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Service life of building elements: An empirical investigation

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Service life of building elements: An empirical investigation

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Abstract

Improvements in building's energy-efficiency hold considerable potential for decreasing energy consumption. Yet, renovations in the building stock could occur belatedly and without the coordination required for fully tapping the energy reduction potentials. In this paper, we use data from a household survey in Switzerland to analyse replacement patterns for windows, heating systems, façades and roofs. As opposed to most previous studies that assume a linear age effect, we model the renovation probability as a conditional hazard rate with a more flexible representation of age effects. We compare the renovation patterns identified by the survival analysis with the service lives determined by building norms. We find systematic deviations between the two, suggesting sub-optimal replacement in many cases, especially for the building envelope. In particular, the results point to a considerable fraction of cases, where the owners refrain from renovation far beyond the end of an element's technical service life. Moreover, the strong differences in renovation timing across various elements could hinder the expected energy savings. We identify a number of determinants for replacement timing, in view of energy policies aiming at the promotion of energy-saving renovations in buildings.

JEL classification: D10, Q40, Q48,

Keywords: Renovation patterns, Survival analysis, Hazard models, Switzerland

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1. Introduction

Improving energy efficiency in the residential building stock is among the most prominent goals of climate policy. Its importance is owed in part to the considerable contribution of the domestic sector to total energy use and carbon emissions, and the correspondingly large saving potential (Dietz et al., 2009; Jakob, 2006). In Switzerland, for instance, the energy used to heat residential buildings accounts for more than 15% of the country's total energy consumption.[3] A significant part of this energy could be saved through energy efficient renovations (Jakob, 2007). At the same time efficiency improvements are economically attractive as they are predicted to yield reductions in energy costs without affecting households' comfort levels or requiring behavioural adaptations (Dietz et al., 2009; Stern, 2014).

Many countries have therefore enacted policy measures including financial incentives, mandatory energy performance disclosures and energy building codes (Hinge, 2017), with the aim of improving energy efficiency for newly constructed and renovated buildings (see, e.g., Enker and Morrison, 2017; Jacobsen and Kotchen, 2011; Kotchen, 2015; Levinson, 2016, for a discussion).[4] While energy/emission standards could effectively improve energy efficiency in new buildings, a large fraction of the building stock made up of old constructions could remain unaffected (Lee and Yik, 2004). Thus, the impact of stringent regulations on total energy consumption and greenhouse gas emissions, depends on the renovation rate of old building elements. Moreover, the achieved energy saving depends on the relative timing of renovation of the relevant elements. Therefore, renovation practices in residential buildings has important implications for the households' long-run energy savings, expected from technological improvements as well as policy measures such as revising building codes.

Building norms presumably play an important role in guiding renovation decisions. However, their predictive power remains limited, mainly because the available approaches in defining the useful lifetime of building elements can vary considerably thus resulting in wide intervals. For instance, guidelines of the Swiss Society of Engineer and Architects (SIA) provide lifetime values for windows ranging from 20 to 50 years (SIA, 2015). Such intervals, while being useful for identifying extreme cases, cannot provide a generally applicable prediction basis. It is also

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[3] This is our estimate calculated in terms of final energy consumption in 2017, based on the official statistics provided by the Swiss Federal Office of Energy for 2017 (BfE/OFEN, 2018). The estimate varies between 15% and 20% depending on the share of households with electric heating and heat pumps, and the share of energy for hot water.

[4] Building energy performance certificates (EPC), i.e. technical documents informing about the energy consumption of a dwelling, are not obligatory in many Swiss cantons, and only required when applying for federal renovation subsidies.

important to note that norms do not usually provide information about the expected distribution of households along the lifetime range. Yet this information is crucial for predicting renovation decisions, required for a realistic assessment of the diffusion of energy efficient technologies in buildings.

In this paper, using data from a household survey in Switzerland we analyse renovation patterns at the household level for four energy-relevant building elements – windows, façades, roofs and the heating system – among a sample of home owners. We contrast these patterns against the corresponding lifetime values derived from the technical literature, allowing us to assess whether these latter values and their underlying assumptions on replacement dynamics adequately describe renovation behaviour in Switzerland. A novelty of this paper is that we consider the distributional form of replacement patterns specifically for each building element.

Our comparison is based on the concept of survival curves that is, the conditional probability that an element remains in place (not renovated) as a function of its life span. Thus, we compare the observed or "empirical" survival curves with the norm-based or "technical" survival curves. In our survival analysis, we consider any observed replacement or a major renovation as the end of the element's service life. Furthermore, as the survey provides rich information on households' socioeconomic variables and some dwelling's physical characteristics, we are able to link the replacement decisions with these determinants. This information is important for the design of policy strategies aiming at a better diffusion of energy-efficient technologies in the built environment.

The rest of the paper is organized as follows. Section 2 provides a review of the previous literature in two separate parts focusing on technical service lives and renovation decisions. After a brief description of data in Section 3, the empirical findings are presented in Section 4. Section 5 concludes the paper with some policy implications.

2. Literature review

2.1. Determinants of renovation decisions

Given the importance of households for an economy's overall energy demand, a large and growing literature is dedicated to understanding renovation choices with a focus on energy-efficient retrofits.[5] This literature has identified a number of socio-economic, structural, legal and motivational characteristics, including financial constraints, information deficits, attitudes towards risk-taking, or building codes and protection orders, which influence the uptake of such renovations.

For instance, using a survey of private homeowners, Jakob (2007) provides a comprehensive discussion of the framework conditions and their effects on building renovations in Switzerland. In particular, Jakob's regression analyses reveal that renovation decisions (energy-related or otherwise) are driven largely by the technical conditions of building elements (e.g., reaching the perceived end of an element's service life) and are associated with the execution of occasional changes in the building (e.g., expanding a room or an attic). Moreover, with an analysis focusing on owners who have performed energy-related retrofits, Jakob (2007) shows that main reasons for these renovations can generally be traced back to structural factors, such as building element's age, and motivational factors, such as environmental. When asked to report ex-post which factors have facilitated their renovation initiatives, the owners rarely mention contextual factors such as budget, regulatory frameworks and information availability.

