq}}/m^2y$) for the B1 case study. The probabilistic LCA [$\mu = 23.22$ kg $CO_{2\text{-eq}}/(m^2y)$, $\sigma^2 = 5.5^2$] is presented with the deterministic LCA of the SIA 2032 [19.2 kg $CO_{2\text{-eq}}/(m^2y)$] and CRB [min=28.1 kg $CO_{2\text{-eq}}/(m^2y)$, mean=18.9 kg $CO_{2\text{-eq}}/(m^2y)$ and max= 15.1 kg $CO_{2\text{-eq}}/(m^2y)$]. The three CRB values (min – mean – max) correspond to the minimum, mean and maximum service lives, which mean maximum, mean and minimum replacement rates, respectively. Furthermore, the 95% confidence interval of the mean is narrow [$\mu = 23.22\ \mathrm{kg\ CO_{2-eq}}\ /(\mathrm{m^2 y}) \pm 0.05$], revealing the accuracy of the simulations. The most probable value of the LCA, i.e., the mode of the distribution (x_m=20 kg $CO_{2\text{-eq}}/m^2y$) is slightly higher than the deterministic SIA 2032 and CRB–mean (4% and 6% respectively).

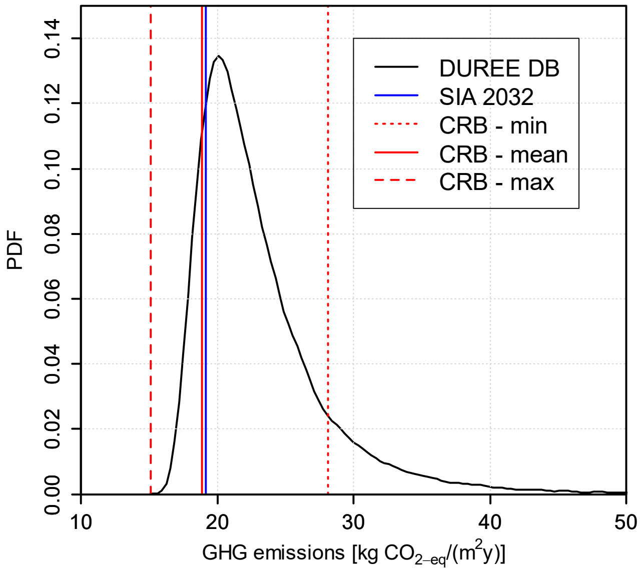

Figure 6: PDF of the probabilistic LCA for the B1 case study and comparison with the deterministic LCA, using the SIA 2032 and CRB service lives

Figure 7 presents the sensitivity indices, which show the element types[8] whose uncertainty most influences the LCA variability. Both the first order index (main effect) along with the total index (total effect, which includes the interactions between the parameters) are plotted[9]. Furthermore, in order to verify the accuracy of the indices, a bootstrapping with 500 replicates was used [37]. The 95% confidence intervals of the indices remained narrow (e.g. for the G2 category, $\mathrm{S_{iG}} = 0.38 \pm 0.05$) and of the same magnitude. Hence, we can be sure about their order, which determines the elements, with

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[8] The names of the element types are not reported in the graphical results in this chapter. The full name of elements are available in Table 6, page 20.

[9] It should be noted that the individual effects and not the interactions among the element types, explain the LCA variability, proving that the initial hypothesis, according to which the replacement of a specific element does not interact with another element's replacement.

the highest impact on the LCA uncertainty [28]. It can be concluded, that the E (façade) and G (interior finishing) element types have the highest impact on the LCA variability. The result is quite straightforward, since the highest LCA uncertainty derives from the element types that have the highest environmental impact (first the external façade – E and then the interior finishing – G) and the highest coefficients of variation, ($cv_E = \frac{sd}{mean} = 1.2 \ and \ cv_G = 1.4$) of the replacement rate distribution. Appendix 3 presents the median LCA results, expressed in GHG emissions and the coefficients of variation of the element types.

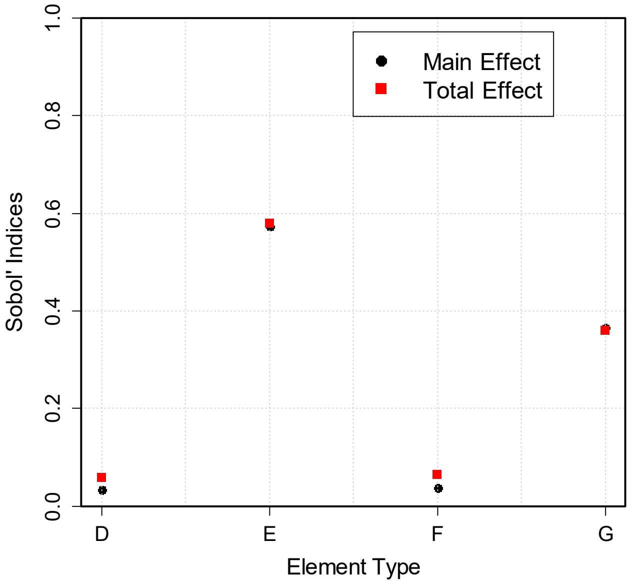

Figure 7: Sobol' Indices for B1 case study

Figure 8 presents the Sobol' Indices (main effects) for the three case studies. The LCA uncertainty, for all case studies, is mostly influenced by the E, D and G uncertainty. Among one specific element type, it is the magnitude of the environmental impact expressed in GHG emissions, which determines the order of the Sobol' Indices, i.e. the variability of the replacement rate has high influence when the unitary GHG emissions of the replaced element is high. The high sensitivity index of the G element type, displayed by the B3 case study, is explained by the choice of the material for the flooring (natural stone), which has higher GHG emissions than the flooring (wood elements), used for the other case studies. As far as the E element type is concerned, the sequence of the three case studies, correspond to the order of the GHG emissions of the three case studies. Appendix 3 summarizes the median GHG emissions results for the first level of analysis.

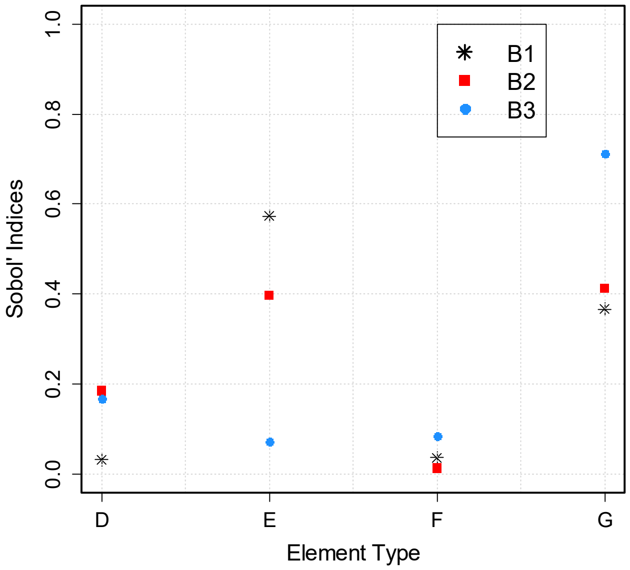

Figure 8: Sobol' Indices for all the case studies and the first analysis.

3.1.2 Second level of analysis – GHG emissions

The second level of analysis follows for the B1 case and the GHG emissions [expressed in kg $CO_{2\text{-}eq}/(m^2y)$]. Figure 9 shows the PDF of the probabilistic LCA, 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 $CO_{2\text{-}eq}/(m^2y)$]. The variance of the LCA ($\sigma^2 = 3^2$) reveals that the LCA can be significantly spread away from the mean [$\mu = 22.0$ kg$CO_{2\text{-}eq}/(m^2y)$]. The most probable LCA value i.e. the mode of the distribution, is 21.6 kg $CO_{2\text{-}eq}/(m^2y)$[10]. 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. However, the CRB – min that corresponds to the minimum service life (i.e. maximum replacement rate) of the elements overestimates 100% of the mode of the distribution.

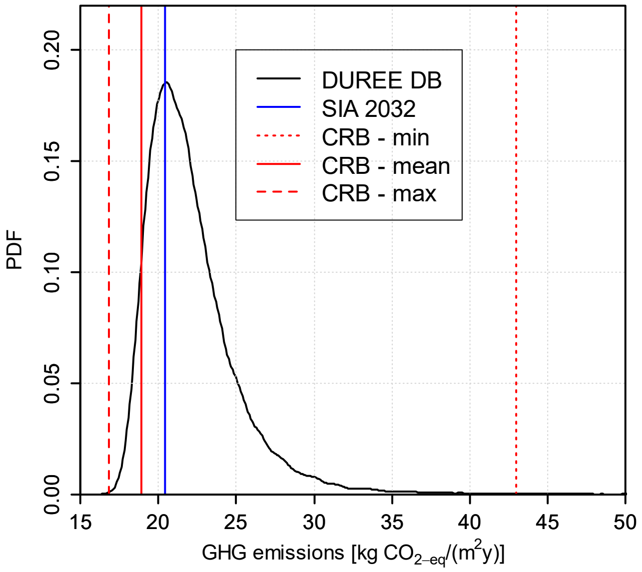

Figure 9: PDF of the probabilistic LCA for the B1 case study and comparison with the deterministic LCA, using the SIA 2032 and CRB service lives

Figure 10 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 median, along with the first and third quartiles, which represent the interquartile interval or the central 50% GHG emissions, are presented for the probabilistic approach. This interquartile range is $Q1 = 17.5 \text{ kg } \mathrm{CO_{2-eq}} / (\mathrm{m^2 y})$ and $Q3 = 23.5 \text{ kg } \mathrm{CO_{2-eq}} / (\mathrm{m^2 y})$, with a median of 19.6 kg $CO_{2\text{-}eq}/(m^2y)$. 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 replacement stage exhibits a slightly lower share, between 14% and 36% but remains comparable with the operational energy use.

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[10] Furthermore, the 95% confidence interval of the mean [$\mu = 22.05$ kg $CO_{2\text{-}eq}/(m^2y)$] is narrow [$\mu = 22.05 \text{ kg } \mathrm{CO_{2-eq}} / (\mathrm{m^2 y}) \pm 0.03$], revealing the accuracy of the simulations.

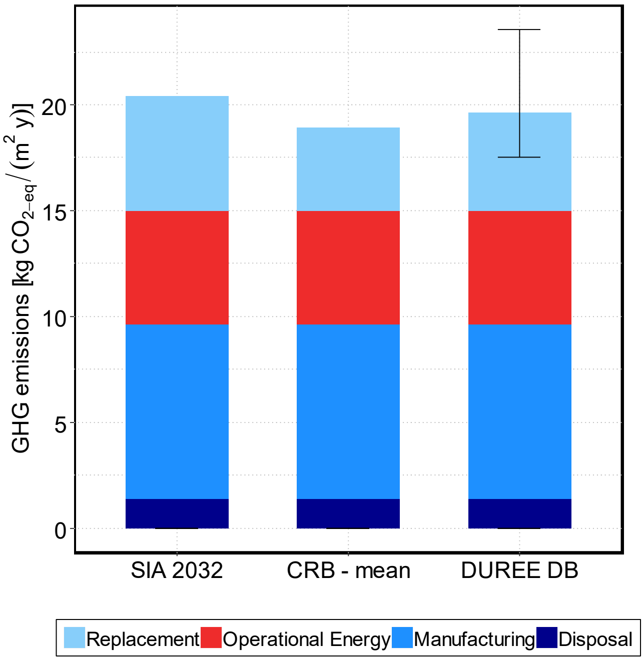

Figure 10: Contribution analyses for the probabilistic LCA and comparison with the deterministic LCA expressed as GHG emissions, using the SIA 2032 and CRB - mean service lives

The Sobol' Indices are plotted in Figure 11 for the second level of analysis[11].Appendix 3 summarizes the median LCA results, expressed in GHG emissions and the coefficients of variation for the element types, as well. The uncertainty of the LCA, expressed in GHG emissions can be mainly explained by five element types, i.e. the E2.2 (façade), E3.1 (windows), F1.3 (roofing), G2 (flooring) and G3 (internal finishing). Among the elements with the highest GHG emissions (first E2.2, followed by F1.3 and G2), it is the replacement rate of G2 that presents the highest coefficient of variation ($cv = 1.25$), followed by E2.2, ($cv = 1.01$), and F1.3 ($cv = 0.98$). The E3.1 and G3 element types, present lower GHG emissions than F1.3, but the coefficient of variation of their replacement rate is more significant, which explains the higher relative sensitivity indices. The Sobol' Indices of the technical systems are found to be close to zero, proving that their service live uncertainty does not affect the GHG emissions uncertainty.

