Reconstitution of the dynamics of an urban building stock

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ABSTRACT

What are the patterns and influences on the lifespan of the building stock? This paper presents (1) the reconstitution of an urban building stock composed of more than 60,000 buildings, (2) the analysis of the development of this stock over a period of 180 years (constructions and demolitions), and (3) the analysis of building mortality patterns and reasons for demolition resulting from historic decisions and regimes. A method to reconstitute the stock from different data sources is presented. The mortality models take into account not only the present demolition rates and the age distribution of the ‘survivors’ but also the disappeared buildings. The main results are new insights into the lifespan behaviour of buildings according to their period of construction (cohorts) as well as the reasons for demolition. The demolitions do not show specific explanation patterns, but changing influences of the construction activities over time. The average demolition age of all buildings in Zurich, Switzerland, decreased from over 200 years to fewer than 70 years. A total of 18,000 buildings have been demolished over the 180-year period. The presented methods and results can be integrated in multidimensional geographical information systems (GIS) as comprehensive planning, scenario and regulatory tools.

KEYWORDS

age; building stock; cities; data collection; demolition; lifespan; lifetime; longitudinal analysis; planning; stock dynamics; urban dynamics

Introduction

In the long-term, the knowledge of the composition and the dynamic of building stocks are crucial for sustainable management of the built environment. The end-of-life phase of buildings, their lifespan and the long-term demolition reasons are not well known due to the lack of methods and the longitudinal data. Central assumptions in stock models often rely on single, context-related expert judgement. The lifespan of buildings depends partially on their construction, use and maintenance. There are also different definitions of lifespans, which are relevant but not the focus of this paper (see Appendix A below for terminology and definitions). Buildings are demolished due to a variety of reasons, which often are related neither to their age nor to their state. The value of the resource ‘building stock’ reflects not only its present composition, state and short-term dynamic but also the long-term development and the historic dynamic. Only the (historic) reconstitution of the stock will provide the necessary information. The method of reconstitution and the insights from the reconstitution are the objective of this paper. The conclusions will allow the research community to improve their models of the development of building stocks, and enable public authorities to obtain new insights into the stock. Moreover, better knowledge about the possible lifespans of buildings will provide strategic information to allow one cope with an urban building stock if the impacts continue to increase and basic resources become scarce.

The lifespan approach is implemented by (1) the reconstitution of an urban building stock, (2) the study of the stock’s long-term development and (3) the analysis of buildings’ mortality patterns and reasons for demolition.

The end-of-life aspects are often overlooked due to lack of appropriate data and processing techniques. In the next section, the state of the art and the objectives of dynamic building stock models are described in general. In the third section, ‘Scientific questions and related methods’, six questions are formulated that approach the mortality of buildings in different ways and present different views of the data. As the necessary data to answer the questions are not directly available, the necessary processing of the data is presented in the fourth section. The fifth section illustrates the results of the reconstitution and answers the six questions. The final sections discuss the results and present conclusions.
State of the art and objectives of dynamic building stock models

Building lifespan

The end-of-life assumptions depend on the scientific questions as well as the available evidence. The assumptions can either serve to reduce complexity (e.g., cohort models, typologies) or they can allow approximations to be made, when there are no available empirical data (e.g., by using standard service-life distributions). The simple question of how long buildings last can find a multitude of answers (Kornmann & Queisser, 2012), generally based on expert judgement. Experts can be quite right when referring to a stock they know well. The application of their assumptions to other stocks can be misleading. A comparative study of Japanese and UK stocks shows the considerable difference of half-lives even for similar types of buildings in the two countries (Tanikawa & Hashimoto, 2009).

The lifespan of an individual building depends, among other things, on building function, building age, and a number of regional and local characteristics. The reasons of obsolescence and demolition can be multiple (Thomsen & van der Flier, 2011). The proposed evidence-based approach builds the detailed study of the lifespan of the individual buildings without a priori considerations of groups or types.

Stock dynamics

Research on building stock generally proceeds by constructing models (Kohler & Hassler, 2002). At the root of most dynamic building stock models, changes to the stock are considered to follow a (life-)cyclic movement. This idea is based on the analogy with biological phenomena. The dynamic of a building stock model is associated with the mortality of different cohorts of a population, in particular, in the form of survival analysis. Mortality modelling has a very long history in different disciplines. Numerous models have been proposed since Gompertz published his law of mortality (Gompertz, 1825). He established different types of tables (like individual mortality tables) showing for each age what the probability is that a person of that age will die before his or her next birthday (‘probability of death’). Cohort mortality tables show the probability of death of people from a specific cohort (in a particular birth year) over the course of their lifetime. The transposition from population mortality models to building mortality models, considering age cohorts as construction ‘types’ with specific properties, therefore seems quite straightforward and plausible. The stock dynamic is generally realized by input–output models. They can roughly be divided into leaching (stationary) models and dynamic models. In leaching models the output is independent of the input. In dynamic models the output depends on the history of the stock, of its life cycle (Bergsdal, Brattebø, Bohne, & Müller, 2007; Sartori, Bergsdal, Müller, & Brattebo, 2008).

In the new construction phase, the growth rate depends on the analysed stock. In the case of spatially defined stocks, in particular national stocks, the construction activity is related to population, to workplaces and to their specific space needs. The growth function resembles a logistic curve (it starts approximately exponentially and with the saturation the growth slows down resulting in the typical ‘S’-shape). The growth function is, therefore, also a logical response to the spatial provision of societal needs. Over longer periods European stocks have a ‘mature’ behaviour: low new construction and low demolition rates with a dominant renovation activity (Meikle & Connaughton, 1994). In the case of ‘young’ stocks, the input evolution is the most important criterion. The planned migration of large populations from rural to urban zones in China becomes a dominant factor (Hu, Bergsdal, van der Voet, Huppes, & Müller, 2010). In general, the objective of the models is to construct different long-term scenarios. In the case of urban stocks the behaviour and the increase rate can, however, be strongly influenced by communal borders, whereas the larger urban agglomeration continues to expand. In the management of owner-defined stocks the input history is estimated on the basis of the age distribution in the existing stock (the survivors). The objective of these models is the management of the stock and input is often not the most important factor. Building cycles due to general economic activity (Barra, 2009) have a considerable short time influence on all types of stocks (Hassler & Kohler, 2004).

