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Norwegian University of
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Residential building stocks and flows as dynamic systems

Chilean dwelling stock and energy modeling,
including earthquakes.

Carla Gallardo

Master in Industrial Ecology
Submission date: June 2012
Supervisor: Helge Brattebø, IVM
Co-supervisor: Nina Sandberg, IVM

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

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Preface

This report is the thesis to achieve the master degree in Industrial Ecology at the Norwegian University of Science and Technology (NTNU).

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Abstract

The building sector comprises a very important part of each country's economy, playing an important role in the consumption of resources and energy. In practice there is little knowledge on how the building stock develops. It is useful then to understand the dynamics and the metabolism of the built environment. Research on building stocks, predominantly on the residential sector, has been performed mainly for developed countries. There is little or none research on building stock for developing countries, so given that there is still a big gap regarding service levels (floor area per capita) between developed and developing countries, it is of importance to understand the dynamics of developing countries as well.

Given that earthquakes occur in populated areas, it is important to assess the dynamics of such systems. The Chilean dwelling stock is subjected to earthquakes, so this focused on including earthquake activity to the dynamic MFA model of the dwelling stock. A leaching approach was used, basing the analysis on the typology distribution of different vulnerability classes. Different scenarios were defined in order to analyze the effect of policies on building codes and practices on the typology distribution of the stock, and hence on the demolition and renovation rate due to earthquakes. Policies for strengthening and renovating the building stock have a large positive impact on overall demolition rates. Patching types of policies have little effect when it comes to making the stock less vulnerable in the long term.

An energy analysis was carried out for the overall stock, based on the mass balance yielded by the building stock dynamic MFA model. Effects of policies on energy and renovation standards are observed through the analysis of scenarios as well. The energy consumption of the stock has not reached saturation yet, and the timing for this will be strongly influenced by the energy intensity development of the stock. The combined effect of policies for decreasing the vulnerability of the dwelling stock and energy efficiency policies could be further explored if each vulnerability class could be described by an energy intensity factor. Further data gathering or modeling on this would be of importance to further understand the system.

Even if there is uncertainty in the data and the model present weaknesses, the approach used for modeling the Chilean dwelling stock allows for a systematic view of the effects earthquakes on the system. Naturally, the building sector is an important contributor of CO_2 emissions. A detailed carbon analysis for the future development of the building stock is then relevant to this study. However, considering the time constraints, this research has focused on the modeling of the building stock including earthquake activity and an overall energy assessment of it. A simplified carbon analysis was left out due to the fact that by considering a constant emission factor the analysis of the trends of CO_2 emissions would be equivalent to the analysis of the energy model.

1. Introduction

Worldwide, the building sector comprises an important part of the economy. By 2006 it represented one third of the global greenhouse gases emissions (Allwood et al., 2011). Hence, this sector plays as well an important role on the consumption of resources and energy. At a national level the energy consumption of the residential sector represents between a 16% and 50% of all the sectors, while the world average is approximately 30% (Swan and Ugursal, 2009). Furthermore, buildings also contribute majorly to the generation of waste. These are all straightforward conclusions but in practice there is little knowledge on how the building stock develops and on the associated energy and waste generation burdens. It is useful then to understand the dynamics and the metabolism of the built environment. This can provide insights on the long term development of the in-use stocks and the related consequences of energy efficiency measures. It also provides information on upstream (construction) and downstream (demolition) processes. Overall, understanding the stock dynamics of the sector can serve to long-term planning, regarding demand for floor area, materials and energy, and also regarding waste management.

Research on building stocks, predominantly on the residential sector, has been performed mainly for developed countries, mostly in Europe. For Norway in particular there have been studies on the dynamics of the building stock, energy demand and construction, renovation and demolition activities. Conversely, there is little or none research on building stock for developing countries. Thus, given the fact that there is still a big gap regarding service levels, such as floor area per capita and persons per dwelling, between developed and developing countries, it is important to understand the dynamics of developing countries as well.