From these results, it can be concluded, that the order of the sensitivity indices is a correlation of the GHG emissions and the uncertainty of the replacement rate of the corresponding element types. There is a tendency of the element types that exhibit higher relative uncertainty on the replacement rate and higher GHG emissions, to demonstrate higher influence on the LCA uncertainty, as well. However, it is not always straightforward, which of the two aforementioned parameters (uncertainty of replacement rate and environmental impacts-GHG emissions) is the most influential.

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[11] The same procedure was followed to validate the confidence of the Sobol' Indices, as before.

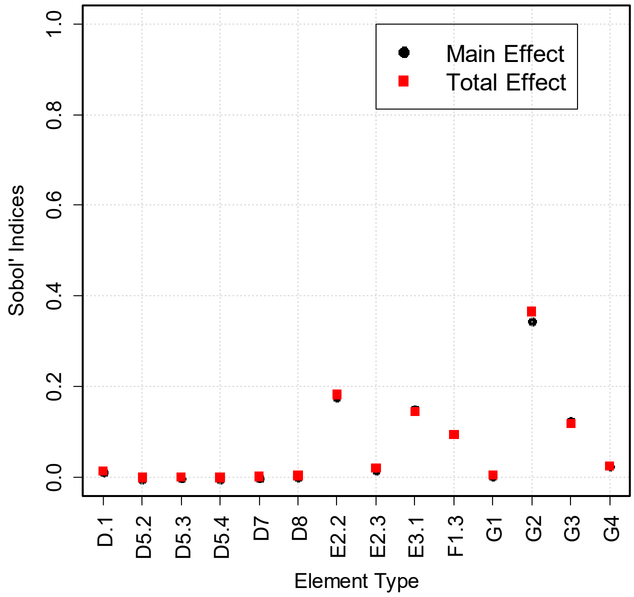

Figure 11: Sobol' indices for the probabilistic LCA of the B1 case study, using the GHG emissions indicator

Figure 12 summarizes the Sobol' Indices (main effects) for the three case studies (B1, B2, B3). The results are consistent with the first analysis in section 3.1.1. The uncertainty of the buildings' GHG emissions is mostly explained by the uncertainty of the E and G element types and more specifically by, the E2.2 (façade), the E3.1 (windows), the F1.3 (roofing), the G2 (flooring), G3 (internal finishing) and G4 (ceiling covering). The LCA of all the three buildings presents low sensitivity (i.e., $S_i < 0.10$) on the uncertainty of the technical systems, independently of the chosen system.

If a threshold is defined at 0.10 for the sensitivity indices, only the six aforementioned element types are the most influential on the LCA uncertainty. This means that in future LCA calculations, special attention should be given on the way the replacement rate for these element types is chosen. Generic deterministic data for a specific element should be avoided, since they could lead to erroneous LCA results and a misleading performance of the building. Furthermore, there is a common trend for the technical systems for all buildings, revealing that in further assessment of the GHG emissions, their service life could be treated deterministically, using reference service life from the literature or the standards (SIA 2032, CRB).

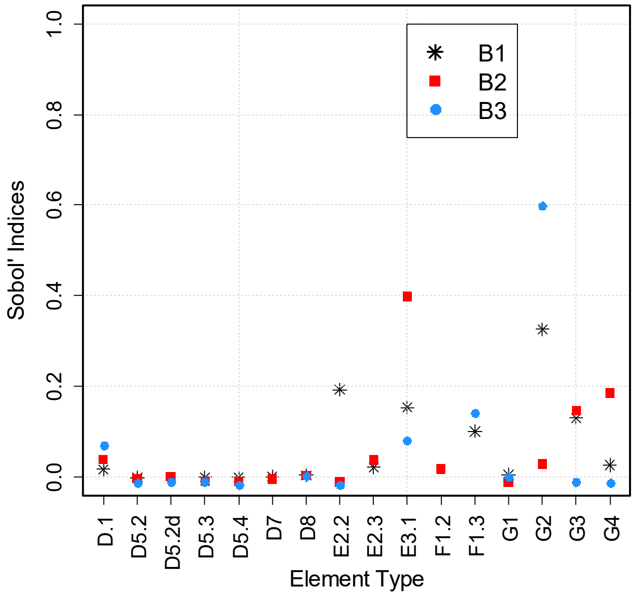

Figure 12: Sobol' Indices of the three case studies

3.1.3 Second analysis – other LCA indicators

3.1.3.1 Primary non-renewable energy (NRE)

The analysis continued for the primary NRE indicator and the B1 case study. Figure 13 presents the PDF of the primary energy [expressed in $\mathrm{kWh_{oil\text{-}eq}/(m^2y)}$], along with the deterministic replacement rates of SIA 2032 [133 $\mathrm{kWh_{oil\text{-}eq}/(m^2y)}$] and CRB [min=192 $\mathrm{kWh_{oil\text{-}eq}/(m^2y)}$, mean=129 $\mathrm{kWh_{oil\text{-}eq}/(m^2y)}$ and max= 115 $\mathrm{kWh_{oil\text{-}eq}/(m^2y)}$], as well. The variance of the PDF is $\sigma^2 = 12^2$, with a mean value of $\mu = 141.40$ [$\mathrm{kWh_{oil\text{-}eq}/(m^2y)}$], while the most probable value, deriving from the Monte Carlo sampling is 136 [$\mathrm{kWh_{oil\text{-}eq}/(m^2y)}$]. The deterministic LCA outputs of the SIA 2032 and CRB - mean are similar, but SIA 2032 is closer to the most probable value of the PDF. However, the CRB – min significantly overestimates the NRE indicator, as it was the case for the GHG emissions. Comparing the PDF between the NRE and GHG emissions indicators, the latter presents a higher dispersion ($cv_{GHG} = 14\%$) than the former ($cv_{NRE} = 9\%$). This difference can be explained by the different contributions attributed to the elements by the two indicators (cf. Figure 14).

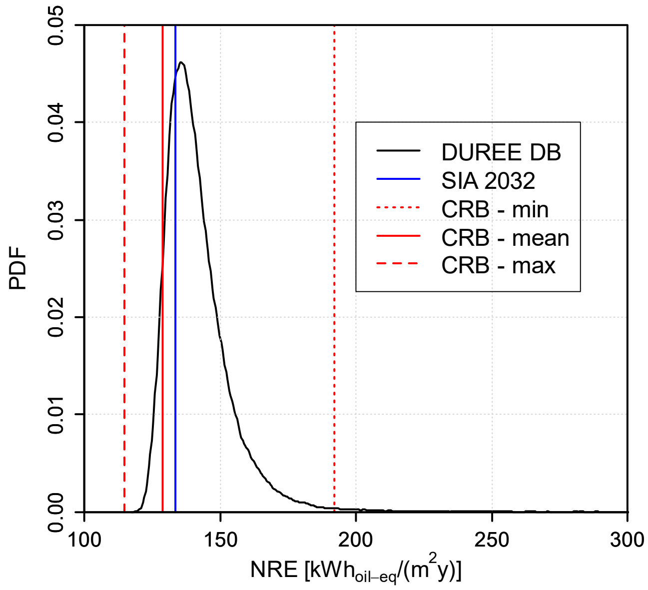

Figure 13: PDF of the probabilistic LCA for the B1 case study and comparison with the deterministic LCA, using the SIA 2032 and CRB service lives for the NRE indicator

Figure 14 shows the contributions of the different life cycle stages for the deterministic and probabilistic approaches. The latter is characterized by the median, along with the first and third quartiles. Fifty per cent of the simulations can be found between the interval $Q1 = 122.2\ \mathrm{KWh_{oil-eq}}/m^2\mathrm{y}$ and $Q3 = 147.34\ \mathrm{KWh_{oil-eq}}/m^2\mathrm{y}$. For this indicator, the operational energy presents the highest share, of the LCA. It can be found between the interval 61% - 51%, by taking into account the central 50% simulations. For the same interval, the manufacturing stage represents 28% - 24%, while the replacement stage represents a share of 8% - 24%.

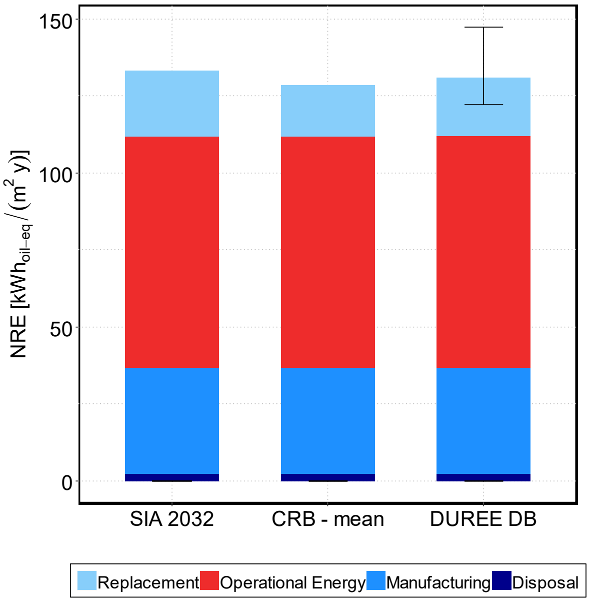

Figure 14: Contribution analyses for the probabilistic LCA and comparison with the deterministic LCA, using the SIA 2032 and CRB - mean service lives for the NRE indicator

The Sobol' Indices[12] are presented in Figure 15. Appendix 3 presents the median LCA results, expressed in primary NRE and the coefficients of variation for the element types. For the NRE indicator, the G2 element type represents the highest part on the LCA uncertainty (expressed in primary NRE), as for the GHG emissions. Seven elements explain the NRE uncertainty, i.e., the same as for the GHG emissions (E2.2, E3.1, F1.3, G2, G3). Additionally, the E2.3 and G4 element types are relatively important, as well. Furthermore, the NRE uncertainty is not affected by the uncertainty of the technical systems, as already found for the GHG indicator. This means that even if the contribution of the environmental impact varies, among the different LCA indicators, the LCA uncertainty is not influenced by the uncertainty on the replacement rates of the technical systems.

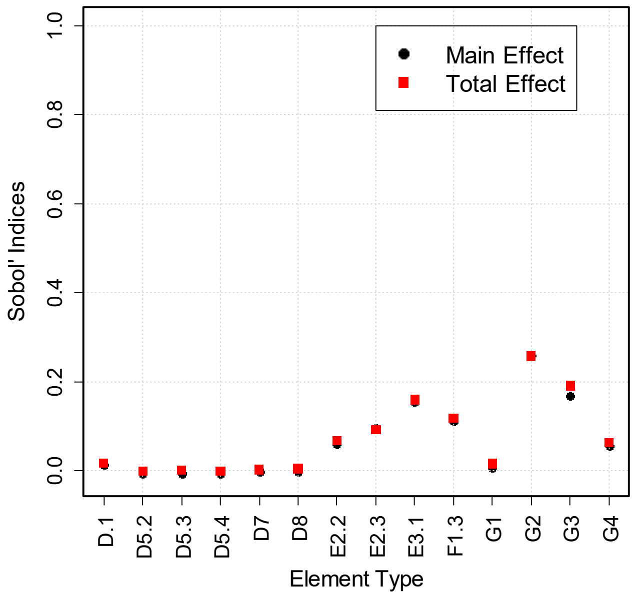

Figure 15: Sobol' indices for the probabilistic LCA and the B1 case study, using the NRE indicator

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[12] The same validation procedure, as presented previously, was followed for the confidence of the estimates (e.g. $S_{iG2} = 0.289 \pm 0.012$)

3.1.3.2 Total environmental impact (UBP)

A final analysis for the B1 case study was performed, using the UBP indicator, expressed in [ecopoints/(m^{2}y)]. The PDF of the probabilistic LCA is presented in Figure 16, with the deterministic SIA 2032 [34706 ecopoints/(m^{2}y)] and CRB [min=50745 ecopoints/(m^{2}y), mean=32750 ecopoints/(m^{2}y) and max=28714 ecopoints/(m^{2}y)]. The variance of the PDF is $\sigma^2 = 3700^2$, with a mean value of $\mu = 35190$ [ecopoints/(m^{2}y)], while the most probable value deriving from the Monte Carlo sampling is 33400 [ecopoints/(m^{2}y)]. The dispersion of the PDF is determined, using the coefficient of variation, $cv = 10\%$, which is of the same magnitude as for the NRE indicator. The SIA 2032 and CRB – mean present a relative good approximation of the mode of the distribution. As it has already mentioned, the CRB – min overestimates significantly the most probable value of the PDF.