In the operation (use) phase, facility management disposes generally of detailed annual cost data, which allows the prediction of the mid-term evolution of costs. Refurbishment frequency and intensity have a great influence on the evolution of the economic, social and cultural value of a stock. The service life potential depends on the quality of new construction, maintenance and renovation. The renovation parameters are crucial for long-term scenarios. Unfortunately, there is little longitudinal information on these parameters. The reason is that refurbishment interventions can be of very different depth and that they do not always need building permits. The prediction of the renovation needs of younger buildings (built after 1950) is generally based on the periodic replacement of components (windows, boilers etc.) (BBSR,
2011). In the case of (mass-)housing built after the Second World War, renovation activities follow decade cohort models. For other (older) parts of the stock, the renovation activities vary strongly and predictions are highly uncertain.

End-of-life models are rare (Huuhka & Lahdensivu, 2016). Due to the very low rate of demolition in European housing stocks (between 0.05% and 0.1%), there are few explicit comprehensive mortality models (Thomsen & van der Flier, 2009, 2011). When extrapolating simply from the present demolition rate, the average lifespan would be around 1000 years, which is not plausible. The reasons for the demolition of buildings and groups of buildings are complex. Monument conservation shows that buildings can be maintained ‘in life’ for several centuries. Buildings are generally not demolished because they are in bad (i.e., decayed or dilapidated) state, they are in bad state because they are planned to be demolished (and therefore are not maintained and become decayed). The information and motivation at the root of the decision of whether to ‘refurbish or demolish’ is generally contradictory (Power, 2010).

**First mortality models**

Gleeson (1986) and Johnstone (1994) were the first to deal theoretically with the application of mortality methods to building stocks. Johnstone showed the possibilities and the limits of the approach and discussed simplified methods and common errors when using mortality notions. He concluded that:

> the average service life and service lifespan of a housing stock are indicators of mortality and are not indicators of the quality of dwelling services provided by a housing stock. (Johnstone, 2001, p. 50)

and that ‘realistic models of housing stocks should be based on empirically established functions of mortality otherwise they will be prone to error’ (Johnstone, 2004, p. 3). He concluded that:

> The mortality of a housing stock can be established empirically by either developing a life table model of the housing stock which makes use of age-specific data on dwelling losses and survivorship or, in the absence of suitable data, a stock and flow model of mortality which is validated against available data. The realism and subsequent precision of each model is limited by the implicit assumptions of mortality built into the model. The ideal life table model is a generation life table based on longitudinal data. A series of generation life tables enable the detection of dynamic mortality and general shifts in mortality over time. (Johnstone, 2001, p. 50)

Survival or life tables give insight into the mortality of a population. For the right interpretation there are restrictions: the proportion between age groups must stay at the same level (Johnstone, 2001). Further information will be the reached age. The buildings achieving a certain age interval \( (u_i) \) or are demolished within it will be counted in the surviving stock \( (B_i + D_i) \). The product of the number of standing buildings and the age at the end of interval will be the ‘stock in age’. Buildings demolished within the interval will be considered only with the half of the years per interval. The number of total useful life will be the sum of the ‘stock in age’ of all older intervals. The average service life will be the quotient of ‘total useful life’ and ‘surviving stock’:

\[
\text{Average service life} = \frac{\sum_{i}^{\max} u_i \times (B_i + D_i)}{B_i + D_i}
\]

where \( B_i \) is the buildings surviving longer than interval \( i \); \( D_i \) is the demolished buildings in interval \( i \); \( u \) is the age at the end of interval \( i \); and \( i \) is the control variable for the intervals.

**Mortality models with longitudinal data**

Mortality models take into account not only the present demolition rates and the age distribution of the ‘survivors’ but also the disappeared buildings. The method of establishing survival rates for building cohorts is explained in detail by Bradley and Kohler (2007). Due to the difficulties in establishing longitudinal data on demolition, few attempts to determine the long-term survival functions exist. Komatsu, Kato, and Yashiro (1994) established a survival function for Japanese one-family buildings (in wood) and apartment buildings (in concrete). The basic information was a ledger containing the transactions over a longer period. The result gives half-lives (the time interval when 50% of the cohort is demolished). For Japanese wooden domestic houses, the estimated half-life is 38.2 years in 1987 and for reinforced concrete offices buildings 34.8 years. Apartment houses had insufficient data. For old buildings, the data for the estimation were insufficient; the extrapolated curve shows that their average half-life would be 50.6 years (Komatsu et al., 1994). Bradley and Kohler (2007) analysed the building stock of a small town in the south of Germany (Ettlingen) with a population of 38 700. The oldest building dated from 1670. The main sources were building statistics and the fire insurance database (for year of construction and demolition). The sample was 1726 in total; the total number of
buildings was 5250. All buildings were localized on a geographical information system (GIS) cadastre plan.

The half-lives of domestic buildings were over 300 years, for non-domestic buildings, 140 years, and for industrial (production) buildings around 50 years. For the older cohorts, the halftime is considerably higher than for the younger cohorts (Bradley & Kohler, 2007). The study by Tanikawa and Hashimoto (2009) is centred on historical mass flows in two situations: a neighbourhood in Salford (UK) and a neighbourhood in Wakayama (Japan). The number of buildings was several thousand and the demolition curves were established by combining national census information and historical GIS analysis. Through an estimation of the demolition curve, the lifespan of buildings in an urban area was found to be shorter than the national average, respectively, at both sites: 81 years in the urban area of Salford compared with 128 years for the UK; and 28 years in Wakayama City centre compared with the Japanese national average of 40 years. The lifespan varied considerably according to the function of the buildings and the year of construction.

In a Dutch study by Hoogers, Gelinck, and Trabsky (2004), the lifespan of existing dwellings in the Netherlands was analysed. The objective was to understand the ‘filtering process’ through which dwellings with the lowest quality are demolished and the remaining dwellings are always adjusted to the changing needs and remain there for ages (Van Nunen, 2010). This filtering process concentrates on the age range between 75 and 125 years. The mortality curve of the dwelling cohorts shows a part with half-lives over 200 years, a part with half-lives around 120 years, and a problematic cohort of small, one-family buildings of bad construction quality with half-lives of 80 years. The data also show that the bigger the dwellings, the greater the chance of survival.