Earthquakes can occur in largely populated areas and therefore it is important to understand their effects to the built environment. In 2010 earthquakes worldwide caused more than 225,000 deaths, approximately USD $40 billion in economic losses and insured losses exceeding USD $10 billion. The last earthquake in Chile in 2010 (magnitude 8.8) was the most costly since the 1994 Northridge California earthquake (magnitude 6.7), which caused economic losses of USD $40 billion (Chávez-López and Zolfaghari, 2010). Hence, a system subjected to earthquakes, such as the Chilean dwelling stock, should include in its dynamics the effects of earthquakes.

This study will model the residential building stock for Chile, including the effects of earthquakes, and using a leaching approach to accomplish this. The effects of earthquakes are ultimately translated into an overall demolition rate, but they are calculated basing on a typological approach where different vulnerability classes for buildings are defined. The typology distribution of the stock based on vulnerability classes, together with a damage distribution table indicating damage grades of vulnerability classes for a given earthquake intensity, will contribute determining the loss extent due to potential future earthquakes included in the model. Different scenarios will be defined in order to analyze the effect of policies on building codes and practices on the typology distribution of the stock, and hence on the overall demolition and renovation rate of the stock.

An energy analysis will be carried out for the overall stock, based on the mass balance yielded by the building stock dynamic MFA model. Historical data (1997-2009) on energy distribution to the residential sector will be used to characterize the historical energy intensity factor for the stock and will also set the basis for the future potential energy analysis. The analysis is then characterized as a top-down one. Effects of policies on energy and renovation standards will be observed through the analysis of scenarios. These scenarios are rather too optimistic, but we have chosen to study the system changes under strong measures, in order to what extent these changes affect the system.

Results are presented and discussed for the building stock and energy model. Even if there is uncertainty in the data, the model serves the purpose to obtain a general picture of the Chilean residential building sector dynamics, and to perform a typology analysis based on vulnerability classes for the building stock in a systematic approach. The vulnerability of the stock could be more interrelated to the energy analysis if an energy intensity factor could describe each vulnerability class. Unfortunately this data is not available, but it could be interesting for further research.

2. Literature review and background on earthquake vulnerability

In this section a literature review is performed regarding previous research on dynamic Material Flow Analysis for the building stock (section 2.1) and how the energy performance of such systems has been modeled (Section 2.2). A theoretical background on earthquake vulnerability of the built environment is given, including important definitions on earthquakes, a short review on seismic vulnerability assessment and background information on seismic activity and its relation to the built environment particularly for Chile.

2.1 Material flow analysis and building stock modeling

Material flow analysis (MFA) comprises a systematic assessment of the flows and stocks of materials within a system defined in space and time. It is based on the law of conservation of matter and its results can be controlled by establishing, for a given process, a material balance relating inputs, outputs and stocks (Brunner and Rechberger, 2004). When implementing a dynamic MFA model the system variables are functions of time. A historical and future analysis of the system can be performed and its dynamic behavior can be understood.

Dynamic MFA is of importance when analyzing change and long term effects in the system. Particularly, the built environment is characterized by a long service lifetime, so a long-term perspective helps understanding the dynamics of the system, its critical variables and also could provide valuable information to support the implementation of sustainable strategies (Brattebø et al., 2009).

The way the building stock has been approached by dynamic MFA in previous research is through the analysis of the floor area and building materials. Müller (2006) performs a dynamic MFA applied to the Dutch dwelling stock for the period 1900-2100. In this study the author relates the material stocks in use to a service, where the central driving forces are population (P) and its lifestyle. When applied to dwelling stocks, lifestyle is further explained with the variables: average size (area) of a dwelling (A_D) and persons per dwelling (P_D). The quotient between average size of a dwelling and persons per dwelling represents a disaggregation of an indicator for floor area per capita, which is frequently used as social indicator for sustainable development in general and for housing quality in particular (Müller, 2006). These three variables together, each of them expressed as a function of time, yield the stock demand, or stock in use, for floor area (equation 2 in section 3.1). This stock in use forms the physical link between resource demand and waste generation, or input and output, respectively (Müller, 2006).