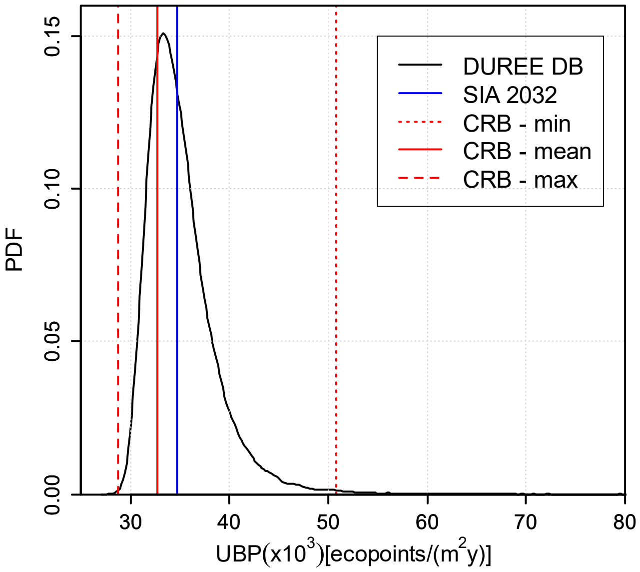

Figure 16: PDF of the probabilistic LCA for the B1 case study and comparison with the deterministic LCA, using the SIA 2032 and CRB service lives for the UBP indicator

Figure 17 presents the contributions of the life cycle stages for the deterministic and probabilistic LCA. The latter is defined by the median together with the first and third quartiles, i.e. $Q1 = 31234\ \mathrm{ecopoints}/(m^2\mathrm{y})$ and $Q3 = 39302\ \mathrm{ecopoints}/(m^2\mathrm{y})$, respectively. For the UBP indicator the operational energy has the highest share on the LCA, as for the NRE indicator. Looking at the probabilistic LCA, for the central 50% simulations, the share of the operational energy can be found between 50% - 40%, the manufacturing stage between 35% - 27% and the replacement stage between 11% - 29% share.

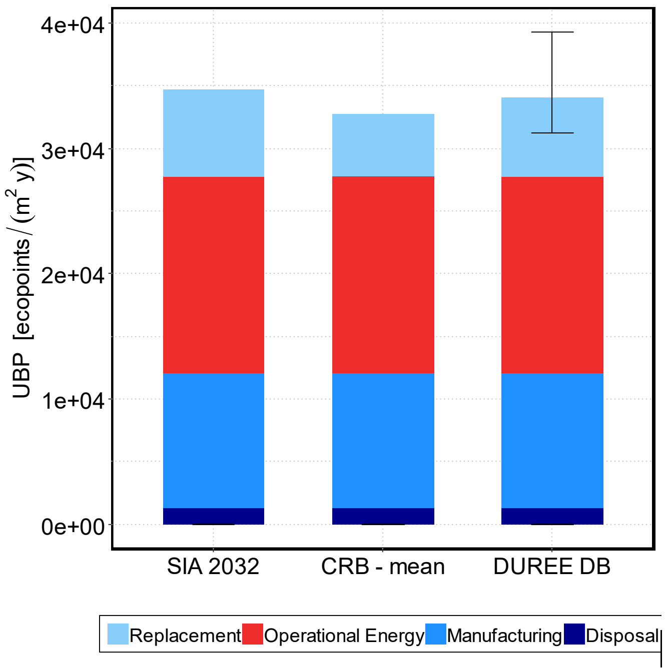

Figure 17: Contribution analyses for the probabilistic LCA and comparison with the deterministic LCA, using the SIA 2032 and CRB - mean service lives for the UBP indicator

The Sobol' Indices[13] are presented in Figure 18. Appendix 3 presents the median LCA results, expressed in UBP and the coefficients of variation for the element types. The highest influence on the LCA uncertainty derives from the G3 uncertainty, which does not have the highest UBP value, but the highest variance of the service life's distribution. Comparing the indices between the UBP indicator and the previous indicators, similarities can be found, regarding the most influential element types on the LCA uncertainty. The latter is mainly explained by five element types, i.e. G3 (internal finishing), G2 (flooring), E3.1 (windows), D1 (electrical installations), and E2.2 (compact façade). An increase on the sensitivity index for the electric installations (D1) is noted unlike the previous indicators. This can be explained by the fact that this indicator is more sensitive to building materials and more precisely to metals used in electric installations [14]. Hence, special attention should be paid on the determination of the service life of the technical systems, when the UBP indicator is used.

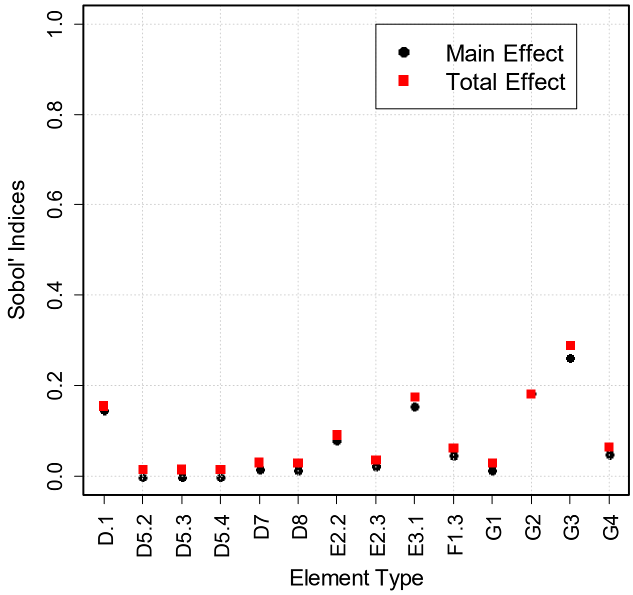

Figure 18: Sobol' Indices for the probabilistic LCA using the total environmental impacts (UBP) indicator

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[13] The same validation procedure, as presented, in section 3.1.1 was followed for the confidence of the estimates.

3.1.4 Life cycle cost assessment

The LCC was conducted for the B1 case study and the PDF, [μ=103.98 CHF/(m^{2}y), σ^2=12^2], is presented in Figure 19. The most probable value of the PDF, i.e. the mode of the distribution, is 98 CHF/(m^{2}y) for the period of the 60 years and it is found to be higher than the deterministic SIA 2032 [92.5 CHF/(m^{2}y)] and CRB [min=151 CHF/(m^{2}y), mean=89 CHF/(m^{2}y) and max= 79 CHF/(m^{2}y)]. The coefficient of variation (*cv* = 10%) is relative low, showing a small dispersion of the distribution and the 95% confidence interval of the mean is [103.98 CHF/(m^{2}y) ±0.1] revealing the accuracy of the simulations. Comparing the LCC with the LCA (for the GHG emissions), it can be noticed that the latter is slightly more spread out with a coefficient of variation (*cv*=14%).

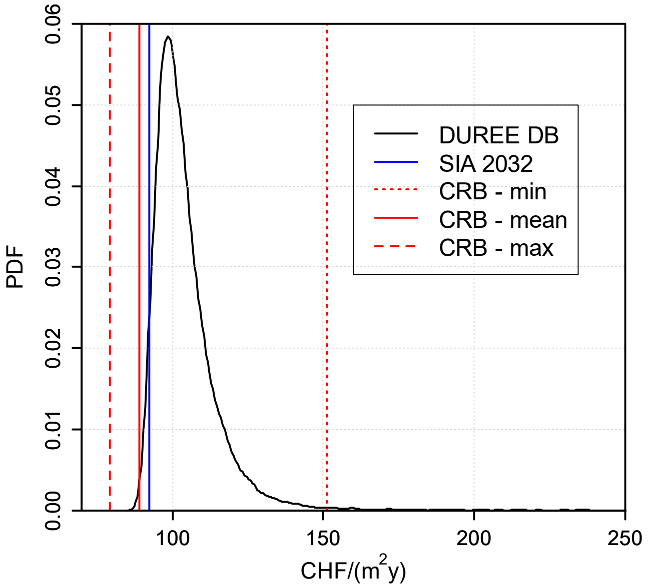

Figure 19: *PDF of the probabilistic LCC for the B1 case study and comparison with the deterministic LCC, using the SIA 2032 and CRB service lives*

Figure 20 presents the contribution analysis for the two deterministic approaches and the probabilistic LCC. For the latter, the first and third quartiles are plotted together with the median value of the replacement rates, i.e. $Q1 = 88\, CHF/(m^2y)$, $Q3 = 108\, CHF/(m^2y)$ and $median = 93\, CHF/(m^2y)$, respectively. For the probabilistic LCC and the central fifty per cent of the simulations, the investment costs represent a share of 72% to 59%, while the replacement stage represents a share of 15% - 30%. The operational energy costs present a small share in the total LCC, i.e. 5% to 6%, as well as the maintenance costs. They are much limited than those for the LCA indicators due to the discounting of the future energy costs and the low energy consumption of the building.

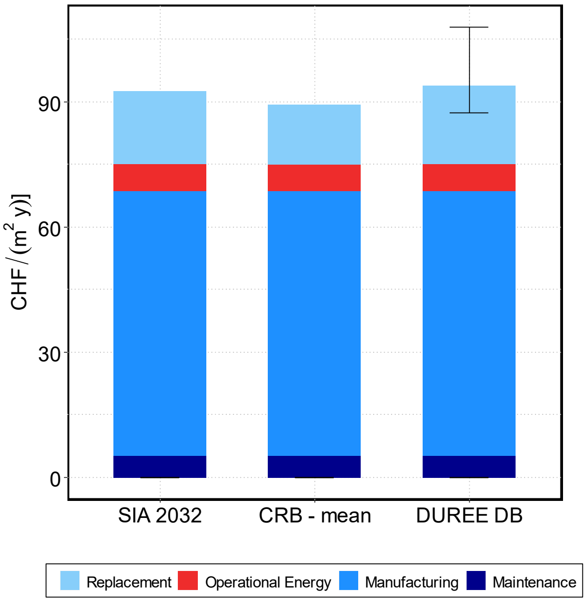

Figure 20: Contribution analyses for the probabilistic LCC and comparison with the deterministic LCC, using the SIA 2032 and CRB - mean service lives

Figure 21 presents the Sobol' Indices for the LCC and the B1 case study. Appendix 3 presents the median LCC results, and the coefficients of variation for the element types. The general tendency of the indices is similar to that of the LCA indicators. The uncertainty on the service lives of the technical systems does not affect the LCC, as found for instance for the GHG emissions. The uncertainty on the service lives of the elements E and G present the highest impact on the LCC uncertainty. More specifically, it is the element G.2 (flooring), which presents the highest Sobol' Index, while the element types E3.1 (windows) and G3 (wall coverings) follow. As already explained for the LCA, this result can be explained by the link between the coefficient of variation of the elements types and the replacement costs, as calculated based on SIA Série de Prix 2010 [21]. However, this relationship is less straightforward than in LCA. In LCC calculation, the stochastic replacement rate is transformed in discounted rate, calculated for all the years in which the replacement occurs.