**Scientific questions and related methods**

The lifespan distribution of a building stock is not given by the existing statistical data; it has to be reconstituted in two steps: (1) collection of raw data from the different sources and the check for completeness and consistency; and (2) processing of the raw data to obtain a georeferenced inventory of the development of the stock on the basis of the districts of the current City of Zurich from 1832 to 2010 with data on the year of construction and the year of demolition of all buildings. A georeferenced inventory with the granularity of buildings has been finalized for the Old City and the quarters Hottingen, Unterstrass and Schwamendingen going back to the 1830s. This approach was not continued for further quarters due to its high time consumption and was not necessary for this paper.

The question ‘how long do buildings live?’ can be differentiated with six questions (Q1–Q6). For each question specific methods (I1–I6) were applied. On this basis, the analysis of the processed data (R1–R6) was implemented and detailed answers were formulated. The six questions are:

Q1: Are buildings demolished following rules or attribute pattern?
Q2: Are there periods in which there are more demolitions than in others?
Q3: Are there buildings from construction years that survive longer?
Q4: Is the age distribution of existing and already demolished buildings similar?
Q5: How long do buildings live on an average? Can they be compared with human lifetimes?
Q6: Is there a concentration of demolitions around a certain age?

The answers to these questions suppose a detailed knowledge of the stock and of all the buildings, which are still standing (the survivors) and all the buildings that have disappeared (including their year of construction and demolition). As the obtained longitudinal data are not available in the usual lifespan predictions and stock models, the answers to the six questions give insights that were not available before.

Referring to the six questions the following methods were implemented (I):

I1: A list of buildings standing at present (or in the reference year) and their assumed construction year is calculated from a reconstituted dataset (REDAT, see the materials section). The diagram helps one to understand the past construction activity.
I2: For this analysis, the number of buildings constructed in a certain year and the number of existing buildings from this very period in the following years is identified from REDAT.
I3: Based on the available raw material, a dataset is reconstituted (REDAT, see the materials section) showing how many buildings of a certain construction year had survived for each year between 1832 and 2010.
I4: Based on REDAT, the distribution of standing (surviving) and demolished buildings is created.
I5: The age of demolished buildings was calculated for each year and the five-year smooth average was established. The average lifetime of the population in Switzerland is added (Statistik Schweiz – Die Volkszählungen im Laufe der Zeit, 2015; Wolff, 1908).
I6: For a survival table following Johnstone (2001), a list of the buildings for one year (2010) and the number of existing and demolished buildings for a period
The City of Zurich has undergone several changes in its spatial limits. The ‘historic’ city covers the period 1230–1832. The settlement of Zurich has existed since Roman times. In the Middle Ages the city became an imperial free city in 1218, and the first city walls were built in 1230. The size of the city remained constant inside the fortification until the beginning of the 18th century. The city had approximately 1150 buildings (Wolff, 1908). A special historical analysis concerned its development since the 14th century, studied by Corrodi-Sulzer (1939) with maps from 1504 and 1824 (Dändliker, 1908; Keller & Hegi, 1829). The analysis covers the surface inside the fortification walls in 1833, the year of the start of the demolition of the medieval fortifications. According to Corrodi-Sulzer (1939), between 1470 and 1920 one hundred and thirty buildings were demolished and reached an average lifespan of 400 years. The increase of the insurance value (Beck, 1983) at a constant building stock size until 1832 indicates that many buildings probably received additional floors, which is also mentioned for the period 1832–60s (Wolff, 1908). The population varied between 5000 and 10 000 inhabitants. Already before the demolition of the city walls (1833) the construction activity around the city increased (Beck, 1983).

The administrative extension began with the integration of seven suburban communes in 1893; the second enlargement concerned six communes in 1934. The industrial city could grow in this enlarged area, the composition of domestic and non-domestic buildings (production and administration) changed. The districts that structure the development of the city were initially all independent communes. The communal limits of the city have remained unchanged since 1934. The population reached 440 000 in 1960. The following decrease is part of a suburbanization process during which the agglomeration Zurich still grew. In Switzerland, the definition of agglomerations changed from the first ones in 1880 to 1980 (Bundesamt für Statistik, 2005, pp. 77–79); for this work the current area was chosen consisting of 131 municipalities and covering an area of 1086 km². In 2010, the city’s population was close to 400 000 again. The agglomeration Zurich comprised approximately 600 000 inhabitants in 1950 (Statistik Schweiz – Die Volkszählungen im Laufe der Zeit, 2015) and the population constantly increased to 1,080,728 inhabitants in 2000 (Bundesamt für Statistik, 2005, pp. 87–89).

The objective at this level was to obtain a georeferenced inventory of the development of the stock on the basis of the districts of the current City of Zurich from 1832 to 2010 with data on the year of construction and the year of demolition of all buildings.

To handle the spatial changes, raw data were acquired at three levels: the City of Zurich (communal limits), districts and individual buildings. Due to the changing size of the commune of Zurich, the data on the current districts are retraced and in some cases individual buildings have been checked to validate the data from the Statistics Office.

Step 2: The inventory of data sources

For several years prior to 1862, the number of domestic buildings in the current Old City of Zurich prior to the additions in 1893 and 1934 is given in the supplemental data online. From the census years 1860, 1870, 1880, 1888, 1900, 1910, 1920 and 1930 (Statistik Schweiz – Die Volkszählungen im Laufe der Zeit, 2015), the number of domestic buildings for the Old City of Zurich and the later added municipalities are known. For 1901–33, the number of new apartments and of new domestic buildings is given by the Statistik Stadt Zürich (2011). From 1934 on, the number of domestic buildings, of new apartments, of new domestic buildings and of demolished domestic buildings are available at the Statistik Stadt Zürich. Since 1955, the number of demolished apartments, grouped by construction periods, is provided by the Statistik Stadt Zürich. Since 1981, for each existing and demolished apartment and domestic building the construction year and demolition year has been collected by Statistik Stadt Zürich.