Similarly, Achternicht and Madlener (2014) report results from a survey of owner-occupied single-family homes in Germany. Asking respondents about the most important drivers and barriers of installing a new heating system or building envelope insulation, they find that owners' willingness to renovate depends critically on three requirements: affordability, profitability and service life conditions. Necessity is however, the prevalent reason for performing a renovation, that is, an old element is renovated when it no longer functions as originally intended. Moreover, in many cases, especially in heating systems and building envelopes, an element needs to reach the end of its service life, before any kind of renovation is seriously considered.

Findings from these two studies are exemplary of a strand of empirical literature underlining the importance of functionality as a key factor in determining energy-related retrofits. They suggest that most owners view energy-efficiency retrofits as a possible option only when the (perceived) aging condition makes a renovation or a major overhaul necessary. This observation highlights the importance of empirical analysis of building elements' service life in the existing building stock. There are however few studies addressing the issue directly.

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[5] Jakob et al. (2014) provide a review of studies focusing on Switzerland. Comprehensive reviews include Friege and Chappin (2014) and Wilson et al. (2015).

The assessment of building elements' service life is subject of a number of technical studies using accelerated aging techniques, i.e. by simulating climate exposure factors in a laboratory setting (e.g., Jelle, 2012). While providing important information on physical nature of aging processes, these experimental studies provide little insight into other determinants such as economic factors, that can explain observed renovations. In particular, such non-technical factors could partly explain why observed and predicted service lives tend to differ considerably (Straub, 2015).

Comprehensive studies that provide empirical analysis of both technical and economic factors are scant. Meyer et al. (1994) is an important exception that studies the effective service life of nine building elements[6] from 120 agency-managed buildings in Switzerland, constructed between 1928 and 1975. Focusing on lifespans from the initial construction year until first renovations, they obtain two major findings. First, the replacement rates differ considerably across elements with most frequent replacement for heat production systems and least renovations in façade plastering. Second, replacement cycles are shorter in relatively new buildings. For instance, the windows' median lifespan (the period in which half of the observed windows are replaced) has fallen from 55 years for windows installed between 1928 and 1938 to about 35 years for those installed between 1958 and 1968. Meyer et al. explain this phenomenon with developments such as decreasing material quality, increasing intensity of use and more aggressive external erosion factors. Meyer et al.'s findings are limited to buildings constructed in another era (before 1975) and can be considered as outdated for any generalization to more recent constructions. In particular, with the adoption of the first Swiss building energy performance requirements in the 1980s, it is likely that building insulation concerns could change exposure factors and usage of materials, thus causing new patterns of effective service lives of various building elements.

The current study contributes to the literature by empirically assessing renovation behavior and its change with increasing an element's age in a representative sample of Swiss home owners. For this purpose, we rely on a survival analysis (Kleinbaum and Klein, 2005), an approach originated from population studies to model a person's death probability before their next birthday. The method has long been used in a variety of economic applications such as duration of unemployment and survival of firms. The closest applications to building renovations are Fernandez (2001) and Young (2008) that used a survival analysis to model the replacement of

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[6] These elements encompass plastering (façade, external surface), façade ornamentation, balcony and loggias, outer doors, roof (inclined and flat), roof edges, windows, weather proofing and sun protection.

home appliances. In these studies an entity's survival time (lifespan) is defined as its age at its replacement. We follow this example, defining the survival time of a building element as its effective service life that is, the period between its installation and its replacement.

2.2. Building element's service life

Information on the lifetime of building elements plays a central role in predicting the impact of building efficiency requirements on the evolution of energy demand and greenhouse gas emissions in the built environment. Renovation rates in the existing stock determine how quickly technological improvements and new building codes diffuse. Moreover, information about the elements' service lives is essential for life-cycle analysis as they determine the horizon over which costs depreciate or ecological impacts accumulate (Gluch and Baumann, 2004; Klunder and Nunen, 2003).

The engineering literature provides a variety of data on the service life and turnover of building elements, commonly based on manufacturer information or expert reviews (Ashworth, 1996; Straub, 2015). We can distinguish two forms of lifetime for building elements: technical service life and economic life cycle. The economic (or useful) life is a measure of a rational replacement cycle considering costs, while the technical life represents an upper limit for physical durability. The technical service life refers to the period after which an element no longer fulfils its intended function in a reasonable manner. In contrast, the end of an element's economic life corresponds to a point in the lifetime when the expected replacement costs for a component exceed its expected yields, which depends to a considerable degree on factors other than the physical condition. These factors include among others, expected fuel prices, regulations, technological development and fashion (Bahr and Lennerts, 2010). Because of these factors, the economic life tends to be shorter than technical service life (Ashworth, 1996).

The technical service life depends on the element's characteristics (e.g., its quality), the mechanical wear and tear the element is exposed to (e.g., intensity of use, radiation, wind and water erosion), and the degree of maintenance and care (CRB, 2012). A common practice is to fix a well-defined set of reference conditions to estimate the technical service lives of various building elements. These conditions concern the element's characteristics, such as its quality and make, specified by technical standards such as the commonly used ISO Standard 15686 (Buildings and constructed assets - Service life planning). The obtained service life given the reference conditions is labelled the Reference Service Life (RSL). A range of plausible RSLs could be specified to account for differences in reference conditions (e.g., Bahr and Lennerts, 2010).