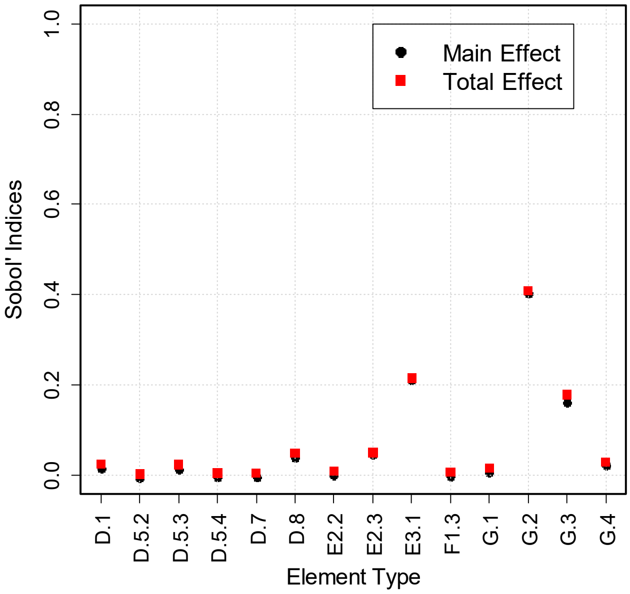

Figure 21: Sobol' Indices for the probabilistic LCC and the B1 case study

3.1.4.1 Uncertainty of economic costs

The investment costs of building elements are likely to present higher uncertainties than the environmental impacts [38]. According to SIA 108 [22], during the preliminary study the precision of the cost estimation should be fixed. The Federal Statistical Office (FSO) and the Center for buildings' rationalization (CRB) recommend that during the preliminary study the precision should be approximately ±25% [39]. Following these recommendations, an additional study is conducted, in order to integrate the uncertainty of the economic data costs. A uniform distribution is added and the uncertainty of the data costs is integrated in the LCC model. The lognormal PDF (μ=103.96, σ^2=14^2) of the new LCC is presented in Figure 22. As expected, the new LCC presents a higher coefficient of variation (cv=14%), than the LCC, without uncertainty (cv=10%). As far as the Sobol' Indices are concerned, there was no significant modification in their tendency, due to the integrated uncertainty on the initial costs. The LCC remained sensitive to the uncertainty of G.2, G.3 and E3.1, as it was the case for the LCC, without the investment costs' uncertainty.

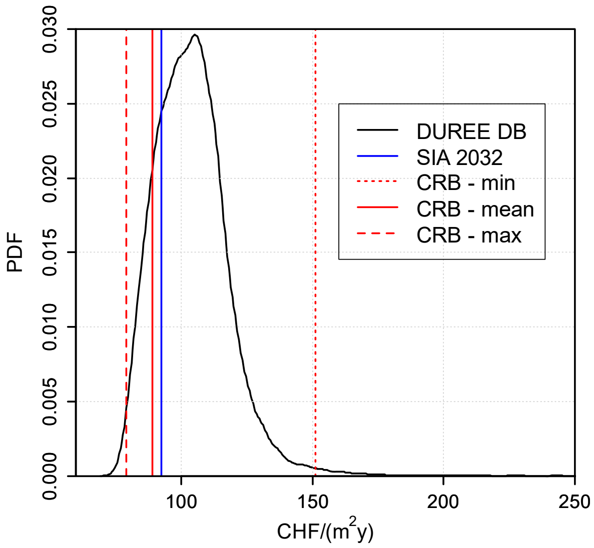

Figure 22: PDF of the probabilistic LCC for the B1 case study and comparison with the deterministic LCC, using the SIA 2032 and CRB service lives

3.2 LCA & LCC for energy-related building renovation

This section presents the probabilistic LCA and LCC for the energy-related renovation case study, which was described in Section 1.1.2. The uncertainty and sensitivity LCA analysis are conducted for the GHG emissions indicator and for the renovated building.

Two datasets are used for the service lives. The first dataset comes from the DUREE database while the second dataset is based on the SHEDS study. The SHEDS data covers estimated service lives of certain elements, which are replaced during energy-related renovations (building envelope and heat producer). The used data are the following: the heat production (D5.2), the compact façade (E2.2) and ventilated façade (E2.3), the windows (E3.1) and the slanted roof (F1.3). The interior elements, i.e. G3 (finishing) and G4 (ceiling) are not part of the WP2 survey. Hence, the data for these elements come from the DUREE DB. Furthermore, concerning the façade, the element type E2.2 (compact façade) was used, instead of the E2.3 (ventilated façade). This difference derives from the small number of data, reported for the ventilated façade that did not allow fitting properly a distribution[14].

3.2.1 GHG emissions

The GHG emissions results, taking into account the DUREE DB, are presented in Figure 29. The probabilistic LCA [μ=5.3 kg $CO_{2\text{-}eq}/(m^2y)$, σ^2=0.3] shows a relative small dispersion from the mean, with a coefficient of variation of *cv*=5.5%. As far as the sensitivity indices are concerned, the LCA uncertainty is mainly explained by the uncertainty due to the service life of windows (E3.1) and that of the heat production (D5.2). It should be noted, that the high LCA sensitivity on D5.2 (heating system) derives from the relative small number of the renovated element types that take part in the LCA, in combination with the relative high GHG emissions of D5.2, i.e. a heat pump of 60kW to cover the heating needs of the 1446 m^2_{ERA} of the case study. The GHG emissions are relatively small in this renovation scenario (5.0 kg $CO_{2\text{-}eq}/(m^2y)$), due to the replacement of the oil boiler by an air-to-water heat pump.

The results with the WP2 dataset are presented in Figure 24. The probabilistic LCA, [μ=5.8kg $CO_{2\text{-}eq}/(m^2y)$, σ^2=1.2], exhibits high dispersion from the mean, with a coefficient of variation of *cv*=20%. The LCA uncertainty based on the WP2 data is higher than the those based on the WP1 data. This means that the variability of the empirical service lives in WP2 is higher than those of the literature in the DUREE DB. However, the ranking and values of the Sobol' Indices remain similar between the two samples, proving that independently of the dataset used, there is a similar inherent variability exhibited by these building elements.

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[14] This switch from E2.2 to E2.3 does not have a high impact on the heating demand. Both allow to reach a similar heating demand and a similar *U*-value for the external walls.

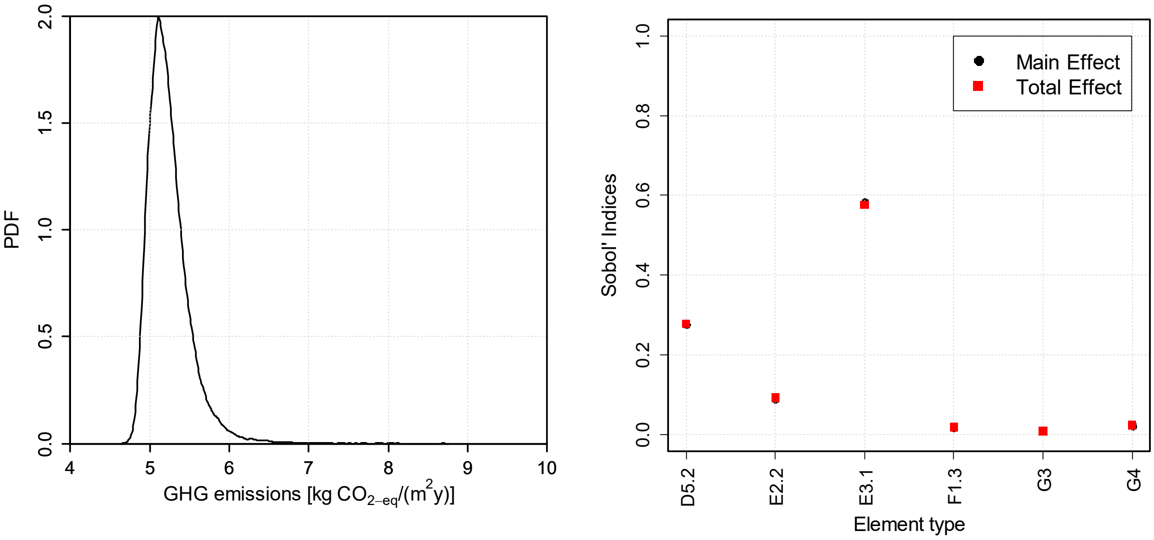

Figure 23: PDF of the probabilistic GHG emissions, based on the WP1 dataset for the energy-related renovation case study (left) and corresponding Sobol' Indices (right).

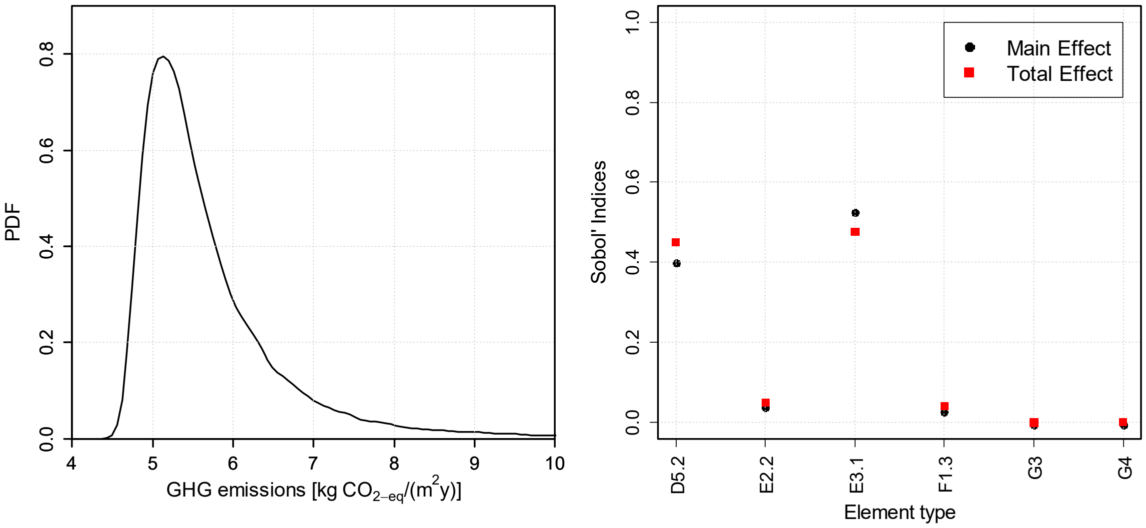

Figure 24: PDF of the probabilistic LCA for the GHG emissions, based on the WP2 dataset for the energy-related renovation case study (left) and corresponding Sobol' Indices (right)

Figure 25 presents the contribution analysis of the probabilistic LCA, using the WP1 and WP2 dataset. The median LCA is plotted along with the first and third quartile. For the renovation case, the operational energy presents the highest contribution in the total LCA, representing a share of 73% of the median LCA, for both datasets. The replacement represents a share of 14% and 13%, for WP1 and WP2 dataset respectively, while the manufacturing stage a share of 11% for both datasets and the median LCA. Finally, the quartiles show the higher dispersion, exhibited for the LCC, using the empirical values, as already discussed above.

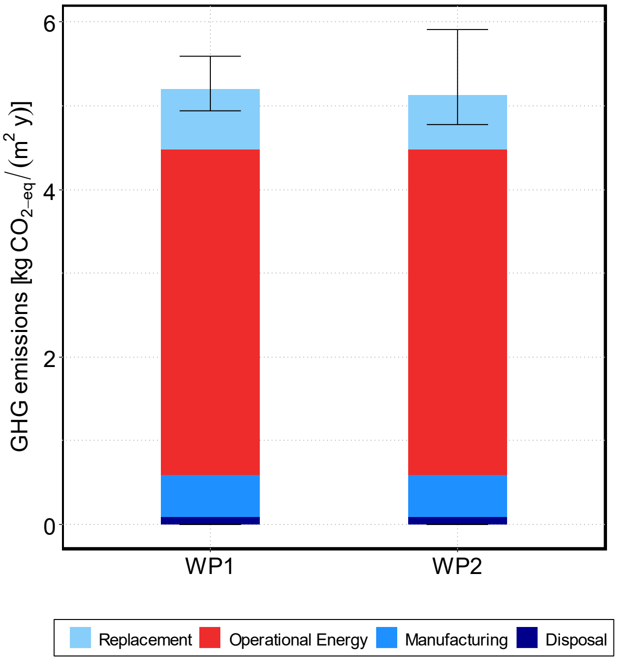

Figure 25: Contribution analyses for the probabilistic LCA, using the WP1 and WP2 dataset.

3.2.2 Life cycle cost

Figure 26 (left) shows the LCC [μ=15 CHF/(m^{2}y), σ^2=1.25] of the WP1 dataset with a coefficient of variation of *cv*=9%. The LCC variability is mainly explained by the uncertainty of the E2.2 element type (compact façade), see Figure 26 (right). This result can be explained by the fact that the E2.2 element type presents by far the highest contribution to the LCC. Figure 27 (left) presents the probabilistic LCC [μ=17.15 CHF/(m^{2}y), σ^2=5], using the WP2 dataset. As expected, it exhibits higher dispersion (*cv*=30%). Finally, the same element types explain the variability of the LCC, using the WP2 dataset, as it was the case for the WP1 dataset, see Figure 27 (right). It is interesting to note that, for the renovation case, the spread of the PDF for the LCC analysis, using the WP2 data is much higher than the spread using the WP1 data, proving the higher variability of the WP2 service lives.