The different sources cover different aspects, different parts of the stock and different periods. The different types of data were structured in a time–space GIS database with a construction year, demolition year and district indication (respectively, former commune indication) for each building. The result was a mosaic of different data that were partially missing, partially not compatible, and with different structures and formats.

Step 3: Procedure for the reconstitution of the stock

The data were organized in a table covering the period 1832–2010 with the construction year (as an attribute) on the x-axis and the time line on the y-axis. The
diagonal resulting from years (time line) and year of construction gives the amount of new construction per year. The result is a triangular table because no building can exist before its construction year.

The processing consisted of five steps. In the first, the development of 1980–2009 was retraced on the basis of demolition data for these years. In the second, the number of demolished apartments from different construction periods known for 1955–80 was distributed on the buildings from the different construction years. The third step starts with the oldest period 1832–1900 and distributes the known decadal increasing number of buildings on the different construction years by using the distribution of the buildings and their construction years in 1955 (derived in the second step). The fourth step comprising data from 1901 to 1930 on the number of new constructions allows one to calculate the demolition rate in this period. The fifth step closes the gap between 1931 and 1954 by distributing the number of demolished buildings on the buildings of all construction years (see Figure 1 and the supplemental data online for details).

Results

The reconstituted dataset (REDAT)

A REDAT that illustrates the development of the domestic buildings of the City of Zurich between 1832 and 2010 is based on the construction and demolition years of individual buildings in the different districts of the city (Figure 2). The available data on the non-domestic part of the stock allowed only a reconstitution on the granularity of the number of buildings in decade cohorts.

In the City of Zurich, more than 46,000 domestic buildings have been constructed in the considered time span. Three per cent were demolished prior to 1930 and around 20% after 1930 (Figure 3). Until 1890, annually an average of about 110 buildings were constructed. For 1891–1920, the average is slightly below 3000 buildings per decade, and for 1921–60, the average is more than 5000 buildings. Later on, the average stays between 1000 and 2000 buildings (Figure 3). Newest data for the period 2004–15 show that the number of new constructions are rising (Rey, 2015). A total of 1175 new domestic replacement buildings make up around 50% of the total new domestic buildings.

The reconstituted non-domestic stock amounts to around 25,000 buildings. More than 29% were demolished in the last 180 years.

Figure 4 shows the number of constructions and demolitions per decade. Due to missing data records, the number of buildings was validated for decades. Until 1890, annually an average of fewer than 70 buildings were constructed. For 1891–1920, the average is about 1000 new buildings per decade. For 1921–50 and after 1980, the average of new non-domestic constructions is approximately 1550 buildings per decade. With 2700 constructed buildings per decade, the period 1951–80 has the highest amount (Figure 4).

The first phase of development (until 1832) was limited by the capacity of the walled city.

The second phase (1833–1950) was limited by the communal limits of the current city borders. From 1950 on, there was a clear saturation of population and internal transformation of the commune. The growth process is accompanied by an internal transformation reflecting the transition from a commercial–artisanal organization to an industrial city and then to a service-based urban region similar to the urbanization processes in other European cities. For each period an observed

![Figure 1. Steps for developing the dataset for the City of Zurich since 1832.](image)
area reaches a clear limit and a change of limits takes place: from the Old City to the current commune of Zurich and to the agglomeration of Zurich. The process can be described through the increase of the stock combined with internal transformations and demolitions. The growth of the agglomeration that became dominant from 1950 on does not yet have a clear limit (physical or institutional).

The growth process of Zurich has a specific form reflecting a number of economic, social and political influences. Several phases can be clearly distinguished. Inside these phases, the growth processes seem to take the ‘S’-shape of a logistic curve, which means that the periods of higher increase are followed by lower increase. There is no overall saturation phenomenon of the region. This is may be due to the parallel development of the transport system and the necessary time to cross a city that seems to stay constant at about one hour (Ausubel & Marchetti, 2001; Marchetti, 1994).

The analysis of mortality was centred on the period from 1832 to 2010 and limited to the area of the commune of Zurich (in 2010, including the integrated communes). The rate of construction outside the former city walls increased rapidly and the highest rate of new construction with a 66% increase over one decade was reached in the 1830s. The next highest rates were reached in the 1890s with over 50% per decade and in the decade of 1920 with 38%. For the following decades, the rate of new construction is between 15% and 30%. This tendency continues and the decade rates between 1930 and 1970 are below 10%. Since 1950, the city has not grown significantly but has transformed and densified. As the development of the ‘historic’ city had reached a limit within the fortifications, in a similar way the development of the current City of Zurich is limited by the communal (administrative jurisdiction) limits. This limit implies that there will be fewer constructions on unbuilt sites, which reduce the average age. The changes in the age distribution of the building stock will mainly depend on replacements.

In absolute numbers, the highest increase took place between 1921 and 1960 with an average of 5500
buildings per decade; these buildings amount for over 60% of the present stock. In the decade of 1920, the extension took place on yet unbuilt land. In the coming decades, partially at least, the replacement constructions took place on the plots of demolished buildings. In the decades before, the average construction rate was below 2000 buildings per decade. Only in the decade of 1890, a larger number of buildings was realized.

If the increase is counted not only in the number of buildings but also in building gross floor area (GFA), footprint and volume, the share of buildings of the decades 1920 and 1950 is considerable. Buildings before these periods were smaller but increased considerably afterwards. These data are compared and validated with the regular census data.

Analysis of mortality

The analysis of the mortality can give answers to several questions about the building stock. Each question requires a different approach to or view on mortality and they have all their limitations. The answers follow the six questions.

(1) Are buildings demolished following rules or attribute pattern?

Illustrating what is left for each construction year gives an insight how the construction industry developed in the observation period of 180 years (Figure 5). The absolute number of demolished buildings per construction year varies (Figure 5) and construction cycles become visible. Set in relation to the total constructed buildings per year, the relation between construction period and percentage of demolitions seems obvious.