The CRB standards, provided by the Swiss Research Centre for Rationalization in Building and Civil Engineering, are widely applied in evaluating replacement needs in Switzerland. Table 1 gives the range of RSL values based on CRB standards (CRB, 2012), estimated for four main building elements studied in this paper. As observed in the table, the RSL values vary in a relatively wide range even within a given building element. Part of these variations can be explained by the fact that each broad building element is made up of different components, whose service lives could vary considerably. For instance, a building's heating system can be considered in three components, heat distribution, heat production, and fuel storage, with average RSL of 60, 20 and 50 years respectively (CRB, 2012). Moreover, different element types can have different service lives. Flat and inclined roofs, for example, differ in average RSL by 10 years. The estimates of RSL in a broad building element depends on the adopted aggregation method, generally based on a (weighted) averaging over smaller components.

INCLUDE Table 1 ABOUT HERE

It is important to note that service life estimates vary significantly even for a specific element of a given type. To obtain a prediction for the expected lifetime of a specific element – called "estimated service life" (ESL) – several different analytical and stochastic methods (or combinations thereof) have been developed (Moser and Edvardsen, 2002). The most common analytical method, in line with the ISO Standard 15686, is the so-called "factor model". This model estimates ESL by weighting RSL values using the expected on-site conditions of the element for seven factors, known to influence service life (Bahr and Lennerts, 2010; CRB, 2012; Straub, 2015). We can classify these into three groups, design, installation and maintenance. Design factors include material quality adjusted for potential damages during transport and storage and the element's integration in the building structure hence, its degree of protection from erosive forces. Installation factors include installation quality, internal environment accounting for erosive forces from the building interior (e.g. humidity of a bathroom), as well as external environment capturing the exposure to corrosive forces outside the building. Maintenance factors include the usage intensity and the maintenance conditions. For each one of these factors, ISO suggests multiplicative adjustment with weights ranging from 0.8 for unfavourable conditions that heavily accelerate deterioration to 1.2 for favourable conditions that greatly prolong the service life. Under favourable conditions on all factors the

ESL value can exceed the corresponding RSL by a factor as large as 3.6, while under adverse conditions ESL could be as small as 20% of the corresponding RSL.

We need to combine this information with further assumptions, in order to generate survival curves for building elements. In particular, we follow two complementary sets of assumptions drawing on the literature studying respectively, the retirement of electric appliances (Brown et al., 2001; Interlaboratory Working Group, 2000) and transportation fleets (Dray, 2013; Morrell and Dray, 2009).

For a first approximation, we assume that the RSL reference conditions hold such 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, t_{min}^{RSL}, and no element survives beyond the maximum reference service life, t_{max}^{RSL}. Moreover, drawing on the literature on electric appliances (Young, 2008), we assume that survival curves of building elements follow a linear function between their minimum and maximum values. We thus assume that the technical survival function, $S_{tech}(t)$, of each element is a piece-wise linear function defined as:

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

where values for α and β are chosen such that boundary values for t_{min}^{RSL} and t_{max}^{RSL} are attained. The upper panel of Figure 1 plots the resulting technical survival curves for the four elements based on RSL values derived from CRB standards (labelled CRB-RSL).

INSERT Figure 1 ABOUT HERE

For a second approximation, we deviate from both assumptions above. Instead, we assume that technical service life is bordered by minimum and maximum expected service life (ESL), considering the worst and best case scenarios of factor conditions.[7] In other words, both minimum and maximum element survival shift further away from the RSL values. Moreover,

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[7] That is, minimum expected service life, t_{min}^{ESL}, is defined as: $t_{min}^{ESL} = t_{min}^{RSL} \times 0.8^7 = 0.21\, t_{min}^{RSL}$, while maximum expected service life, t_{max}^{ESL}, is given by: $t_{max}^{ESL} = t_{max}^{RSL} \times 1.2^7 = 3.58\, t_{max}^{RSL}$.

we draw on the literature for vehicle replacement (Morrell and Dray, 2009) and assume that technical survival curves follow a log-logistic function of the following form:

$$S_{tech}(t) = 1 - e^{-e^{\left(\alpha+\beta\left(t-t_{min}^{ESL}\right)\right)}}, \qquad (2)$$

where α and β are obtained by approximating the boundary conditions at t_{min}^{ESL} and t_{max}^{ESL}.[8] The lower panel of Figure 1 plots the corresponding log-logistic technical survival curves for the four elements based on ESL values derived from CRB standards (labelled CRB-ESL).

To what extent these technical specifications explain the actual home-owners' renovation behaviour is essentially an empirical question. In the following, we will address this question by applying a survival analysis to the observed renovations in the household-level data.

3. Data

To identify empirical survival curves and the determinants of renovation decisions, we draw on two waves of the Swiss Household Energy Demand Survey (SHEDS), an online survey conducted among 5000 households (cf. Weber et al., 2017).[9] The SHEDS second and third waves (2017 and 2018) contain a series of items concerning the general characteristics of the respondent's present residence and its renovation history, focusing on four building elements: windows, heating system, façade and roof. The survey retains only individuals who are at least partially responsible for household decisions. The dependent variables used in this study are the survival times (life spans) in years of all four building elements. In order to use the data efficiently, for each element, we use one observation per household focusing on the most recent reported replacement or major renovation. That is, for respondents who report an element's replacement, the life span concerns the retired (or renovated) element. For these cases, the life span is the element's age reported by the respondent at the time of last reported replacement (or major renovation). In contrast, for respondents who do not report an element's renovation since the construction year, the life span is right-censored, namely the number of years elapsed since the building's construction year.

To obtain the age of a building element at the time of last renovation, we follow the following procedure. For each element the respondent reports a replacement (or major renovation), we

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[8] Note that the range of the log-log function is only defined for the open interval (0,1). Therefore instead of assuming 0 and 100% failure at t_{min}^{ESL} and t_{max}^{ESL}, we allow for a marginal difference of 0.001% for each threshold.