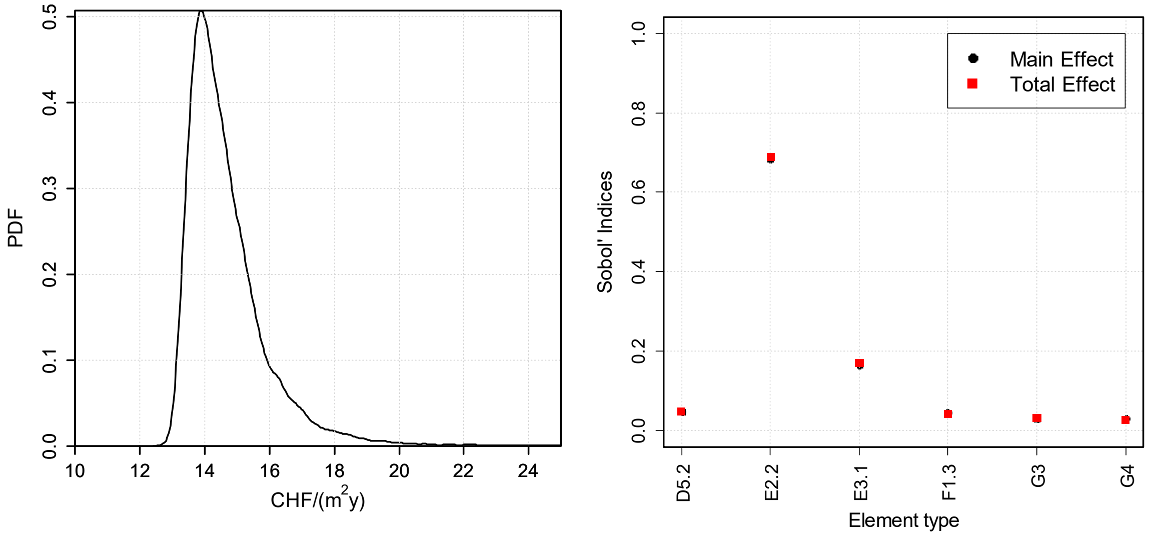

Figure 26: PDF of the probabilistic LCC, based on the WP1 dataset for the e-Ren case study (left) and Sobol' Indices (right).

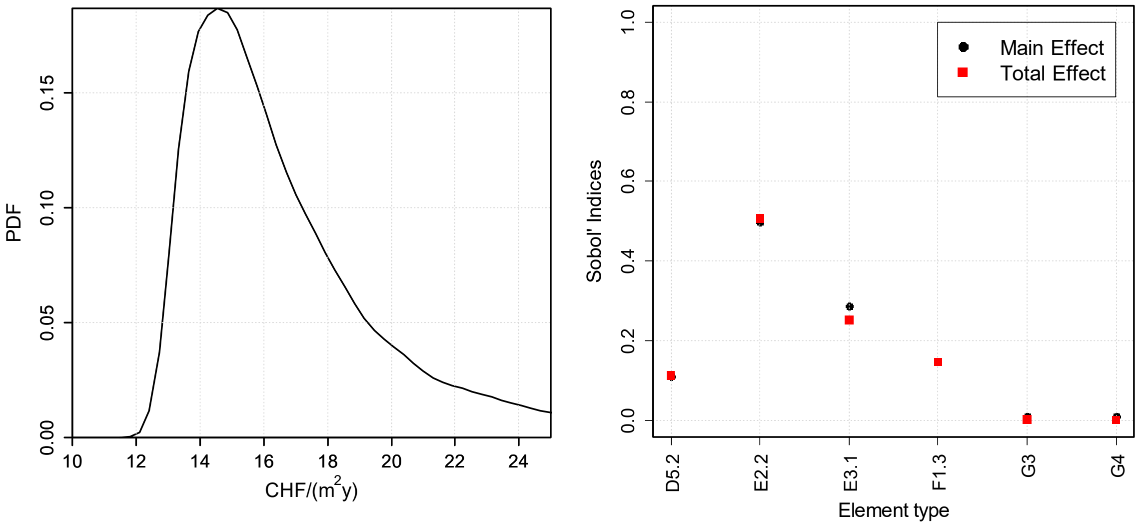

Figure 27: PDF of the probabilistic LCC, based on the WP2 dataset for the e-Ren case study (left) and Sobol' Indices (right).

Figure 28 shows the contribution analysis for the probabilistic LCC for both datasets, along with the first and third quartiles. The manufacturing stage presents the highest share, that of 56% of the LCC, for the median value. The operational energy follows, with 23 % and the replacement stage with 21%, for the WP1 dataset. There are no significant differences concerning the shares of the different stages, between the two datasets. Finally, the quartiles show the higher dispersion of the LCC, calculated with the empirical values.

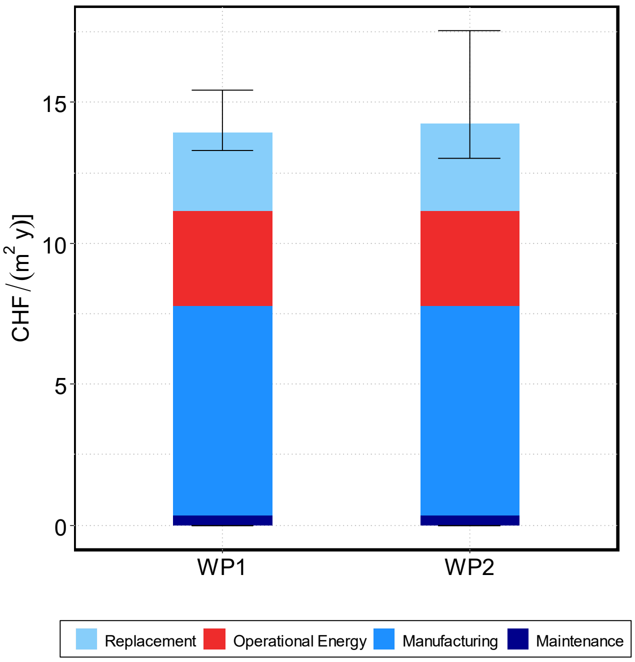

Figure 28: Contribution analyses for the probabilistic LCC, using the WP1 (DUREE database) and WP2 (SHEDS) dataset.

4 Discussions

In this section, different methodological alternatives and model assumptions are discussed. Based on the baseline calculation of the previous sections (B1 case study for the second analysis), i.e. the building lifetime, the calculation mode of the replacement rate (fractional vs. rounded up) and the wall types (compact vs. ventilated) are varied. In the end, the relationship between the contribution of the element types on the LCA/LCC and their sensitivity indices is discussed.

4.1 Variation of the building lifetime

4.1.1 LCA

The first analysis concerns the variation of the reference study period (RSP). According to SN EN 15978 standard [40], the RSP is a highly uncertain parameter, since it is not clear how many years a building remains in function. The national LCA methods generally uses conventional values for this parameter. In Switzerland, the LCA national method (SIA 2032 and SIA 2040 technical books [12]) proposes 60 years. The SIA 480 standard does not define an RSP but the service life of the building structure instead. The SIA 480:2004 standard [41] considers from 80 to 100 years while the revised 2016 version considers from 40 to 120 years with an intermediate value at 75 years [42]. In addition, the SNARC method, used in early design stages, considers 30 years [43]. Other LCA methods in Europe consider 50 years [44], 80 years [45] or even 120 years [46].

In these scenario analyses, the building RSP is varied from 30 up to 120 years, with intermediate values of 50, 60, 80 and 100 years, in order to identify the sensitivity on the LCA and LCC of this methodological convention, among different methods and countries. The intermediate values derive from the most common used RSP among the LCA methodologies, applied in different countries [47]. The calculation was conducted for the B1 case study. The contribution analyses and the sensitivity indices were calculated for the GHG emissions indicator. Figure 29 presents the contribution analyses of the B1 for the different RSP, for the probabilistic GHG emissions. The median of the replacement rate is plotted, along with the first and third quartiles. As expected, looking at the median value, the share of the manufacturing stage decreases, from 57% to 23%, while the replacement environmental impact increases, from 15% to 42%, when shifting from 30 years to 120 years. This is due to the shift in the life cycle stages, when the RSP is extended: the share of the replacement phase increases, since replacement occurs more times, during 120 years, while the impact of the initial construction (manufacturing stage) decreases, since it is apportioned to much more years.

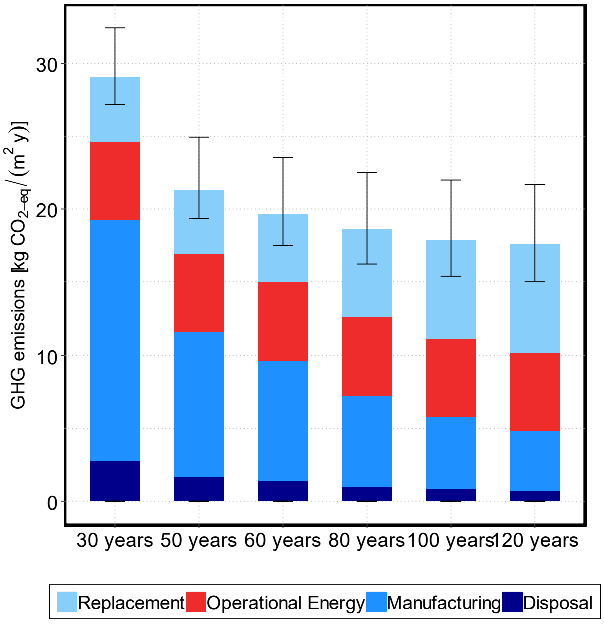

Figure 29: Contribution analyses for the probabilistic GHG emissions using the DUREE database for different building lifetimes of 30 up to 120 years

Figure 30 presents the first order Sobol' Indices for the different RSP. The results show that the LCA uncertainty can be significantly influenced by the variation of the RSP. Moving from 30 to 120 years, important variations of the Sobol' indices can be found since the replacement rate and consequently the sensitivity indices change in function of the RSP. For example, as far as the 30 years of RSP is concerned, the LCA variability is mainly explained by the uncertainty of the flooring (G.2), while for an RSP of 120 years, the LCA variability is explained by the G.2, along with the F.1.3 and E.2.1. However, even if the impact of the element types varies among the different RSP, the same element types are always responsible for the uncertainty of the LCA, i.e. the G.2 (flooring), E.2.2 (compact façade), E3.1 (windows), F.1.3 (roof) and G.3 (internal coatings). Finally, it is important to note that, the LCA uncertainty is not affected by the uncertainty of the service lives of the technical systems (D1 to D8), whatever the RSP is.

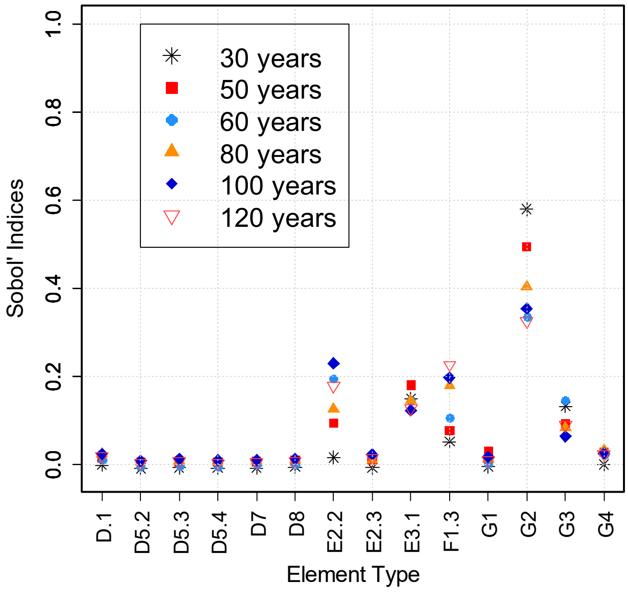

Figure 30: Sobol' Indices for the GHG emissions and the B1 case study for different building lifetimes of 30, 50, 60, 80 and 100 years

4.1.2 LCC

In Chapter 3, the LCC was calculated using an RSP of 60 years and the costs were equally apportioned to each year for this period, in order to be consistent with the LCA methodology and the CRB guidelines. However, in the literature, there are LCC studies that use an RSP of 30 years, as for example in [48]. In the current study, the RSP is varied from 30 to 60 years, with an intermediate value of 50 years. The upper limit of the study was defined at 60 years, since the period beyond this limit does not represent a realistic economic payback period. Furthermore, there is uncertainty linked to the fluctuation of the discount and inflation rates, which does not allow to long-term future predictions. Figure 31 presents the contribution analysis for the different RSP.