Nevertheless, there are times of higher and lower construction activities, whereby the driving forces do not need to have been the same (Table 1). It depends very much on the assumption that the buildings have been demolished with a similar ratio to keep the relationship between the constructions periods comparable. Despite the 10-year
Figure 4. Reconstitution of the non-domestic stock of Zurich, 1840–2010 (number of buildings per decade).
Note: The construction decades are differentiated by their colour; the end of an interval is given in the legend. Positive numbers are existing buildings in one year of the time line. Negative numbers represent cumulative demolished buildings up to a certain year on the time line for the construction decade with the same colour.

Figure 5. Remaining domestic buildings and losses per construction year in the stock of 2010.
Note: New constructed buildings per year (black frame), sum of demolitions until 2010 per construction year (black) and remaining stock in 2010 per construction year (grey). The construction cycles and overall losses are clearly visible.
sliding average, the demolition rate per construction year differs (Figure 6); this means that the buildings have been demolished with different ratios.

(2) *Are there periods in which there are more demolitions than in others?*

In the three decades 1931–60 the demolition rates were high, especially involving buildings from the 1830s–50s (Table 1 and Figure 7). From the 1930s to the 1970s there were high demolition rates based on the standing stock in the previous decade comprising 3–5% of the whole cohort per decade (Table 1, right column). The demolition periods covering several construction periods are not dependent on the year of construction. To understand the construction activities in detail, it is necessary to find out when the losses of the buildings from different construction periods took place.

Table 1 shows the data differentiating the demolition percentages per construction decade. Here the absolute number of demolitions per decade was considered. The older the year of construction, the more buildings have been demolished. The loss per construction period (measured in decades) varies between 0% for the youngest buildings and nearly 90% for oldest ones, *i.e.*, 70% of buildings from the period 1831–70, where a typical construction type was developed, do not exist anymore, despite their quality (Zürich, 2011). The buildings from the first two decades of the 20th century still exist at about 70%. For the buildings from the 1920s to the 1950s, 88% of the constructions were still standing. A possible continuous decrease is interrupted by three exceptions:

- the oldest construction period (buildings from before 1832) lost only 38%, whereas one could expect a demolition percentage of more than 89% of the initially constructed buildings
- buildings from the 1840s seem to have vanished slightly less than expected; an expected rate would be greater than 86%, instead of 79%
- buildings from the 1920s still stand for nearly 90%; the comparison with the surrounding decades would suggest a surviving rate of less than 75%

The demolition rates per decade for all construction decades vary between 1% and 6% based on the standing stock in the previous decade (Table 1, right column), with a high phase in the 1930s–70s considering the absolute number of buildings (circa 1300 demolitions of domestic buildings per decade). This rate might seem low. Due to the general growth of the building stock, certain construction periods, *i.e.*, the buildings from the 1830s or the 1850s, have been demolished at a rate of up to 28% in the 1930s. Therefore, even if the highest demolition rates, based on the whole building stock, were 88%, the absolute number of demolitions was lower than expected.
The percentage of surviving buildings from three older construction periods illustrates the loss over time (Figure 8). There construction periods can be compared by checking the parallelism of the curves. The illustration seems to show that the buildings from the oldest construction period are demolished at a higher rate, but the maximum age for the buildings in this category is several hundred years,
Figure 7. Initial constructions per decade in 1920, 1950, 1980 and 2010 (grey and black) since 1832, demolished buildings (black) and remaining buildings (grey) in the respective year. Note: The years stand for the previous decade, i.e. ‘1840’ stands for the years 1831–40.
whereas the maximum age for the other construction periods is 30 years. Therefore, the buildings in the oldest construction period require often a special approach, otherwise the results may be biased.

Prospective estimations, how long surviving buildings will live, are shown in Figure 8 and Table 2. Figure 8 extrapolates surviving rates of the last 10, 50 and 100 years, and shows that the stewardship of the building stock has probably changed. The demolition rate of the older construction period has decreased. Table 2 reflects the future potential by the ‘average service life’ that makes up a constantly increasing overall achievable age, which increases with age. The comparison between the achieved age of buildings and people shows a social and cultural impact of the changes. Whereas in the past buildings could be used as landmarks over generations, nowadays on average a whole city with several hundred thousand inhabitants will be completely transformed within a human lifetime.

This representation is completed with calculations of the future development of the stock. Three possibilities are the prolongation of the curves based on the average demolition rate in the last 10, 50 and 100 years.

From the construction period ‘prior to 1921’, 50% were still standing in 2010. Between 1921 and 1990, 40% of the buildings have been demolished. In the last two decades the demolition rate has decreased and 5% have vanished. The buildings in the oldest construction period will decrease (only 30% are left) if the demolition rate follows the average of the last 100 years and the least (more than 40% are left) if the 10-year average will continue.

The buildings constructed from 1921 to 1950 have lost 14% of their initial stock. If the 10-year average continues more buildings (down to 70%) will be removed for a demolition rate following the 100-year average (more than 80% left). From the construction period 1951–80, more than 5% have been demolished. For the youngest cohort the averages are only available for the last 10 and 50 years. An additional demolition percentage of 5–10% is likely to follow until 2050.

The buildings from the two younger construction periods were demolished more in the last 10 years than in the longer retrospective periods.

If age is an indicator for mortality, then the annual percentage of losses and of survivors must be dependent on the construction year and result in the same curve. Figure 6 shows the percentage of remaining buildings in 2010 based on the initial stock of each construction year since 1832 (dashed line). The 10-year sliding average for the percentages is calculated.
Table 2. Life-time table according to the surviving building stock in 2010 (a) and to the whole stock including demolished buildings between 1832 and 2010 (b).