Müller (2006) addresses the fact that the stock in use can have different lifetimes, so he defines a lifetime distribution that links the input and output to the stock in use. Then the output will depend on the probability of a service unit, in this case square meter, to be discarded at a time t if it entered use at a time t'. Please refer to equation 1 below.

$$A_{out}(t) = \int_{t_0}^{t} L(t,t') \cdot A_{in}(t')dt' \qquad 1.$$

Müller (2006) concludes that stocks in use play an important role in understanding long-term changes of societal metabolism, since they reflect better quality of life than inflows. In particular, Müller observed that the shape of the floor area stock curve determines the general shape of construction and demolition curves, and related the accentuation of this curve's saturation to the wave observed in construction and demolition. The long lifetime of dwellings (100 years) is the reason behind a long term fluctuation of both construction and demolition. Moreover, the increase in stock replacement needs, due to a wave of demolition in the future, triggers a high resource demand, making growth more expensive.

Several other studies on building stock modeling have used the approach proposed by Müller (2006), such as Bergsdal et al. (2007) in their dynamic MFA for the Norwegian residential stock; Sartori et al. (2008) in their model of construction, renovation and demolition activities also for the Norwegian residential stock and Brattebø et al. (2009) in their generic model framework for studying the material and energy metabolism of built environment stocks. Hu et al. (2010a) have studied the dynamics of urban and rural housing stocks in China and Hu et al. (2010b) have applied a dynamic MFA to study the urban housing system in Beijing. In general these studies conclude that by modeling flows and stocks for dwellings, although there are uncertainties regarding input parameters, such as lifetime (Bergsdal et al., 2007; Hu et al., 2010a) it is possible to understand patterns in the long-term development systems (Brattebø et al., 2009).

In their dynamic MFA of the Norwegian residential building stock, Bergsdal et al. (2007) also observed a cyclic behavior of the stock, where peaks in demolition are displaced by one lifetime relative to construction, also inducing a new peak in construction. A sensitivity analysis was performed by running simulations for different scenario alternatives, concluding that stock demand is expected to increase in all cases except for one alternative where the floor area per dwelling decreases. Moreover the building stock development due to changes in population follows similar trends compared to when changes are applied to lifestyle parameters (P_D and A_D). This is not very surprising, since the relationship between the stock and population and the lifestyle parameters is linear by definition (please refer to the methodology section, equation 2). On the other hand, changing the lifetime of the buildings has a big impact in construction and demolition flows, affecting the development trends (timing) and magnitudes (deviation from the medium scenario) significantly. A shorter lifetime will imply a more rapid turnover of floor area, where a peak in inflows will be observed much earlier compared to other scenarios of high development for population and lifestyle parameters. The parameter with most uncertainty and as well with higher impact on the scenarios is lifetime.

Sartori et al. (2008) also performed a dynamic MFA on the Norwegian dwelling stock for the period 1900-2100, using the same approach proposed by Müller (2006), but including renovation activity that will alter a dwelling's energy performance. The purpose of the study was to provide a basis for future analysis of materials demands and waste generation and opportunities of energy performance improvement. Renovation is addressed as a flow that re-circulates inside the stock, so renovation flows are linked to the floor area turnover. Moreover, this activity is represented by a probability function describing the cyclic renovation profile. The probability distribution is normal (with a mean of 40 years), weighted against the lifetime distribution, in order to avoid the renovation of buildings that are close to be demolished. Renovation activity does not influence the lifetime though. When comparing results from the model with statistics in Norway, Sartori et al. (2008) finds that the model might be underestimating renovation rates. For the period 1971-2001 statistics estimate that 50% of the building stock has been renovated (based on number of dwellings), while Sartori's model estimates that a 19% of the building stock has been renovated in those 30 years (based on m^2). Naturally the information from statistics might not reflect completely the reality due to possible misinterpretation of the renovation concept by the survey participants, but it still gives an idea on the renovation levels for that period. Furthermore, the number of times an average square meter in the stock is renovated is 1.01 in the medium modeled scenario, considering 30 years of mean value for renovation interval. Sartori states in his study that the renovation activity is expected to increase in absolute figures in the nearest decades, mainly due to a peak in construction in the 1980s.