[9] More information is available at: www.sccer-crest.ch/research/swiss-household-energy-demand-survey-sheds.

ask whether this has been the only replacement throughout the building's lifetime, in which case the element's age is obtained by the difference between the replacement year and the building's construction year. Should the respondent report more than one major renovation, we ask them to indicate the renovated element's age at the time of renovation. The respondents that do not know the specific year have the opportunity of selecting among several 5-year intervals so that they can report a range. This applies to renovation year as well as the building's construction year.[10]

To obtain more credible results, we exclude observations where the reported element's age is above 100 years,[11] or greater than the building's age. After excluding these observations, there remain about 2'500 respondents from owner-occupied homes with valid and sufficient information to compute the element's age for at least one of the four studied elements. Depending on the building element, between 4% and 7% of owner-occupiers reported not to know the renovation year. [12]

When the element's specific age cannot be calculated, but the reported intervals allow an approximation, we transform the reported intervals into continuous years using mid-points as the best estimate. Depending on the element between 10% to 15% of the observed survival time are based on mid-point approximations. The resulting sample include renovation information from slightly more than 2'000 owner-occupied homes.

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[10] Survey questions are detailed in Lasvaux et al. (2019).

[11] The choice of this threshold is motivated by the observation that the longest uncensored survival periods across elements was found to be just under 100 years. By applying this threshold we lose between 1.9 % (windows) and 3.6 % (façade) of owner-occupied households. Results remain largely identical when we change the threshold to 50 or to 150 years.

[12] We have performed separate analyses with a sample of tenants from SHEDS, yielding results largely similar to the ones presented below (see, Lasvaux et al., 2019, for details). However, for a number of reasons, we believe that the data from owners for owner-occupied homes is more reliable than those reported by tenants. First, the share of tenants with reported renovation intervals (rather than specific years) is about three times greater than the corresponding share among owners. For instance, for 42.7% of tenants but only 13.7% of owners window's age is reported in intervals. Similar differences exist for other elements: 41.4% compared to 14.9% for heating systems, 38.9% as opposed to 12.5% for façades, and 37.2% versus 11.5% for roofs. Second, heaping at round numbers is more frequent among tenants. For instance, roughly one third of the tenants reports their dwelling's construction year in a multiple of 10, compared to 15% of owners. Third, between 36% (heating system) and 45% (windows) of tenants report renovations dates prior to them moving into the building, suggesting that a substantial share of them are forced to rely on third party information, such as documentation, anecdotes or guessing when reporting on the building's renovation history. Given the relative reliability of owners' data, we focus on owner-occupied homes.

4. Empirical findings

4.1. Life tables and empirical survival curves

Descriptive statistics on the survival time of the four building elements are based on the Kaplan Meier estimator of survival probabilities (Kaplan and Meier, 1958). In our context, the estimator $\hat{S}(t)$ denotes the probability of an element not to be replaced for exactly t years, which can be specified as:

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

where $t_{(i)}$ is the rank-ordered survival time with i ranging from 1 to 100 years (our adopted threshold), n_i is the number of elements that are not replaced at the beginning of year i and r_i is the number of observed replacements in that year. That is, the probability of an element to survive t years is the product of the probabilities of surviving (not being replaced) over all the previous years.

Based on equation (1) one can readily obtain estimates of the survival probability for key quantiles of the survival time distribution, with the estimate of the p^{th} percentile of survival time being:

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

Table 2 gives this information for the first quartile ($\hat{t}_{25}$), the median ($\hat{t}_{50}$) and the third quartile ($\hat{t}_{75}$) of the survival time distribution for SHEDS respondents owning their place of residence. The table also provides basic sample information on the four building elements.

INSERT Table 2 ABOUT HERE

Information on the 25th, 50th and 75th percentile of the survival time distribution is given in the first three columns of Table 2. Corresponding 95% confidence intervals are given in the brackets below the point estimates. The following columns give the total number of observations and the number of reported renovations, i.e. respondents reporting at least one renovation. For instance, we have valid information of window age from 2’413 SHEDS home-owners, of which 1’073 report at least one window renovation since their building’s construction. Among this sample, 25% of windows are replaced in the 26 years following their installation. Another quarter of windows are replaced in the ensuing 9 years, and yet another 25% are not renovated after 48 years. Average annual replacement rates are given in the final column of Table 2. There is considerable variation in survival probabilities and thus replacement rates across the building elements. In particular, windows and heating systems are replaced at a much higher rate than façades and roofs.

To obtain a more comprehensive overview of the distribution of empirical service life of building elements, Figure 2 shows the plots of their Kaplan Meier survival curves (and corresponding 95% confidence intervals) along with the norm-based technical survival for all four building elements over their lifespans derived in section 3. The curves show the probability of an element not being renovated in a specific year for each year since installation (ranging from one to 100), conditional on not having been renovated before.

INSERT Figure 2 ABOUT HERE

Results suggest that 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. In the first 10 years after installation only about 3.7% of windows, 6.7% of heating systems, 3.5% of facades, 2.7% of roofs have been replaced. Replacement rates 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. The empirical curves also indicate a rapid acceleration of replacement “hazards” for windows and heating systems with few non-renovated elements remaining after about 60 years. Whereas, roofs and façades represent a rather gradual increase with an almost linear trend hence a constant annual renovation rate after an initial period of 20 to 30 years, but a substantial share of non-renovated elements even after 80 years.

When contrasting empirical survival curves with those constructed upon CRB norms, several deviations become apparent. While in some cases, such as the log-logistic specification (CRB-ESL) for windows or the piece-wise linear specification (CRB-RSL) for roofs, norm-based survival is close to what we observe empirically, there are significant sections across all elements where the technical survival curves run outside the 95% confidence interval of the empirical ones. This is consistent with the results of Kolmogorov-Smirnov tests comparing empirical against technical curves, which strongly reject the equality of the two survival distributions. We can also observe that, except for the case of roofs the piece-wise linear model (CRB-RSL) tends to fare poorly in capturing empirical survival curves. This clearly shows that the linear model, as applied for instance in the literature on electronic appliance replacements (Interlaboratory Working Group, 2000), is not adequate for describing replacement patterns of building elements.