(a)

| 1. Age interval | 2. Surviving stock at the start of the interval | 3. Stock losses over the interval | 4. Stock in the age interval | 5. Total useful life at the start of the interval | 6. Average service life at the start of the interval |
|-----------------|---------------------------------------------|-------------------------------|----------------------------|---------------------------------|---------------------------------|
| Building stock, 2010 | Number of buildings |        | Building years |      |                  | Years                  |                  |
| 0–10            | 54046                        | 3607                        | 558495                      | 4226530                        | 78                  |
| 11–20           | 50439                        | 2316                        | 515970                      | 3668035                        | 73                  |
| 21–30           | 48123                        | 2740                        | 494930                      | 3122655                        | 66                  |
| 31–40           | 45383                        | 3611                        | 471885                      | 2657135                        | 59                  |
| 41–50           | 41772                        | 4232                        | 438880                      | 2185250                        | 52                  |
| 51–60           | 37540                        | 7277                        | 411785                      | 1746370                        | 47                  |
| 61–70           | 30263                        | 6133                        | 333295                      | 1334585                        | 44                  |
| 71–80           | 24130                        | 6573                        | 274165                      | 1001290                        | 41                  |
| 81–90           | 17557                        | 9836                        | 204750                      | 727125                         | 41                  |
| 91–100          | 11721                        | 2648                        | 130450                      | 523235                         | 45                  |
| 101–110         | 9073                         | 1910                        | 100280                      | 391925                         | 43                  |
| 111–120         | 7163                         | 3186                        | 87560                       | 291645                         | 41                  |
| 121–130         | 3977                         | 873                         | 44135                       | 204085                         | 51                  |
| 131–140         | 3104                         | 831                         | 35195                       | 159950                         | 52                  |
| 141–150         | 2273                         | 506                         | 25280                       | 12755                          | 55                  |
| 151–160         | 1767                         | 236                         | 18850                       | 99495                          | 56                  |
| 161–170         | 1531                         | 168                         | 16150                       | 80645                          | 53                  |
| 171–180         | 1363                         | 173                         | 14495                       | 64495                          | 47                  |
| 181–190         | 1190                         | 141                         | 12605                       | 50000                          | 42                  |
| 191–200         | 1049                         | 471                         | 12845                       | 37395                          | 36                  |
| 201–210         | 578                          | 41                          | 5985                        | 24550                          | 42                  |
| 211–220         | 537                          | 8                            | 5410                        | 18565                          | 35                  |
| 221–230         | 529                          | 18                          | 5380                        | 13155                          | 25                  |
| 231–240         | 511                          | 500                          | 7610                        | 7775                           | 15                  |
| 241–250         | 11                           | 11                           | 165                         | 165                            | 15                  |

(b)

| 1. Age interval | 2. Surviving stock at the start of the interval | 3. Stock losses over the interval | 4. Stock in the age interval | 5. Total useful life at the start of the interval | 6. Average service life at the start of the interval |
|-----------------|---------------------------------------------|-------------------------------|----------------------------|---------------------------------|---------------------------------|
| Building stock, 1832-2010 | Number of buildings |        | Building years |      |                  | Years                  |                  |
| 0-10            | 71247                        | 1420                        | 719570                      | 6022080                        | 85                  |
| 11-20           | 69827                        | 3549                        | 716015                      | 5302515                        | 76                  |
| 21-30           | 66278                        | 3689                        | 681225                      | 4586500                        | 69                  |
| 31-40           | 62589                        | 4524                        | 648510                      | 3905275                        | 62                  |
| 41-50           | 58065                        | 5845                        | 609875                      | 3256765                        | 56                  |
| 51-60           | 52220                        | 8307                        | 563735                      | 2646890                        | 51                  |
| 61-70           | 43913                        | 9789                        | 488075                      | 2083155                        | 47                  |
| 71-80           | 34124                        | 7353                        | 378005                      | 1595080                        | 47                  |
| 81-90           | 26771                        | 8094                        | 308180                      | 1217075                        | 45                  |
| 91-100          | 18677                        | 3959                        | 206565                      | 908895                         | 49                  |
| 101-110         | 14718                        | 3346                        | 163910                      | 702330                         | 48                  |
| 111-120         | 11372                        | 3960                        | 133520                      | 538420                         | 47                  |
| 121-130         | 7412                         | 1870                        | 83470                       | 404900                         | 55                  |
| 131-140         | 5542                         | 1454                        | 62690                       | 321430                         | 58                  |
| 141-150         | 4088                         | 914                         | 45450                       | 258740                         | 63                  |
| 151-160         | 3174                         | 517                         | 34325                       | 213290                         | 67                  |
| 161-170         | 2657                         | 452                         | 28830                       | 178965                         | 67                  |
| 171-180         | 2205                         | 347                         | 23785                       | 150135                         | 68                  |
| 181-190         | 1858                         | 46                           | 18810                       | 126350                         | 68                  |
| 191-200         | 1812                         | 46                           | 18350                       | 107540                         | 59                  |
| 201-210         | 1766                         | 34                           | 17830                       | 89190                          | 51                  |
| 211-220         | 1732                         | 17                           | 17405                       | 71360                          | 41                  |
| 221-230         | 1715                         | 17                           | 17235                       | 53955                          | 31                  |
| 231-240         | 1698                         | 573                         | 19845                       | 36720                          | 22                  |
| 241-250         | 1125                         | 1125                        | 16875                       | 16875                          | 15                  |
Nevertheless, there are construction periods that have survived on a much higher level than a perfect curve would predict. This is especially the case for buildings constructed around 1850, at the beginning of the 1880s and in the mid-1900s – all these have clearly survived at a higher rate. On the other hand, buildings from the mid-20th century were demolished at a higher percentage.

(4) *Is the age distribution of existing and already demolished buildings similar?*

The comparison of the age of demolished and surviving buildings within the whole observation period shows that a higher demolition rate is not proportionally dependent on age. The distribution of demolished and remaining buildings differs in the whole observation period 1832–2010 (Figure 9). The ratio between the two categories varies strongly for the age intervals, *i.e.*, while the number of demolished buildings between 41 and 70 years is almost constant, the standing buildings differ much more. In more detail, buildings with ages between 30 and 50 years have been demolished at a higher rate, but it is not visible from which construction period the buildings derive. This means that there is no connection between age and the rate of demolition in these 180 years.

(5) *How long do buildings live on average?*

For the City of Zurich, an average age of more than 200 years was possible in the 19th century. This age decreases more or less continuously. At the end of the 1940s and the beginning of the 1950s, the average demolition age is shortly rising. This can be explained by the Second World War and the assumption that demolition decisions were more cautious. In the 1970s, a minimum of around 68 years is reached. At the end of the 1970s and the 1980s, there is an increase again. This time, the energy crisis can have led to a more careful handling of the resource ‘building stock’. If the age of the building is not proportionally linked with its demolition and if the construction periods differ, the average age in the year of demolition shows that buildings are demolished at younger ages than in the past (Figure 10). In the City of Zurich, currently the average age at demolition is around 70 years (Figure 10). This is in contrast to the reached age of the population, which increased steadily to above 80 years.