As expected the manufacturing stage has the highest share on the probabilistic LCC for all RSPs, with shares of 63% to 67% at 30 years, for the central 50% simulations. It is further reduced when moving towards 60 years. As far as the replacement stage is concerned, at 30 years, it represents 23% to 28% of the LCC, while at 60 years, it represents a share of 15% to 30%, on the total LCC. The tendency of the replacement rate is different, between the LCA and LCC. This fact derives from the different discounted values of the costs, between 30 and 60 years, since the economic value is reduced progressively, when moving towards 30 to 60 years. For example, by assuming the same replacement rate for both 30 and 60 years, the discounted costs for 30 years are higher than that of 60 years, i.e., with a replacement rate of *k*=1, at 30 years, the replacement occurs at 15 years while for the scenario of an RSP=60 years, it occurs at 30 years.

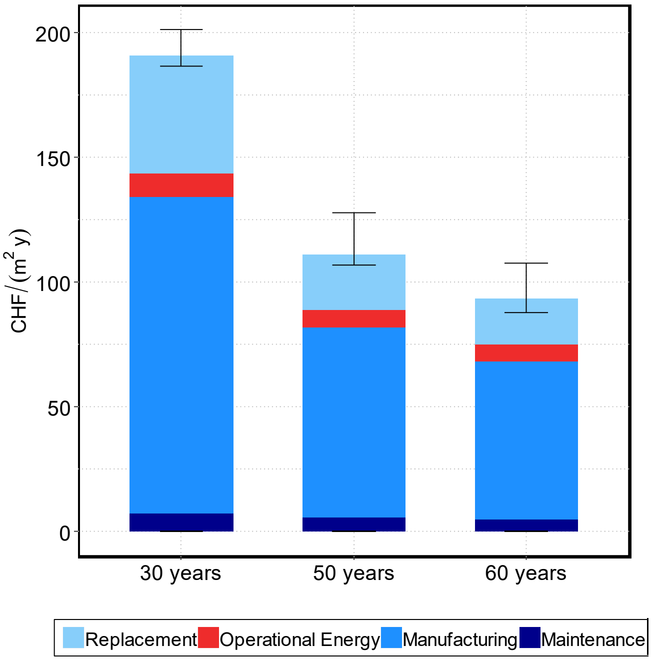

Figure 31: Contribution analyses for the probabilistic LCC using the DUREE database for different building lifetimes of 30, 50, and 60 years

Figure 32 presents the sensitivity indices for the B1 case study and the three aforementioned RSP. The results show that the LCC is significantly sensitive to the building's lifetime variation, with indices varying from $S_{iE2.3} = 0.2$ to $S_{iE2.3} = 0.03$ for the E.2.3 element type (ventilated façade). However, the uncertainty of the LCC is explained with a systematic way for the three RSPs, i.e., the same element types describe the LCC uncertainty, i.e. G.2, G.3, E3.1 and E2.3. Finally, it is interesting to note that the technical systems (D1 to D8) do not influence the LCC uncertainty for all the different RSP, as it was the case for the LCA uncertainty. Hence, both for the LCA and LCC calculations, special attention should be paid to the choice of the RSP.

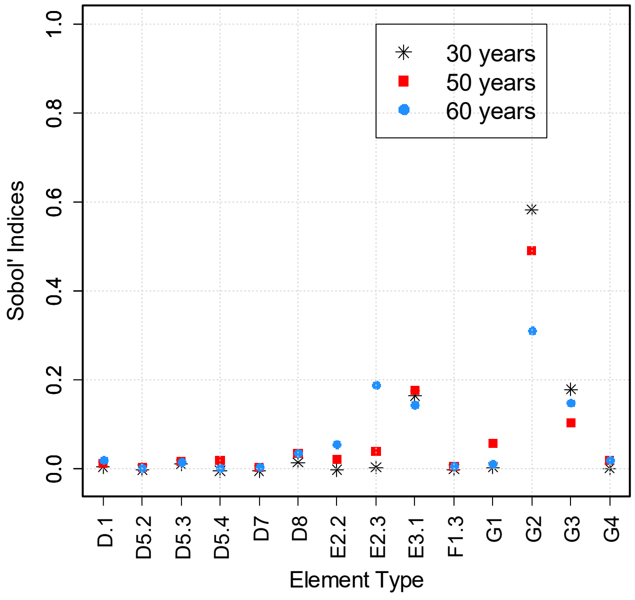

Figure 32: Sobol' indices for the probabilistic LCC and the B1 case study for different building lifetimes, i.e. 30, 50, and 60 years.

4.2 Fractional versus rounded replacement rate

The baseline scenario for reporting the LCA and LCC results in Chapter 3 considers the fractional mode, as defined in SIA 2032 and SIA 2040. In the current section, the fractional mode is compared with the rounded mode, according to SN EN 15978 [1]. In addition, the “rounded - 20%” mode is included. According to this mode the replacement rate is rounded up, in case that it is higher than 20% of its integer value, otherwise it is rounded down. Such a calculation mode is implemented in some of the building LCA calculation software, as for example in [45]. Like that, overestimation is avoided in case that the replacement rate is very small, e.g. k = 1.05. Figure 33 presents the Sobol’ Indices for the three different calculation modes for the replacement rate. The results show that the tendency of the sensitivity indices remains the same, independently of the calculation type. As a result, even if rounded up, or rounded - 20% may better reflect the reality of the replacement rates, the use of the fractional replacement rate does not change the order of the sensitivity indices and their impact on the LCA uncertainty.

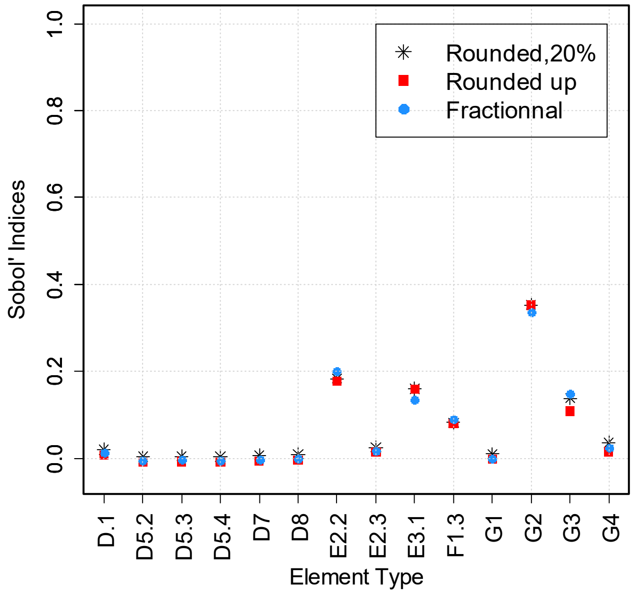

Figure 33: Fractional, rounded up, rounded 20% influence on the Sobol’ Indices for the GHG emissions and the B1 case study

4.3 Variation of the façade type

The influence of the different façade types (ventilated vs. compact) on the sensitivity indices was evaluated and it is presented in this section. The analysis is conducted for the GHG emissions and the B1 case study, which includes these two types of external walls. Three alternatives are considered:

- the baseline result “as built” with a mix of compact and ventilated façades;
- a variant with 100% ventilated façade by adjusting the LCA values and the service lives of the compact façade elements to a ventilated facade;
- a variant with 100% of compact façade by adjusting the LCA values and the service lives of the ventilated façade elements to a compact façade.

The Sobol’ Indices are presented in Figure 34. Concerning the case of the 100% compact façade, it is the uncertainty of the service life of the E.2.2, (compact façade) that explains a significant portion of the LCA uncertainty. Contrary to the two other cases, for which the G.2 element type (flooring) has the highest influence on the LCA uncertainty. This difference can be explained by the relative higher environmental impact (GHG emissions) of the concrete compact façade, compared to the ventilated wooden façade. Hence, it is interesting to note that for the case of the compact façade, even if the dispersion of the E2.2 (external insulation and rendering) distribution is not the highest, it is its environmental impact that determines the order of the sensitivity index.

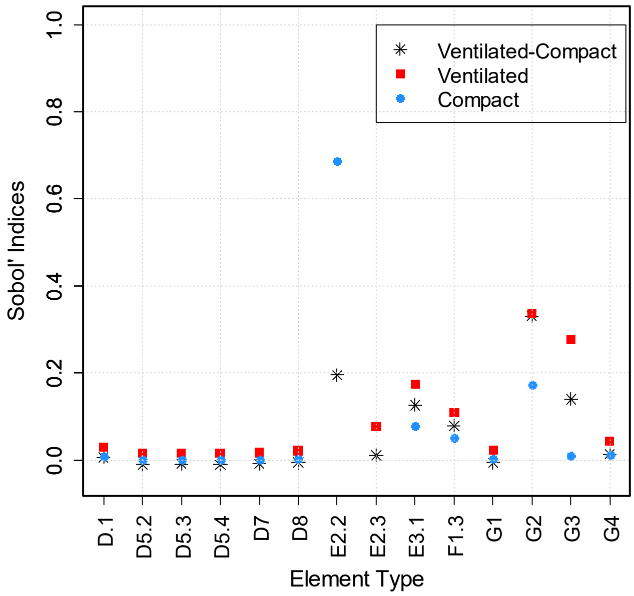

Figure 34: Sobol' Indices for the B1 case study for different façade configuration, i.e.as-built: ventilated-compact, 100% ventilated and 100% compact

4.4 Contribution analysis vs. sensitivity analysis

Previous studies have shown the contribution of the parameter's uncertainty to the output's uncertainty, as a function of their environmental contribution to the output. Examples of such studies are presented in Heijungs R [49], Hoxha et al. [50] and Häfliger et al. [6]. Heijungs R [49] presents a qualitative relationship between the uncertainty of the input data and their contribution to the final LCA output. Hoxha et al. [50] and Häfliger et al. [6] reported several variations of the aforementioned concept, in order to evaluate the uncertainty on the LCA output, based on the uncertainty of input data. In this section, we discuss the relationship among the relative environmental contribution of the element types to the LCA output and their contribution to the LCA uncertainty (i.e. sensitivity indices), as well as to the uncertainty of the replacement rate (input).

Figure 35 (upper part) presents the coefficients of variation of the different element types, as a function of their contributions to the LCA, expressed in GHG emissions. By doing so, the relationship of the input uncertainty to the output of the model (LCA) for the different element types can be identified. The service life of the element types is attributed, as in the first level of analysis (construction categories: C: structure, D: technical systems, E: façade coatings, F: roof, G: interior coverings). This visualisation is similar with the concept introduced by Heijungs R [49]. The results show that the C element type has a high contribution to the environmental impacts, and zero input uncertainty on the model (the RSP being a deterministic parameter in this study). The D and F element types have low contributions to the GHG emissions and low input uncertainty on the model. On the contrary, the E and G element types can have low to high contributions to impacts and relatively high input uncertainty on the model.

Figure 35 (lower part) presents a scatterplot of the Sobol' Indices, as a function of the median contributions to the LCA, expressed in GHG emissions based on the results of this study. Like that, the relationship between the contributions to the building LCA uncertainty (Sobol' Indices) and the relative contributions to the LCA of the different element types is demonstrated. Furthermore, the median value of the service life's PDF is chosen, in order to calculate the contributions of each element type. From the results, it can be concluded that the technical equipment (D) and the roofing (F) exhibit low contribution to the impacts (GHG emissions), as well as to the building LCA uncertainty. On the contrary, the E and G element types tend to contribute more to the building LCA uncertainty and to the environmental impacts.

These comparative results show that the Sobol' Indices are able to rank differently a same element for the three buildings while the coefficient of variation of the element types' service life remains the same whatever the building. This comparison shows the benefits of relying on GSA techniques (e.g., Sobol' Indices) to identify in a robust way the sensitivity of the input parameters.