More importantly, for most elements, one can observe a number of systematic deviations between empirical and technical survival curves. In particular, CRB norms appear to under-estimate replacement rates for lower age ranges, while over-estimating rates among older building elements. For instance, CRB norms suggest that about 70% of façades should be replaced at an age of 55 (CRB-ESL) to 65 years (CRB-RSL), while the empirical curve shows that it takes about 80 years to reach this threshold. On the other hand, technical survival curves suggest that almost no façade should experience a renovation within the first 20 years after installation, the empirical curve indicates renovations for about 15% of observations.

A notable exception to this general pattern is heating systems, where empirical replacement rates exceed the CRB-based predictions across almost the entire observable survival period (Figure 2). This suggests that the observed renovations in heating systems are overall more frequent than what is required by technical norms. This could be partly related to an increasing concern about heating fuels and energy saving objectives. Part of this massive observed difference between technical and empirical survival curves could be related to important service life differences between production and distribution components. Heating production systems such as boilers and furnaces tend to have a much shorter service life than heat distribution components, such as radiators and tubing. However, the SHEDS respondents are likely to report any type of change to the heating system, which is more likely to be an element of heat production rather than distribution. It is therefore likely that the empirical survival curve obtained from the SHEDS sample is comprised of replacements of the system of heat production, while the CRB-values refer to an average of technical service lives of both components.

4.2. Determinants of renovation

We make use of the semiparametric proportional hazards model introduced by Cox (1972), to analyse the renovation probabilities. This model allows us to relate renovation timing to a broad set of characteristics that previous research has identified as important for renovation decisions (Friege and Chappin, 2014; Jakob et al., 2014; Wilson et al., 2015). Rather than imposing a parametric specification for the change in survival probability with element's age, the model permits to derive replacement hazards from the data.[13] In this framework the replacement hazard at time t, defined as conditional probability of replacement given that the element has survived up to that point in time, can be written as:

$$h(t, \boldsymbol{x}, \beta) = h_0(t) e^{\sum_{i=1}^{k} \beta_i X_i} \tag{3}$$

where $h_0(t)$ is the baseline hazard function, which describes the change in replacement hazards as a function of survival time, while the exponential function $e^{\sum_{i=1}^{k} \beta_i X_i}$ characterizes how this hazard depends on 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. 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 validity of the proportional hazards (PH) assumption is evaluated in two different ways. First, we tested specifications based on Schoenfeld residuals (Grambsch and Therneau, 1994). These tests did not allow to 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 estimated fully parameterized versions of the Cox models allowing the effects of all covariates (except canton 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 parametrized models compared to that of the proportional specification. The main exception to this general observation are cantonal fixed effects, which violate the PH assumption in most estimations. In order to deal with this violation, we follow a standard solution to such issues (cf. Kleinbaum and Klein, 2005) 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 (3) is relaxed to:

$$h(t, \boldsymbol{x}, \beta) = h_{0c}(t) e^{\sum_{i=1}^{k} \beta_i X_i}, \tag{4}$$

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

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[13] We have likewise used alternative parametric models including Weibull, Lognormal, and Log-logistic parameterizations. All yield estimates similar to the ones presented below. Yet, a comparison of goodness-of-fit based on Akaike Information Criteria strongly favors the Cox model for all elements and almost all specifications.

The explanatory variables, X_k, encompass a range of time-invariant factors including the type of the dwelling (single-family house or multi-family house), the location (city, agglomeration, countryside), the size of the residence in square meters, and the geographical region (French Switzerland, Alps and Pre-Alps, Western Midlands, Eastern Midlands). Moreover, controls include a variable measuring the household's gross monthly income in Swiss Francs in 2017,[14] as well as the respondent's risk attitude. 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, in order to control for technological developments, we control for building cohorts as well as element cohort. After several exploratory analyses (more details reported in Lasvaux et al., 2019), due to multicollinearity issues, we decided to focus on two dummy variables distinguishing between buildings constructed before and after 1990, as well as elements installed before and after 1990.

Table 3 provides results from survival estimation models for all four elements. For each element, the table lists the effect of each variable on the replacement rate. The coefficients are given as hazard ratios. That is, coefficients larger than one imply an increased probability of replacement and therefore a lower empirical service live, while estimates below one indicate reduced replacement probability hence, longer element survival. It is therefore important to consider that statistical tests of significance should test against the null hypothesis: H_0: $\beta_k = 1$.

INCLUDE Table 3 ABOUT HERE

Despite some variation in point estimates across elements, results from Table 3 show a number of common patterns. First, we observe that only a few variables are statistically significant (hazard ratio different from 1). In particular, there is no statistically significant relationship

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[14] Income is considered in three categories based on monthly income: low-income (less than CHF 4'500), middle-income (between 4'500 and 9'000) and high-income (CHF 9'000 or more). Moreover, as over 15% of respondents prefer not to give information on this item, we create a separate category for those individuals.

between replacement rates and current household income, which could suggest a limited scope for policies providing financial incentives for renovation. However, given the strong unobserved heterogeneity of home-owners regarding investment preferences, omitted from our model, the model's power in detecting income effects might be low. Moreover, our income measure could be a noisy measure of a household's income at the time of renovation decision. As a consequence, the statistical insignificance of income effect does not necessarily imply no effect. Rather, it simply means that the present data does not allow us to reject the null hypothesis of no income effect.

The estimated effect of risk attitudes is mostly (with the exception of roof renovations) plausible with higher levels of risk tolerance related with higher replacement hazards, hence greater probability of renovation investment. In contrast with estimated income effects, the partially-significant relationship between risk attitude and renovation investment could suggest that financial considerations are likely to have bearings on renovation decisions.