(6) *Is there a concentration of demolitions around a certain age?*

Two resulting life-time tables (Table 2(a) and (b)) show the life table in decadal intervals (‘1. Age interval’) following Johnstone (2001). The buildings achieving a certain age interval or demolished within it are counted in the surviving stock (Table 2(a) and (b), ‘2. Surviving stock at start of the interval’ and ‘3. Stock losses over interval’). Column ‘4. Stock in age interval’ is calculated according to equation (1) (e.g., for the age interval 11–20: 50 439 buildings*10 years + 2316 buildings*5 years = 515 970 building-years). Column ‘5. Total useful life at start of interval’ is the sum of column ‘4. Stock in age interval’ of all older intervals (e.g., for the age interval 221–230: 16 875 building-years + 19 845 building-years + 17 235 building-years = 53 955 building-years). Column ‘6.
Average service life at start of interval’ result by dividing column ‘5. Total useful life at start of interval’ by column ‘2. Surviving stock at start of the interval’.

Table 2(a) represents the situation in 2010; Table 2(b) comprises all buildings that have existed in the City of Zurich since 1832.

In absolute numbers, only around 58,065 buildings have reached the age of 50 years. However, around 5,845 of these buildings are demolished within a decade (Table 2(b)).

Younger buildings seem to survive less long. The minimum is 95 years (the sum of the first and last columns) and the sum is increasing. A comparison of the last columns in Tables 2(a) and 2(b) underlines this difference. Especially for the ages 130–180 years, the ‘average service life at start of interval’ increases from 47 to 68. Buildings that survived 180 years or more will reach a lifetime of more than 250 years on average.

Discussion

Relation between new construction, demolition and stock

In spite of the rich available data, it is difficult to represent the relations between new construction and demolition over longer periods. The analysis of the current stock (Figure 5, grey) gives only an idea of the construction activity cycles and even less insight into the development of the stock. A reworking of the demolition illustration (Figure 5, black) clarifies the actual constructed buildings and losses. The reconstitution of the historic building stock was achieved due to the granularity of individual buildings only for domestic buildings. The relation is more complex than it appears when only looking at the results of input or output models, which are generally represented by cumulative curves (typically logistic curves) flattened out by decade representations. When looking at the absolute stock increase by year over a long period, cycles of approximately 20 years appear clearly. These building cycles (Barras, 2009) depend on general economic cycles. Other cycles of considerably longer duration, like the Kuznets and Kondratieff cycles, can be found in the German industrial economic cycles and the composition of the industrial building stock (Hassler & Kohler, 2004). For the City of Zurich such cycles are not immediately visible, i.e., if the relation of the number of constructions and demolitions for all buildings is taken into account.

For non-domestic buildings, the data on building attributes and age of demolition were complete only for 1980–2010. The reconstitution of the non-domestic stock at the level of decades since 1840 is plausible but needs further verification at the district level.

Uncertainty of the data

The first main difficulty concerns the consistency of data. The changes of statistical classes and the introduction of grouped data at specific dates were identified. The sources have different definitions for domestic and non-domestic buildings. The use of buildings changes over time, which is not documented. This is only visible by the decreased number of buildings in one category and the increased number in another.

A second difficulty is missing data. The available identification data are rarely complete and consistent,
and in general parts are missing. Building attribute data tend to be incomplete and over longer periods data are often not consistent. Researchers are obliged to choose between investing time in searching for more data in the available sources and establishing multiple links between different sources (e.g., fire insurance data and cadastre data). The generalization of GIS-based cadastres and the adoption of building numbers linked to Gauss Krüger coordinates allows the possibility of relating systematically sources that were inaccessible until now. The main problem is the absence of regular information about the year of construction of non-domestic buildings and their location when demolished before 1980.

Another difficulty is missing renovation data. New building and demolition is historically subject to an authorization that is one of the ‘backbones’ of stock data. As renovation and large maintenance activities do not always need a formal authorization, the data on this type of activity are missing or incomplete. Partial renovation data for Zurich exist for 15 years and have been used at a district level by Friedrich (2004). There are, however, no real longitudinal renovation data.

The frame given by the different source was so tight that there was no margin left for the final result of the reconstitution of the data.

**Approaches differ in their assumptions**

Traditional approaches to building stock management in research, tool development and practice can give reasonable results for a time horizon of 20–30 years. This is the time interval of accumulated refurbishment interventions. Studies on shorter time periods, such as a decade (Rey, 2015), give good insights into a historic or the current construction activity (i.e., intensifying replacement period), but a generalization or derivation of long-term dynamics is not appropriate. When looking only on a yearly base at the present demolition rates of European stocks, which are well below the 1% limit, it is evident that a direct deduction of a 0.2% demolition rate corresponds to an average life expectation of 500 years is irrelevant. The time horizon, which most researchers in the environment and energy sector share, is approximately 50 years. Simulation models of national energy consumption give plausible answers in this period. As regards the building stock, they generally predict the necessity to increase the demolition rates drastically by up to 1% or 2% (Kytzia & Dürrenberger, 1999). The basic assumption behind all these models is a life cycle–mortality–cohort assumption. This approach is practical but has severe drawbacks: it implies fundamentally a causal relation between input and output of the stock that does not exist. There is no simple relation between the age of a building and its survival. Buildings can be maintained ‘in life’ over very long periods, whereas in a reliability assessment the life of human beings (demography), the effect of medical treatment (e.g., oncology, etc.) or mechanical components all explicitly disappear within years or decades. Mortality models are in conclusion plausible and useful but they are not causal models and they do not allow as such the prediction of the complex process of stock and city development. They can indicate time horizons for certain processes.

