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Too little too late: An empirical study of renovation of building elements

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Abstract

Building retrofits hold considerable potentials for reducing energy consumption. A full exploitation of such potentials requires timely renovations and sufficient investment in the existing building stock, in accordance with economic considerations. Using data from a household survey in Switzerland and focusing on replacement patterns for heating systems, windows, façades and roofs, we analyze the owners' renovation behavior and its possible deviations from norm-based recommendations. 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 significant deviations between the two, suggesting sub-optimal replacement but a mitigated picture of renovation delays as compared to norm-based values. While renovation of heating systems and windows represent no systematic delay, façades and roofs show a strong tendency for belated or little renovation. In particular, the results point to a considerable fraction of owners refraining from façade and roof retrofits, far beyond their technical service lives. We also identify a number of determinants for replacement timing, in view of energy policies aiming at the promotion of energy-saving renovations.

JEL classification: D10, Q40, Q48,

Keywords: Building renovation, Energy efficiency, 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). 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. Building retrofits are important vectors of energy efficiency improvements either directly through better materials and technologies, or indirectly via opportunities they provide for additional energy-saving investments. Moreover, renovation practices in residential buildings have important implications for the households' long-run energy savings, expected from technological improvements as well as policy measures such as revising building codes.

Therefore, any deviation of renovation timing from an optimal path bears consequences for building energy efficiency. In other words, the so-called energy efficiency gap in the built environment is closely linked to a "renovation gap" in energy-relevant building elements. By renovation gap, we mean possible delays in replacement of a building element beyond its economic service life. Optimal renovation decisions depend on many economic and technical factors. Building technical norms presumably play an important role in guiding optimal renovation decisions. While bearing important shortcomings such as relatively wide intervals

[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.

and lack of many economic factors such as energy prices, we argue that the building norms could be considered as a safe upper-bound reference for optimal service life of various building elements.

In this paper, using data from a household survey in Switzerland we analyze renovation patterns at the household level for four energy-relevant building elements – windows, façades, roofs and the heating system – for a sample of home owners. We contrast these patterns against the corresponding lifetime values derived from technical norms, and analyze the differences between the two counterpart distributions. This analysis allows us to assess the "renovation gap", that is, the renovation delays observed in Switzerland, compared to optimal renovation patterns. A novelty of this paper is that while considering specific replacement patterns for each building element, we account for the distribution of renovation probabilities and their variation with the element's age.

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. We use the results for drawing policy implications for 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.[4] This literature has identified a number of socio-economic, structural, legal

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

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, his 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.

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[5] 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 mortality probability. 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 home appliances. We follow this example, defining the survival time of a building element as its effective service life that is, the element's age at the time of its replacement.

[5] 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.

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 in the built environment. Renovation rates in the existing stock determine the diffusion rate of new technologies. 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 optimal 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 , that in general favour a replacement before the end of physical durability, the technical service life can be considered as an upper bound for the economic life (Ashworth, 1996).

In this paper, we use technical life values as a reference baseline for measuring the "renovation gap" for a given element. This implies that any renovation delay can be considered sub-optimal accounting for economic considerations. However, a renovation taking place earlier than the end of technical life, does not necessarily present a sub-optimal decision because such renovations could be economically viable even though from a technical standpoint, the replaced element could still function in an adequate manner.

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 is known as the Reference Service Life (RSL). Plausible values of RSL could be specified to account for differences in reference conditions (e.g., Bahr and Lennerts, 2010).

Table 1 gives the range of RSL values based on CRB standards[6], estimated for four main building elements studied in this paper. The estimates of RSL in a broad building element depends on the adopted aggregation method, generally based on a (weighted) averaging over smaller components. RSL varies in a relatively wide range for a given building element depending on service life differences across various types and components. These differences could be considerable. For instance, flat and inclined roofs differ in average RSL by 10 years. The service life of a heating system's component could vary on average from 20 years for a furnace to 60 years for heat distribution (CRB, 2012).

INSERT 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 Expected 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

[6] The CRB standards, provided by the Swiss Research Centre for Rationalization in Building and Civil Engineering (CRB, 2012), are widely applied in evaluating replacement needs in Switzerland.

from 0.8 for adverse conditions that heavily accelerate deterioration to 1.2 for favorable conditions that greatly prolong the service life. Under favorable 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; Inter-laboratory 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:

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

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 a minimum and a maximum ESL, considering the extreme case scenarios of factor conditions.[7] For the variation of service life between the two bounds,

[7] 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:

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

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).