Unlike individual-level characteristics, location and building-specific factors are strongly and (usually) significantly associated with the timing of renovation works. Compared to home-owners residing in multi-family buildings, those living in single-family homes report significantly and substantially lower replacement hazards. Estimated hazard rates for single family houses range between 0.60 for roofs and 0.87 for the heating system, suggesting that compared to multi-family buildings, in single-family houses the roof renovation hazard is 40% lower and heating system replacements are 13% less frequent. These findings are in line with previous studies on dwelling-specific differences in renovation behaviour in Switzerland, which report substantially lower renovation rates, in particular for energy-efficiency upgrades, in single-family homes (for a recent meta-analysis of Swiss findings, see Jakob et al., 2014). This difference could be related to potentially lower renovation cost for home-owners residing in apartments thanks to a distribution of fixed costs over more parties.

Moreover, dwellings standing outside urban centres tend to have higher replacement rates than comparable dwellings in cities. 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. This could be partly related a relatively greater number of protected buildings in inner city areas. Lehman et al. (2015) identify historical preservation orders as one of the important barriers to energetically upgrading of façades and windows. One can also imagine that higher real estate prices in city centres could have a negative impact on owners' incentives to renovate their property. However, this hypothesis does not bear out the data regarding heating systems and roofs.

Finally, for all building elements we find that both element and building cohort can be related to replacement hazards. First, as expected, buildings constructed after 1990 are subject to fewer renovations in all four elements (especially roofs). This can be explained by the relatively low building's age (lower than 28 years) for this cohort. Second, after controlling for the building cohort, elements belonging to a later installation cohort (i.e. those installed in 1990 or after) show substantially higher replacement hazards. That is, elements belonging to a more recent cohort tend to face higher replacement rate at each stage of their service life.

It is important to note that the two cohort dummies are highly correlated, such that the magnitude of coefficients is likely subject to multi-collinearity. Our complementary analyses show that excluding either one of the cohort dummies decreases the coefficients substantially. Therefore, the estimated coefficients with both cohort dummies (Table 3) are likely to exaggerate the difference between older and newer buildings/elements. Yet, the general pattern, namely shorter replacement cycles among more recently installed elements (and older buildings) is valid even with various cohort definitions. In particular, we found identical patterns when, in addition to two element cohorts, we controlled for three building age groups.[15]

Overall, the results suggest that the building's age matters beyond and above the element's age that is directly modeled in the survival function's baseline hazard function (equation 3): Newer building groups tend to have relatively less frequent renovations. However, element cohorts installed more recently are more likely to have ensuing renovations. Even though the results are not directly comparable to Meyer et al. (1994)'s findings,[16] they point to a similar overall pattern with relatively shorter service lives for newer elements. However, given the apparently opposing pattern observed in building groups, this trend cannot be related to a diminishing quality of materials (as suggested by Meyer et al.) but could point to differences between a first replacement after construction and the ensuing renovations. That is, following a first renovation, the ensuing renovation cycles tend to become shorter. This could be simply because

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[15] We shifted the threshold of the element cohort 10 years in either direction: 1980 and 2000, while keeping three building groups each representing about a third of the sample, that is, buildings constructed before 1970, constructed between 1970 and 1999, and those constructed after 1999. More comprehensive results are reported in Lasvaux et al. (2019).

[16] Meyer et al.'s sample is limited to buildings constructed before 1975 whereas in our sample, about half of the observations are from buildings constructed after that period. Another difference is that unlike Meyer et al.'s study we control for both building cohort and element cohort.

the building's overall age could bring more renovation needs in addition to the element's aging process. This could be especially important if the first renovation is not a complete replacement. In our data, we cannot distinguish between complete replacements and major renovations. More frequent renovations following an initial one, could also reflect the replacement of other components of the same element.[17] Further research is needed to address the variations of effective service lives among different element and building cohorts.

5. Conclusions and Policy implications

The results presented in this paper provide evidence on the shape and the key parameters of the empirical survival curves of building elements in Switzerland, as well as on important determinants shifting this function. Moreover, empirical survival functions were compared to a set of technical survival functions drawn from technical norms. Our focus is on four main elements, windows, roofs, façades and heating systems.

Findings suggest that renovation patterns of Swiss households differ from the norm-based values based on the most commonly used CRB standards. In particular, significant differences emerge for roofs, façades and heating systems. While on average heating systems are replaced earlier than is recommended by norms, façades and roofs remain much longer in use than they should be according to norms. Our estimations indicate an average renovation delay of about 10 to 20 years for the building envelope. The only exception is the case of windows whose median effective service life coincide with average predictions from CRB norms. More importantly, the results show an important variation in timing the renovations across various elements. This variation, in contrast with the norm-based average service lives suggesting the same average service life (35 years) for all envelope's elements, could significantly hinder the expected energy savings. Moreover, we observe important differences in the tails of the survival distributions with a share of elements that are replaced "too early", before their (minimum) reference service life, or more importantly, a considerable share that are used well beyond the end of their norm-based technical service life.

These findings have two policy implications for energy savings resulting from renovations. First, to the extent that home-owners retain their aging elements for longer (shorter) than assumed by technical norms, these norms will overestimate (underestimate) the diffusion rate

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[17] It is also possible that some survey participants report partial renovations as a major renovation. For instance, respondents might confuse the heat production system with the entire heating system.

of new technologies in the building sector. In particular, technological innovations in heating systems are likely to spread much quicker than assumed, while the diffusion of energy-efficient building envelopes is likely to take considerably longer than expected. Together both effects suggest that relying on information from norms to perform ecological or economic life cycle analyses could yield biased estimates of energy consumption. Quantifying such biases requires further research beyond the scope of this paper.

Secondly, the deviation in the right tail of survival distributions between norm-based and empirical service lives observed across all elements, implies that a sizeable share of home owners refrain from renovating a building element long after its technical service life has ended. In addition, in many cases, the renovation of various elements is not synchronized so as to tap the greatest energy saving benefits. Given that such patterns have a negative impact on energy-efficiency, particular groups of home-owners could be identified to present a natural target group for policies aiming to reduce energy consumption.