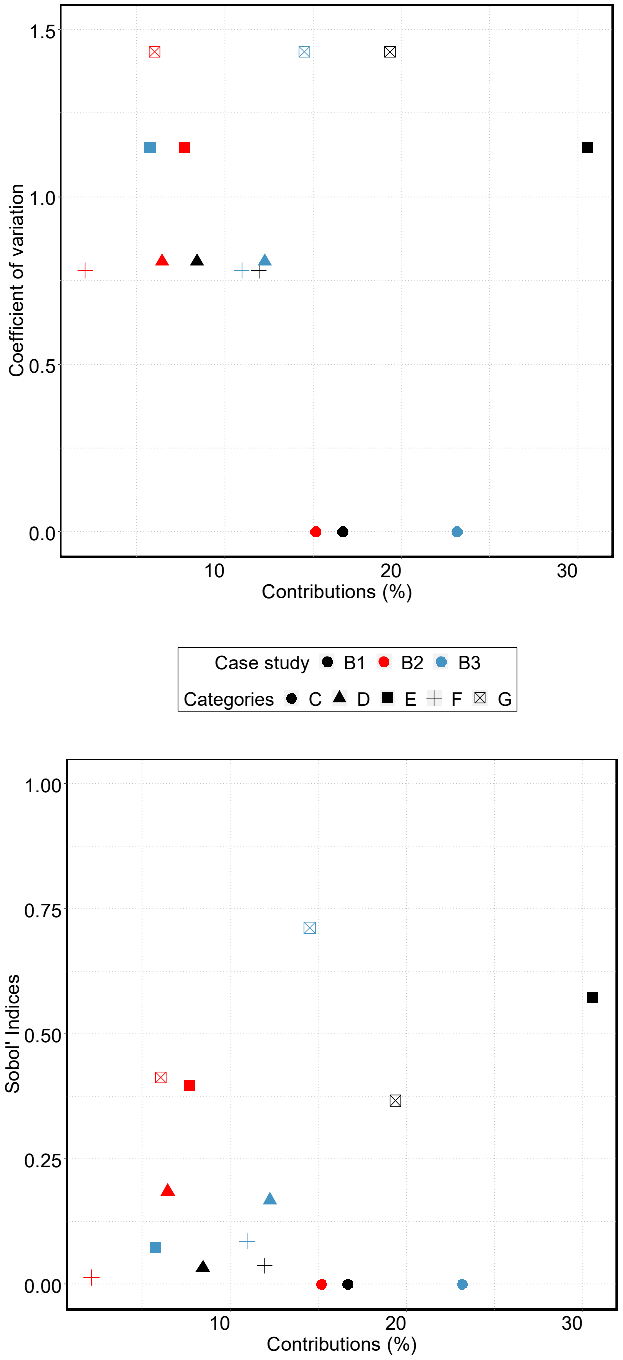

Figure 35: Coefficient of variation (input of the model) as a function of the contribution to the GHG emissions (upper scatterplot) and Sobol' Indices (contributions to uncertainty) as a function of the contribution to the GHG emissions (lower scatterplot) for the different construction categories (C: structure, D: technical systems, E: façade coatings, F: roof, G: interior coverings)

5 Limitations of the study and future work

a) Influence of the number of the input data

The DUREE DB was extended, thanks to the participation in the IEA-EBC Annex 72 project [46], where partners supplied additional service lives from Europe and North America. The first version of the DUREE DB comprised 34 sources and 54 input data (as of 31st December 2018), while the second version (as of 1st May 2019) comprised 67 sources and 95 input data. Figure 36 present the Sobol' Indices for the two different DB versions. The results did not change and the same element types explained the LCA uncertainty, for both versions. The ranking among the most influential elements, i.e. the order of the Sobol' Indices, have only slightly changed.

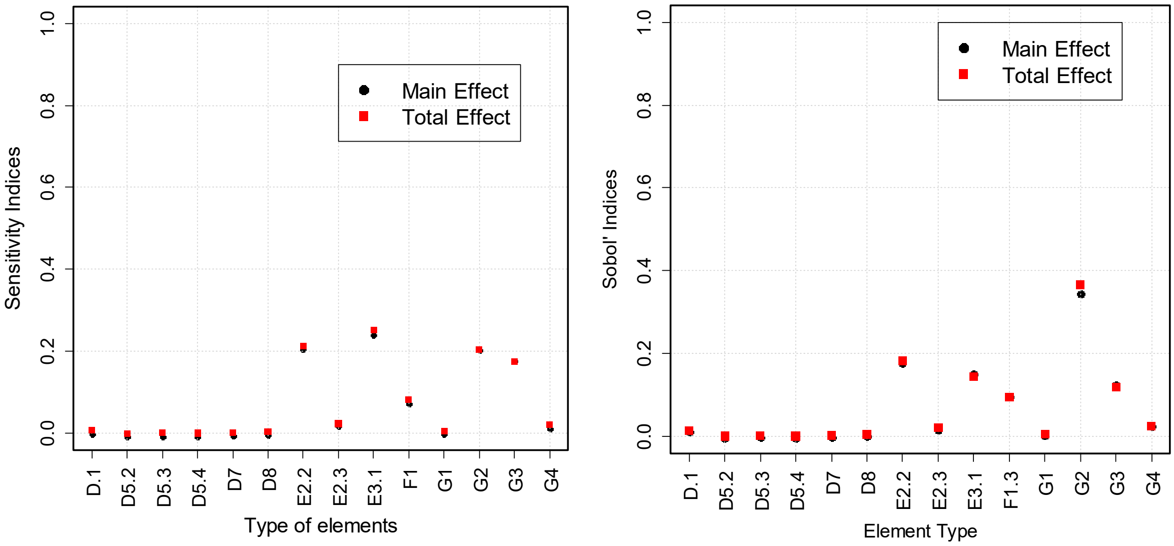

Figure 36: Left - Sensitivity indices for the DUREE Database – Version 1 (as of March 2019). Right – Sensitivity indices for the DUREE Database – Version 2 (as of May 2019).

b) Number of case studies and generalization of the results

The study showed a relatively small variability of the sensitivity indices among the analysed buildings. However, LCA uncertainty is mainly sensitive to six to seven element types in the second analysis.

Future work

a) The DUREE Database could be enriched, in order to include more data.
b) Additional case studies are also needed to secure these findings.
c) The probabilistic methodology of the current study (presented also in Figure 4) can be applied to the parameters for the calculation of the heating demand, according to the SIA 380/1 standard or the other parameters of the LCA & LCC analysis. Preliminary studies include the analysis of the performance gap of the heating consumption in a new building (Padey et al 2018 [51], UserGap SFOE project) or the analysis of renovation scenarios in Galimshina et al 2019 [52], funded by the Swiss National Foundation (SNF).

6 Main outcomes and recommendations

The main outcomes and recommendations based on the analysed building case studies are the following:

Main outcomes

- A systematic way to treat probabilistically the replacement rate of the element types, is to use the DUREE DB and proceed to the identification of the element types PDFs.
- The uncertainty of the replacement rate can significantly affect the LCA uncertainty, evaluated with the coefficient of variation, *cv*=14%.
- The replacement stage within a probabilistic framework, accounts for 14% - 36% of the GHG emissions for an SFH (new construction).
- There is a relative small variability of the ranking of the most influential elements on the LCA (ranking of the sensitivity indices), linked to the type of the building. 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 (compact facade), the E3.1 (windows), the F1.3 (roofing), the G2 (flooring), G3 (internal finishing) and G4 (ceiling covering). This means that special attention should be given on the way the replacement rate for these element types is chosen, in further LCA calculations.
- The uncertainty of the elements replacement rate affects similarly both LCA and LCC analyses. In addition, the same element types explain the uncertainty of both outputs, apart from the D1 element type (electrical installation) for the UBP indicator and the E2.2 (compact façade) for the GHGe. Hence, for the UBP indicator and the GHGe special attention should be given to the attribution of the D1 and E2.2 service life, respectively;
- Elements that exhibit high relative environmental impact and high coefficient of variation are susceptible to have a higher impact on the LCA uncertainty. For these elements types, a probabilistic analysis is recommended, especially when building energy labelling is aimed.
- 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 (except for the D1 (electrical installations) for the UBP). In further probabilistic LCA analysis, the LCA model could be simplified using deterministic values from existing standards (SIA 2032, CRB).
- The empirical service lives from SHEDS present higher variability than that of the literature (DUREE DB), as showed by the coefficient of variation of the LCA for an energy-related building renovation, *cv*=5.5% and *cv*=23% respectively.

Recommendations for building LCA/LCC method developers

- The building RSP is an influential parameter on the LCA and LCC uncertainty. Different scenario analyses are recommended to capture more accurately the variability of the LCA and LCC.
- The LCA uncertainty is 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. Hence, either of these modes could be used in further LCA and LCC analysis.

Recommendations for LCA/LCC practitioners

- The minimum, mean and maximum CRB values of the elements service lives can successfully capture the variability of the probabilistic LCA. These three values can be used to determine the LCA variation, in order to avoid the probabilistic analysis.
- The deterministic SIA 2032 service lives values present a relative good approximation of the LCA mode, i.e. the most probable value of the probabilistic LCA.

7 Conclusions

This study presented a systematic way to deal with the service life uncertainty of building elements on the LCA and LCC calculations. More specifically, this study discussed the influence of the service lives uncertainty on the LCA and LCC and the identification of the element types' that most influence the LCA/LCC uncertainty. Monte Carlo simulations were computed, in order to take into account probabilistically the replacement rate and the Sobol' Sensitivity Indices were calculated to determine the impact of the service lives' variability on the LCA, for the different element types. This methodology was applied to three building case studies that corresponded to new constructions and one renovation case study. Two analyses were conducted for two levels of details and three LCA indicators were calculated, as well as the LCC.

For the new constructions, the first level of analysis (first level of details of the DUREE Database) showed that the LCA result is less sensitive to the uncertainty of the technical equipment (D) and the roofing (F), than to the wall coatings (E) and the interior coverings (G). The second level of analysis that used a lower level of details from the DUREE Database confirmed these findings and identified in further detail the most influencing element types on the LCA uncertainty, i.e. the E2.2 (façade), E3.1 (windows), F1.3 (roofing), G2 (flooring) and G3 (internal finishing). Furthermore, the results showed that the magnitude of the Sobol' Indices and the contribution of the replacement phase on the total LCA highly depend on the chosen indicators, e.g. the replacement share is more important for the GHG emissions than for the primary NRE and the UBP. As far as the LCA of the energy-related building renovation is concerned, the uncertainty of the E3.1 (windows) is the most influential on the LCA uncertainty, for both datasets (DUREE DB and SHEDS).

Except for the baseline study, the influence of different methodological choices on the LCA and LCC result was studied. In the beginning, the RSP was varied from 30 to 120 years and the results showed that the contributions of the LCA and LCC stages change as a function of the chosen RSP, as well as the magnitude of the Sobol' Indices. On the contrary, the output was sensitive to the variability of the same elements' service life. The second study, conducted for three calculation modes of the replacement rate (fractional vs rounded and rounded – 20%), showed that the mode does not influence the LCA result and the Sobol' Indices. The last analysis concerned the variation of the façade type (ventilated – compact) and the results showed the relative high influence of its selection. Finally, a summarizing graph of the parameters, i.e. uncertainties of the input (service lives of element types), contributions of the input on the output (LCA result) and the sensitivity of the output, was produced, in order to identify their possible links.