**Conclusions**

**Reconstitution of the stock**

There is a general agreement that the dynamics of building stocks are not well known but that they are important. There are several motivations to analyse this dynamic in depth and the results are quite different. In the multitude of indications (both descriptive and normative) there are considerable differences between national studies and sectorial approaches. They indicate large differences in the rate of new construction and the rate of demolition in Europe (Itard & Klunder, 2007). It is not possible to evaluate and compare results from European stocks and Chinese stock, for example, without detailed information about both stocks. A comparative study can only be based on a reconstitution of the stocks, even if the quality of the reconstitution might remain very basic for some time. The only way to improve the information about the stock is reconstitution of the whole stock (including the historic stock) and the creation of a data repository in a temporal-spatial GIS with the granularity of individual buildings and with an interface to the urban infrastructure systems. The reconstitution shows the long-term dynamic as well as certain cyclic phenomena and discrepancy. Only the complete reconstitution allowed the visualization of these transformations. Based on the quality of the reconstitution, specific models can be defined and the attributes of the stock analysed. The reconstitution of the urban building stocks should be identified as a central task for urban planning and governance. It could be considered as a combined extension of general public statistics (population, activity etc.) and the cadastre and building register. Such a database could take the form of space–time GIS.

**New insights resulting from longitudinal data**

The availability of longitudinal data and the operationalization of this information certainly offer new possibilities for reconstituting building stocks. The view of
the historic development of a building stock concerns not only the size of the stock but also the nature and activities that occur in the buildings. The reconstruction of the stock gives new insights but also raises new questions about the nature of survival and demolition:

- **What are the different survival rates of buildings from certain construction periods and how do these vary over time?**
  
  If circumstances have no influence or are the same, then the survival curves must develop in parallel. If they do not develop in parallel, then internal or external reasons can be the cause. Internal reasons are qualitative differences, i.e., durability, flexibility, etc. External reasons can be of geographical, economic or other influences. The fact that many demolitions occur at the same time or in the same place can be visualized as well. Short periods can be shown without bias in this view because the time line is continuously present.

- **What is the age of buildings when demolished?**
  
  The results of Figure 10 (average age of demolished buildings) gives the best insight into how old buildings became in the last 200 years, and before. In other methods changes in the demolition ages become only indirectly visible, i.e., in Figure 8. Concentration of demolitions within a certain period cannot be seen in this view. A long observation period is necessary, otherwise this view is biased too strongly and may lead to incorrect interpretations.

- **What is the influence of demolition years or periods?**
  
  If the year of demolition has no influence (i.e., if its influence is respectively the same), then the survival curves of the construction periods must be similar. If they are parallel, this indicates a temporal delay. If they do not follow such a structure, then a concentrated period of demolitions of buildings from several construction periods is obvious and indicates the existence of external reasons. A long observation period is not necessary; nevertheless, the comparability within the time line increases, which supports more long-term interpretations.

**Transformation of the stock**

The building stock is a human-made resource, a complex social–ecological system. In an adaptive cycle model, the question of how fast building stocks could and should adapt to short-term changes is limited by the very slow speed of 'natural' transformation. This leads to the question of an optimal speed of transformation. The decrease of the demolition age of domestic buildings shows that a transformation is taking place. The economic, ecological, social, and cultural impacts and risks are not yet visible. Even if a building or a neighbourhood is adapted to the present situation, it is uncertain how the building stock will react if, for example, energy prices increase, resources become rare or changes occur in regulations or ownership. The discussion about the possibility of anticipating such changes and the reaction to unknown changes has shown the importance of new directions in research. The discussion of resilience-based strategies shows a new level of interaction between different disciplines (Hassler & Kohler, 2014; Kohler & Hassler, 2015).

**Importance of mortality analysis**

The initial question ‘how long do buildings last?’ does not have a single answer. The results show that depending on the approach (the question) and the context, different answers are possible. The mortality analysis shows significant differences between domestic and non-domestic buildings. At the city level, the change scale of the stock is rather in the range of 50–100 years. The mortality and its representations are not causes of the change; they reflect different types of change and allow for understanding or interpreting the changes. The conclusion is that mortality models must be differentiated into several geographical levels and several time periods. Districts may undergo totally differing development within the same decade but a similar development may be found earlier or later on. Models need, therefore, to consist of a temporal and spatial mosaic. An example is demolition activity in the Zurich cohort between 1870 and 1890 or the apparent cyclic development (Figure 5) of the construction and demolition activity up to 1950. The periods can be identified and localized through the analysis of the spatial and temporal states of the stock, but their explanation why these processes took place can only be found through the study of urban history. The mortality research will have to be related to historical urban research to investigate the complex processes that have influenced the mortality of the stocks. The results can be used in long-term scenarios of urban development and to assist with the formulation and validation of policy and strategy. The results of mortality research should also be integrated in the constitution of multidimensional GIS as new planning and regulatory tools.

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**Appendix A: Terminology**

*Cohort life tables*: probability of death of buildings from a given cohort (especially year of construction) over the course of their lifetime.

*Delay model*: outflow in a certain year is a function of the past inflow, characteristically one lifespan ago.

*Design life of a component or product*: period of time during which the item is expected by its designers to work within its specified parameters.

*Economic lifespan/time*: period over which an entity expects to be able to use a building, and the period over which it is depreciated.

*Half-lifetime (median lifetime)*: time when 50% of the initial population/stock has disappeared.

*Leaching model*: outflow is considered equal to a constant fraction of the stock.

*Mortality table (life table)*: shows for each age what the probability is that a building of that age will be demolished before its next birthday (probability of death).

*Maximum service lifespan* (Johnstone, 1994): maximum service lifespan of buildings is taken as the age at which only 0.1% of an original cohort still survives.

*Mortality rate*: measure of the number of events (deaths, demolitions etc.) in a population (stock), scaled to the size of that population, per unit of time.

*Period or static life tables*: current probability of demolition (for buildings of different ages, in the current year).

*Physical lifespan/lifetime*: total time period between the construction of a building and its complete demolition (including foundations) (König, Kohler, Kreißig, & Lützkendorf, 2009).

*Residual lifespan*: covers the period from the point in time under observation to the end of the (remaining) service life.

*Service life according to ISO 15686-1*: period of time after installation during which a building or its part meet or exceed performance requirements.

*Survival analysis – the survival function or survival probability* $S(t)$: defined as the probability that demolition occurs after reaching age $t$.

*Technical lifespan/time*: total time period during which a building can technically perform/function before it must be replaced.