Our regressions point to a number of determinant factors that predict the age at which a building element is replaced. In particular, we find that structural factors such as the type of home, its construction period or its placement along the rural-urban continuum are significant predictors of renovations. In summary, our analysis suggests that renovation rates are lowest among urban households residing in recently constructed single-family homes. While being in line with previous studies on renovation behaviour in Switzerland (cf. Jakob et al., 2014), our findings highlight the importance of the potential renovation delays in specific building groups such as single-family homes and relatively new buildings. Given that part of the delay in single-family homes could be related to lower scale economies as opposed to multi-family buildings, financial incentive could be an important barrier to target for this group of home owners. Moreover, given the emphasis of previous studies on renovation barriers in old buildings, our results highlights the importance of relatively new buildings whose renovation delays could perpetuate the energy-efficiency gap in the built environment.

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Tables

Table 1: Reference Service Life (RSL) values from CRB standards

Building element	Service life		
	Minimum	Average	Maximum
Windows	25	35	45
Heating system	30	45	60
Façade with external insulation	20	35	80
Roofs	20	35	100

Note: These numbers are provided by the Swiss Research Centre for Rationalization in Building and Civil Engineering (CRB, 2012). They are based on an aggregation over components' service lives accounting for each component's construction cost category according to the Life Cycle Cost methodology .

Table 2: Life tables for Swiss building elements

	Survival time (in years)			Observ-ations	Observed renovations	Annual replacement rate (%)
	25%	50%	75%			
SHEDS, owner-occupied dwellings						
Window	26 [25, 27]	35 [33, 35]	48 [46, 50]	2413	1073	1.89 [1.82, 1.96]
Heating system	20 [20, 20]	28 [27, 29]	40 [38, 41]	2291	1170	2.47 [2.39, 2.59]
Façade	29 [27, 30]	42 [42, 47]	74 [70, 82]	2287	777	1.33 [1.25, 1.41]
Roof	37 [32, 37]	55 [50, 57]	80 [70, 83]	2297	622	1.06 [0.97, 1.09]

Note: 95% confidence intervals are given in brackets. Estimated intervals are based on the Delta method for survival times, and the bootstrap method with 250 draws for replacement rates.

Table 3: Results from semi-parametric proportional hazard models

Element	(1) Windows	(2) Heating system	(3) Façade	(4) Roof
Size of living space (log m^2)	1.0703	1.1073	0.9884	1.0071
	(0.0866)	(0.0771)	(0.0842)	(0.0969)
Monthly household income group in year of interview (ref.: Bottom)				
Middle	0.9554	1.0258	1.0658	0.9370
	(0.1147)	(0.1162)	(0.1433)	(0.1434)
Top	0.9537	1.1381	1.0089	1.0720
	(0.1147)	(0.1358)	(0.1373)	(0.1529)
Missing income	0.9199	1.1912	1.0849	0.9734
	(0.1284)	(0.1614)	(0.1667)	(0.1781)
House type (ref.: Multi-family house)				
Single family house	0.7755***	0.8687*	0.6303***	0.6043***
	(0.0643)	(0.0686)	(0.0588)	(0.0647)
Region (ref.: Ostmittelland)				
Suisse romande	1.1401	1.1862	1.5638	1.3879
	(0.3095)	(0.3616)	(0.5577)	(0.5396)
Alpen und Voralpen	0.9384	1.0139	0.9900	0.4993**
	(0.2235)	(0.2776)	(0.3242)	(0.1630)
Westmittelland	1.0649	0.9838	1.3237	0.7815
	(0.2055)	(0.2176)	(0.3158)	(0.2100)
Urbanity (ref.: City)				
Agglomeration	1.3218***	1.0786	1.3049***	1.0084
	(0.1066)	(0.0886)	(0.1278)	(0.1156)
Countryside	1.2735***	1.0521	1.2376*	0.9860
	(0.1134)	(0.0969)	(0.1362)	(0.1156)
Risk attitudes (ref.: Risk averse)				
Rather risk averse	1.1164	1.1231	0.9498	0.8133*
	(0.0913)	(0.0939)	(0.0983)	(0.0903)
Risk neutral	1.1536*	1.1382	0.9945	0.9325
	(0.0967)	(0.1011)	(0.1038)	(0.1136)
Risk seeking or rather risk	1.0362	1.2328*	1.0556	0.8951
Seeking	(0.1254)	(0.1465)	(0.1408)	(0.1441)
Element cohort (ref.: installed in 1990 or before)				
installed after 1990	19.7042***	10.5860***	25.0596***	26.7773***
	(2.4278)	(1.0788)	(4.1942)	(5.8826)
Building cohort (ref.: built 1990 or earlier)				
built after 1990	0.0743***	0.2280***	0.0977***	0.0367***
	(0.0119)	(0.0278)	(0.0172)	(0.0099)
Survey year (ref.: 2017				
2018	0.7736***	0.7028***	0.6150***	0.5633***
	(0.0539)	(0.0491)	(0.0556)	(0.0553)
Stratified by canton	Yes	Yes	Yes	Yes
No. of subjects	2167	2024	2054	2061
No. of renovations	1026	1104	744	586
Years at risk	55975	46559	57939	59869

All coefficients are given in terms of hazard ratio.