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 used the following procedure. For each element the respondent reports a replacement (or major renovation), we 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

[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.

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 10% to 15% of the observed survival times are based on mid-point approximations. The resulting sample include renovation information from slightly more than 2'000 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

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

[11] The choice of threshold is motivated by the observation that the longest uncensored survival periods across elements is 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 all., 2019, for details). However, given the relative reliability of owners' data, we focus thus on owner-occupied homes. We observe for instance, that the share of tenants with reported renovation intervals (rather than specific years) is 39% to 43%, about three times greater than that of owners (11% to 14%). Roughly one third of the tenants reports their dwelling's construction year in a multiple of ten years, compared to 15% of owners.

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 25$^{\text{th}}$, 50$^{\text{th}}$ and 75$^{\text{th}}$ 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 (Inter-laboratory 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. On the other hand, 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.

Overall, the data do not bear out a general systematic renovation delay across all four elements. As opposed to roofs and façades, the renovation patterns of windows and heating systems do not show any evidence of a systematic delay. On the other hand, considerable delays in renovation of façades and roofs suggest that it is likely that the energy efficiency gap in residential buildings is characterized by a lack of investment in building envelopes.

4.2. Determinants of renovation

We make use of the semiparametric proportional hazards model introduced by Cox (1972), to analyse the renovation probabilities. [13] While accounting for aging effects, 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 hazard rates from the data. 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:

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

where $h_0(t)$ is the baseline hazard function, which describes the change in replacement hazard rates as a function of survival time, and the exponential function $e^{\sum_{i=1}^{k} \beta_i x_i}$ characterizes how

[13] To deal with the tied "failures" we rely on Efron's (1977) approximation of marginal probabilities.

this hazard rate depends on covariates, $X_1, \ldots, X_k$. Thus, the parameters of interest, β_1 to β_k, represent the marginal effect of explanatory variables on replacement hazards.

Considered covariates 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.

The validity of the proportional hazards (PH) assumption is evaluated in two different ways.[15] First, we tested specifications based on Schoenfeld residuals (Grambsch and Therneau, 1994). 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 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 is the canton

[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.
[15] 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.

fixed effects, which violate the PH assumption in most estimations. In order to deal with this difficulty, we follow a standard stratification strategy (cf. Kleinbaum and Klein, 2005) assuming that baseline hazards vary across cantons, such that equation (3) is generalized 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.

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 between replacement rates and current household income, which could suggest a limited scope for policies providing financial incentives for renovation. However, the partially-significant relationship between risk attitude and renovation investment suggests that financial considerations are likely to have bearings on renovation decisions.

Moreover, dwellings outside urban centers 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 centers. 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 centers 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 a 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.[16]

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,[17] 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. The building's overall age could bring more renovation needs in addition to the element's aging process, through a greater exposition to environmental factors. On the other hand, this might point to a deliberate tendency of owners toward selecting a lower quality for replaced elements compared to the initial

[16] 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).

[17] 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.

elements. Economically, great investments in building elements could be less justified in relatively old buildings compared to new constructions with longer expected lives. Richer data and further research is needed to disentangle these potential effects.

5. Conclusions and Policy implications

We 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 their replacement patterns. We compare the empirical functions to a set of survival curves drawn from technical norms. Our focus is on four main elements- windows, roofs, façades and heating systems- whose renovation provides an important opportunity for improving energy efficiency in the built environment. Given that technical norms provide an upper bound for an element's economic service life, the observed renovation delays (renovation gaps) compared to norm-based service lives can be considered as indicative measures of an energy efficiency gap in buildings.

Our 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. The only exception is the case of windows whose median effective service life coincide with average predictions from CRB norms. While on average heating systems tend to be replaced earlier than is recommended by norms, long delays are observed for façades and roofs, which remain in use, on average about 10 to 20 years longer than they should be according to norms. Moreover, different expected service lives across various envelope elements is in contrast with norm-based recommendations giving a similar average service life (35 years) for roofs, façades and windows. We also 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, and more importantly, a considerable share that are used well beyond the end of their norm-based technical service life.