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Appendix 1: Goodness of fit for the lognormal distributions

Table 7 : WP1 dataset from the DUREE database (new construction & renovation case studies). Building elements codes from the DUREE database (WP1 study). Values in italic do not respect the limit (p-value < 0.05)

Element Type	Statistic	p-value	Element Type	Statistic	p-value
C	1.00	0.36	**E 2.2b**	0.94	*0.39*
C 1	1.09	0.31	**E 2.3**	0.41	*0.83*
C 2	1.31	0.23	**E 2.3a**	1.46	*0.19*
C 2.1a	0.88	0.42	**E 2.3b**	0.56	*0.68*
C 2.1b	1.13	0.30	**E 2.4**	0.83	*0.46*
C 2.2	1.65	0.15	**E 2.5**	1.32	*0.22*
C 3	1.40	0.20	**E 2.6**	0.21	*0.99*
C 4	1.31	0.23	**E 3**	1.30	*0.23*
C 4.1	1.13	0.30	**E 3.1**	0.78	*0.49*
C 4.2	1.17	0.28	**E 3.1a**	0.30	*0.94*
C 4.3	1.14	0.29	**E 3.1b**	0.35	*0.90*
C 4.4	0.39	0.86	**E 3.1c**	Fitting impossible due to limited number of data	
D	0.40	0.852	**E 3.1d**	0.39	*0.86*
D 1	0.56	0.683	**E 3.2**	0.77	*0.51*
D 1.3	1.17	0.280	**E 3.3**	0.69	*0.57*
D 1.2a	0.31	0.927	**F**	1.06	*0.33*
D 2	1.09	0.311	**F 1**	0.86	*0.44*
D 3	0.68	0.576	**F 1.1**	Fitting impossible due to limited number of data	
D 4	0.48	0.762	**F 1.2**	1.23	*0.26*
D 5	0.66	0.592	**F 1.3**	0.82	*0.46*
D 5.1	0.55	0.696	**F 1.4**	0.63	*0.61*
D 5.2	0.72	0.544	**F 2**	0.70	*0.56*
D 5.2a	0.71	0.545	**F 2.1**	0.40	*0.85*
D 5.2c	0.34	0.908	**F 2.1a**	2.79	*0.04*
D 5.2f	Fitting impossible due to limited number of data		**F 2.1b**	0.65	0.60
D 5.2d	2.24	*0.069*	**F 2.1c**	0.58	*0.67*
D 5.2e	2.00	*0.092*	**F 2.2**	0.31	*0.93*
D 5.3	0.58	*0.666*	**F 2.2a**	2.10	*0.08*
D 5.4	0.43	*0.817*	**F 2.2b**	0.15	*1.00*
D 6	0.66	*0.593*	**F 2.2c**	1.19	*0.27*
D 7	1.70	*0.136*	**F 2.2d**	0.35	*0.90*
D 7.1	0.60	*0.649*	**F 2.2e**	0.77	*0.50*
D 7.2	0.31	*0.933*	**G**	0.48	*0.77*
D 7.3	0.36	*0.887*	**G 1**	0.28	*0.95*
D 7.4	0.97	*0.373*	**G 1.1**	0.74	*0.52*
D 7.5	Fitting impossible due to limited number of data		**G 1.2**	0.30	0.94
D 8	0.64	*0.615*	**G 1.3**	0.40	*0.85*
D 8.0	1.02	*0.347*	**G 1.4**	0.76	*0.51*
D 9	0.53	*0.711*	**G 2**	0.64	*0.61*
D 9.1	0.65	*0.604*	**G 2.1**	0.36	*0.88*
E	0.36	*0.88*	**G 2.2**	0.38	*0.87*
E 1	0.24	*0.98*	**G 3**	1.07	*0.32*
E 1.1	0.28	*0.95*	**G 3.1**	0.28	*0.95*
E 1.2	0.44	*0.81*	**G 3.2**	0.86	*0.44*
E 2	1.44	*0.19*	**G 4**	0.74	*0.52*
E 2.0	0.70	*0.56*	**G 4.2**	0.73	*0.53*
E 2.1	0.87	*0.43*	**G 5**	0.70	*0.56*
E 2.2	0.52	*0.72*			
E 2.2a	1.76	*0.13*			

Table 8 : WP2 dataset from the SHEDS (Renovation case study). Building elements from the DUREE database (WP1 study). Values in italic do not respect the p-value limit (p-value < 0.05)

Element Type	Statistic	p.value	Element Type	Statistic	p.value
D5.2	4.4772	0.005124	**E3.1**	*13.812*	*6.073e-07*
E2.2	0.89633	0.4162	**F1.3**	0.63543	0.6146

Appendix 2: Lognormal distributions for service lives data

Table 9 : Parameters of the lognormal distributions of the element types

Element Type	meanlog	sdlog	Element Type	meanlog	sdlog
C	4.20	0.43	**E 2.2b**	3.43	0.52
C 1	4.17	0.51	**E 2.3**	3.78	0.34
C 2	4.30	0.35	**E 2.3a**	3.88	0.46
C 2.1a	4.29	0.36	**E 2.3b**	3.88	0.33
C 2.1b	4.29	0.36	**E 2.4**	3.82	0.47
C 2.2	4.42	0.30	**E 2.5**	2.79	0.74
C 3	4.35	0.46	**E 2.6**	3.99	0.39
C 4	4.17	0.46	**E 3**	3.37	0.43
C 4.1	4.41	0.31	**E 3.1**	3.37	0.46
C 4.2	4.11	0.51	**E 3.1a**	3.62	0.32
C 4.3	4.02	0.52	**E 3.1b**	3.60	0.38
C 4.4	4.31	0.30	**E 3.1c**	Fitting impossible due to limited number of data	
D	3.252	0.334	**E 3.1d**	3.47	0.37
D 1	3.324	0.463	**E 3.2**	3.40	0.50
D 1.3	2.761	0.654	**E 3.3**	3.14	0.55
D 1.2a	3.063	0.270	**F**	3.53	0.35
D 2	3.002	0.670	**F 1**	3.52	0.37
D 3	2.643	0.519	**F 1.1**	Fitting impossible due to limited number of data	
D 4	2.985	0.456	**F 1.2**	3.46	0.40
D 5	3.175	0.351	**F 1.3**	3.72	0.41
D 5.1	3.318	0.459	**F 1.4**	3.60	0.32
D 5.2	2.905	0.295	**F 2**	3.50	0.38
D 5.2a	3.023	0.225	**F 2.1**	3.40	0.31
D 5.2c	2.764	0.254	**F 2.1a**	3.45	0.15
D 5.2f	Fitting impossible due to limited number of data		**F 2.1b**	3.37	0.38
D 5.2d	3.013	0.228	**F 2.1c**	3.33	0.34
D 5.2e	2.814	0.419	**F 2.2**	3.54	0.38
D 5.3	3.345	0.483	**F 2.2a**	3.49	0.16
D 5.4	3.363	0.377	**F 2.2b**	3.42	0.40
D 6	2.845	0.420	**F 2.2c**	3.45	0.21
D 7	3.150	0.299	**F 2.2d**	3.40	0.38
D 7.1	3.008	0.519	**F 2.2e**	3.45	0.30
D 7.2	2.883	0.423	**G**	3.44	0.52
D 7.3	3.464	0.267	**G 1**	3.64	0.43
D 7.4	3.112	0.225	**G 1.1**	3.84	0.63
D 7.5	Fitting impossible due to limited number of data		**G 1.2**	3.64	0.37
D 8	3.456	0.373	**G 1.3**	3.51	0.74
D 8.0	3.418	0.331	**G 1.4**	3.48	0.54
D 9	3.214	0.442	**G 2**	3.40	0.55
D 9.1	3.233	0.434	**G 2.1**	3.93	0.37
E	3.44	0.48	**G 2.2**	3.22	0.61
E 1	3.74	0.47	**G 3**	3.39	0.63
E 1.1	3.84	0.47	**G 3.1**	3.64	0.60
E 1.2	3.77	0.49	**G 3.2**	3.28	0.71
E 2	3.38	0.68	**G 4**	3.46	0.56
E 2.0	3.93	0.49	**G 4.2**	3.44	0.61
E 2.1	3.15	0.72	**G 5**	3.28	0.50
E 2.2	3.63	0.32			
E 2.2a	3.81	0.46			

Appendix 3: Median building LCA and LCC results

1. First level of analysis

Table 10 : GHG emissions [kg CO2eq/(m2y)] for the B1 case study in the first analysis

Element Type	Manufacturing	Disposal	Replacement	Coefficient of variation (cv)
C	3.1	0.3		
D	0.5	0.1	0.8	0.82
E	2.2	0.5	2.1	1.2
F	1.1	0.2	1.0	0.8
G	1.3	0.3	1.4	1.4
Operational Energy			5.4	

Table 11 : GHG emissions [kg CO2eq/(m2y)] for the B2 case study in the first analysis

Element Type	Manufacturing	Disposal	Replacement	Coefficient of variation (cv)
C	2.0	0.1		
D	0.7	0.2	1.1	0.82
Geothermal Probes	0.45	0.05	0.2	-
E	1.0	0.1	0.8	1.2
F	0.1	0.1	0.2	0.8
G	0.8	0.1	0.7	1.4
Operational Energy			3.6	

Table 12 : GHG emissions [kg CO2eq/(m2y)] for the B3 case study in the first analysis

Element Type	Manufacturing	Disposal	Replacement	Coefficient of variation (cv)
C	2.9	0.3	0.0	
D	0.5	0.1	0.8	0.82
Geothermal Probes	0.3	0.0	0.2	-
E	0.3	0.0	0.3	1.2
F	0.5	0.3	0.6	0.8
G	0.8	0.1	0.7	1.4
Operational Energy			4.2	

2. Second level of analysis – B1 Case study

Table 13 : GHG emissions [kg CO2eq/(m2y)] for the B1 case study in the second analysis

Element Type	Manufacturing	Disposal	Replacement	Replacement (%)	Coefficient of variation (cv)
C	3.1	0.3			
D1	0.2	0.1	0.2	4	1.12
D5.2	0.025	0.001	0.1	2	0.44
D5.3	0.1	0.03	0.1	2	0.74
D5.4	0.04	0.01	0.1	2	0.74
D7	0.1	0.01	0.2	4	0.7
D8	0.2	0.03	0.2	4	1.0
E2.2	1.1	0.4	1.0	20	1.0
E2.3	0.4	0.01	0.1	2	1.6
E3.1	0.7	0.1	0.9	18	1.12
F1.3	1.1	0.2	0.7	14	1.0
G1	0.2	0.004	0.1	2	1.2
G2	0.7	0.3	0.8	16	1.25
G3	0.3	0.04	0.3	6	1.8
G4	0.2	0.03	0.2	4	1.56
Operational Energy			5.4		

Table 14 : Primary NRE [kWh/(m2y)] for the B1 case study in the second analysis

Element Type	Manufacturing	Disposal	Replacement	Replacement (%)	Coefficient of variation (cv)
C	9.8	1.2			
D1	0.9	0.01	0.98	5.1	1.12
D5.2	0.113	0.001	0.254	1.3	0.44
D5.3	0.4	0.0	0.5	2.6	0.74
D5.4	0.20	0.04	0.26	1.4	0.74
D7	0.5	0.001	0.8	4.2	0.7
D8	0.8	0.006	0.7	3.7	1.0
E2.2	3.6	0.1	2.2	11.5	1.0
E2.3	2.9	0.05	1.1	5.8	1.6
E3.1	3.0	0.0	2.8	14.7	1.12
F1.3	5.6	0.1	3.1	16.2	1.0
G1	1.2	0.02	0.8	4.2	1.2
G2	2.7	0.6	3.1	16.2	1.25
G3	1.5	0.1	1.4	7.3	1.8
G4	1.2	0.02	1.1	5.8	1.56
Operational Energy			75.3		

Table 15 : Total environmental impact expressed in UBP [ecopoints/(m2y)] for the B1 case study in the second analysis

Element Type	Manufacturing	Disposal	Replacement	Replacement (%)	Coefficient of variation (cv)
C	3815.2	592.1			
D1	756.7	30.3	838.5	13.3	1.12
D5.2	59.3	0.5	133.4	2.1	0.44
D5.3	50.7	16.6	89.6	1.4	0.74
D5.4	231.7	18.2	272.1	4.3	0.74
D7	360.0	6.2	530.2	8.4	0.7
D8	386.7	13.9	325.3	5.2	1.0
E2.2	977.6	235.3	708.2	11.3	1.0
E2.3	439.4	15.7	173.7	2.8	1.6
E3.1	884.2	48.7	854.0	13.6	1.12
F1.3	1010.0	98.6	598.0	9.5	1.0
G1	344.8	11.1	226.7	3.6	1.2
G2	596.2	172.5	734.7	11.7	1.25
G3	516.2	33.1	502.2	8.0	1.8
G4	334.0	18.7	304.1	4.8	1.56
Operational Energy			15686.87		

Table 16 : LCC [CHF] for the B1 case study in the second analysis

Element Type	Manufacturing & Application (CHF)	Specific value Maintenance (%)	Replacement (CHF)	Replacement (%)	Coefficient of variation (cv)
C	303270	0.1			
D1	48000	1.25	24736.8	6.3	1.12
D5.2	26400	0.90	25608.6	6.5	0.44
D5.3	66200	0.90	39468.6	10.0	0.74
D5.4	37000	0.90	19368.8	4.9	0.74
D7	32740	2.05	20628.4	5.2	0.7
D8	101980	0.70	33429.3	8.5	1.0
E2.2	69550	0.10	19343.7	4.9	1.0
E2.3	99740	0.10	23001.2	5.8	1.6
E3.1	147960	0.10	57091.8	14.5	1.12
F1.3	70408	0.10	18941.7	4.8	1.0
G1	53570	0.10	15577.0	3.9	1.2
G2	177750	0.10	63274.8	16.0	1.25
G3	64150	0.10	22390.7	5.7	1.8
G4	35199	0.10	11779.8	3.0	1.56
Operational Energy			136856.1		