*** p<0.01, ** p<0.05, * p<0.1 (significance in rejecting $H_0: \beta = 1.$).

Figures

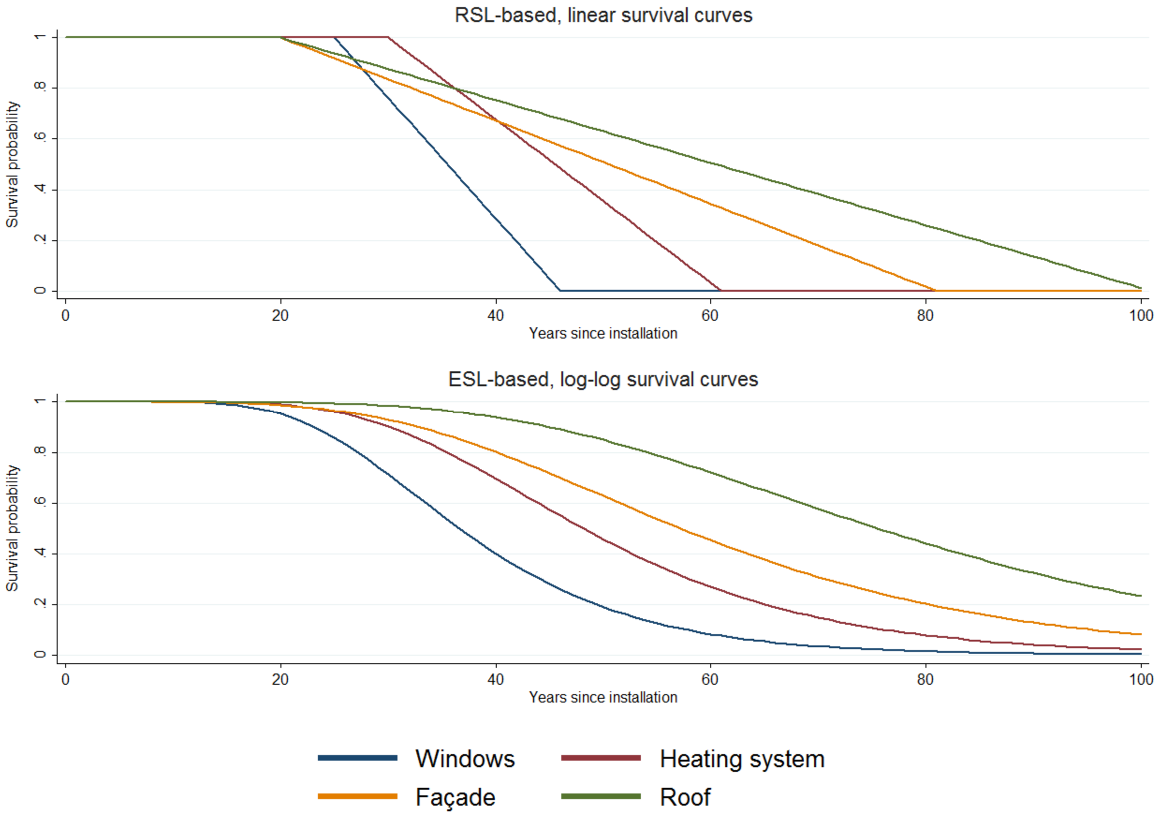

Figure 1: Technical survival curves of building elements based on CRB assumptions with reference service life (RSL) and estimated service life (ESL)

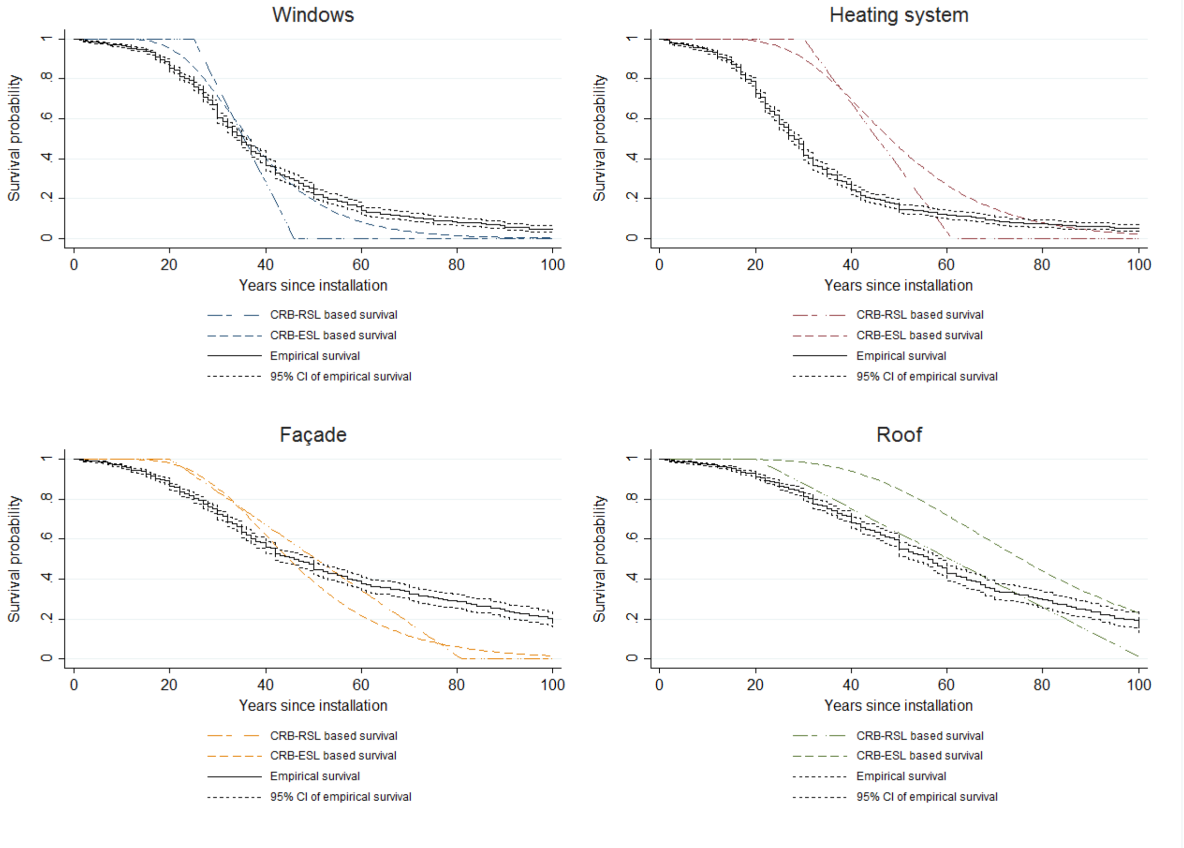

Figure 2: Contrasting technical and empirical survival curves