These patterns have important consequences for energy efficiency in residential buildings. First, delayed envelope renovations, suggest that potentially important energy savings could be achieved by applying technical standards. Secondly, the observed variation in timing the renovations across various elements could hinder the expected energy savings from simultaneous renovation. Finally, the energy efficiency gap is characterized by a sizeable share of home owners that refrain from renovating a building element long after its technical service life has ended. This lag is particularly important for façades and roofs with a disproportionate share of no renovation for extremely old buildings.

Our regressions identify a number of determinant factors of renovation behavior that show a significant effect beyond aging. In particular, we find that structural factors such as the building type and location are significant predictors of renovations. Renovation rates are relatively low in urban areas and single-family homes, with the latter group showing an especially low propensity for renovating roofs and façades. Compared to old buildings constructed before the 1990s, relatively recent constructions are less likely to get renovated. While being in line with previous studies on renovation behavior 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.

The findings reported in this paper have three important policy implications for energy savings resulting from renovations. First, to the extent that home-owners renovate their old heating systems earlier than assumed by technical norms, these norms tend to underestimate the diffusion rate of new heating technologies in residential buildings. In contrast, the spread of technological innovations in building insulation is likely to take considerably longer than expected. Secondly, given that a significant fraction of home owners fail to renovate façades and roofs beyond their reasonable useful lives, policy measures should specifically focus on targeting this lack of investment in extremely old buildings and single-family homes. While financial incentives seem to play an important role, further research is required to better identify other relevant market barriers in these cases.

Finally, we can identify an important group of buildings, namely those constructed in the 1990s, that can specifically be targeted by tailored policy measures. While previous studies emphasize the renovation barriers in old buildings, our results highlight 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)
Building type (ref.: Multi-family building)				
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 (propensity to renovation).
*** p<0.01, ** p<0.05, * p<0.1 (significance in rejecting H_0: $\beta = 1.$).

Figures

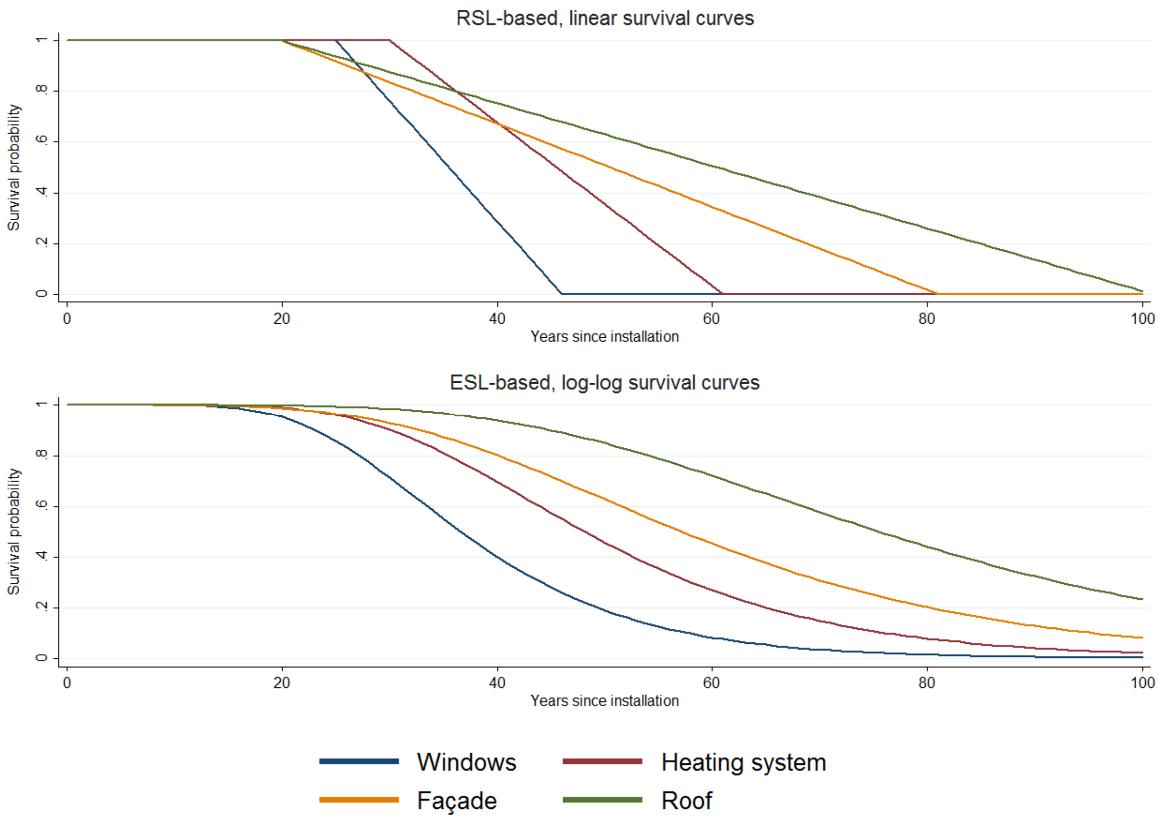

Figure 1: Technical survival curves of building elements based on CRB assumptions with reference service life (RSL) and estimated service life (ESL)

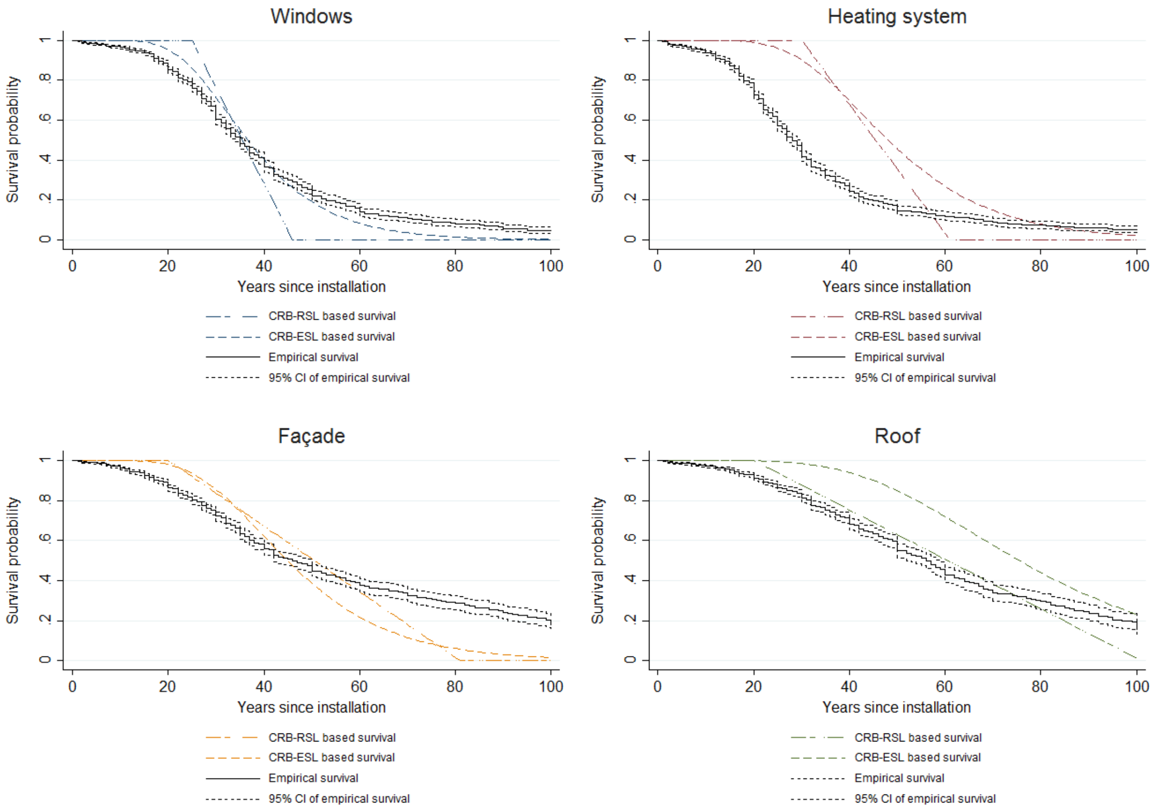

Figure 2: Contrasting technical and empirical survival curves