As mentioned above, the dynamic MFA of building stocks has been approached by using lifetime distributions; this is called a *delay model*. Another modeling approach is the leaching model, where outflows are proportional to the size of the stock for each year. These models are useful when age is of no importance and each element of the system has the same probability of being discarded (van der Voet et al., 2002). This statement excludes the utilization of the leaching model to the modeling of building stocks; however, it represents a simplified and flexible way of modeling earthquake damage, given that the driving force behind an event like this is not ageing, but leaching (van der Voet et al., 2002). Given that the Chilean building stock was modeled using the delay model as well in the project previous to this thesis (Gallardo, 2011) a comparison of both approaches will be provided in section 3.1.1.

2.2 Energy assessment/modeling for building stocks

2.2.1 Different modeling approaches: top-down and bottom-up

Two approaches are identified when modeling the energy consumption of the residential sector: top-down and bottom-up. Swan and Ugursal (2009) performed a review on modeling techniques and explain the differences between these two approaches. Top-down models use the estimate of total residential sector energy consumption and other variables to attribute the energy consumption to characteristics of the entire residential sector. These models treat the residential sector as an energy sink and do not make distinctions on individual end-uses. On the other hand, bottom-up models are based on the calculation of energy consumption of individual or group of houses in order to extrapolate those results to represent a larger share of the stock, such as a region or a nation. The hierarchal level from where input data is obtained is lower than the one describing the sector as a whole.

A very important quality that a bottom-up model has compared to a top-down one is that its level of detail provides the ability to model technological options, making it suitable to identify areas of improvement and, moreover, making it capable to estimate energy consumption independently from historical data. Its drawback though is that the high level of detail in the input data makes these methods very data intensive and hence more complex to simulate. Furthermore, top-down models heavily weigh the historical energy consumption, which gives the model an important indication of the change rate for consumption. These models usually falter when discontinuity appears, which can be on the technological or supply side (Swan and Ugursal, 2009).

2.2.2 Energy modeling based on dynamic MFA for building stock

Sandberg et al. (2011) performed a historical energy analysis (from 1960 to 2004) based on the results of the dynamic MFA for the Norwegian dwelling stock by Bergsdal et al. (2007). Energy intensities (kWh/m^2) were used in order to analyze the historical energy consumption of the residential building stock, considering direct and indirect energy consumption. The results by Sandberg et al. (2011) show that energy consumption has reached saturation the last decade of the study and furthermore that it is mostly dominated by the use phase. Reasons behind the low contribution of the upstream and downstream activities are partly due to the long lifetime of buildings. Comparing the development of total energy consumption with the energy intensity a reduction in energy consumption per square meter has been observed. However this energy efficiency improvement is offset by the increased stock of floor area, given that the energy consumption has doubled for the studied period. The study by Sandberg et al. (2011) concluded, among other things, that underlying drivers in the building stock model are as well of importance when aiming for energy efficiency improvements, particularly the system should be influenced to reduce per capita and total floor area demand. Also, increased per-capita energy consumption can be explained through a higher wealth level of the population and also a more energy-demanding lifestyle.

A follow up study was performed by Sandberg and Brattebø (2012) this time on future trends for the Norwegian dwelling stock, from year 2000 to 2050. In this study the effect of changes in the dwelling stock size, energy consumption and supply energy mix were assessed. A change in the projected population growth changes significantly the results for the building stock model, increasing the floor area stock demand and predicting a new peak in inflows around year 2015. Direct energy consumption is assessed by subdividing it into three end uses: space heating, water heating and electrical appliances. The most relevant end use for total energy consumption is space heating, hence its intensity is also the most important when it comes to trigger changes in the total energy demand. However, even if a decrease in future energy intensities is assumed, the energy demand will increase substantially in the coming decade. Hence, the increase in floor area stock demand will not be compensated by the assumed energy efficiency improvements. These results, and their comparison with other studies for the energy consumption of the Norwegian dwelling stock, evidence the importance of basing an energy analysis on a dynamic building stock modeling. Furthermore, this outlines the importance of a growing population when trying to reach national targets for energy efficiency and hence green house gases emissions.

2.3 Earthquake vulnerability of the built environment

2.3.1 Earthquakes – Important definitions

An earthquake is defined as a spasm of ground shaking caused by a sudden release of energy in the earth's lithosphere. The main cause of seismicity is tectonic activity (Dowrick, 2009d). A world seismicity map for the period 1900-2010 is shown in Figure 2.1 below, where we can see that earthquakes occur in highly populated regions.

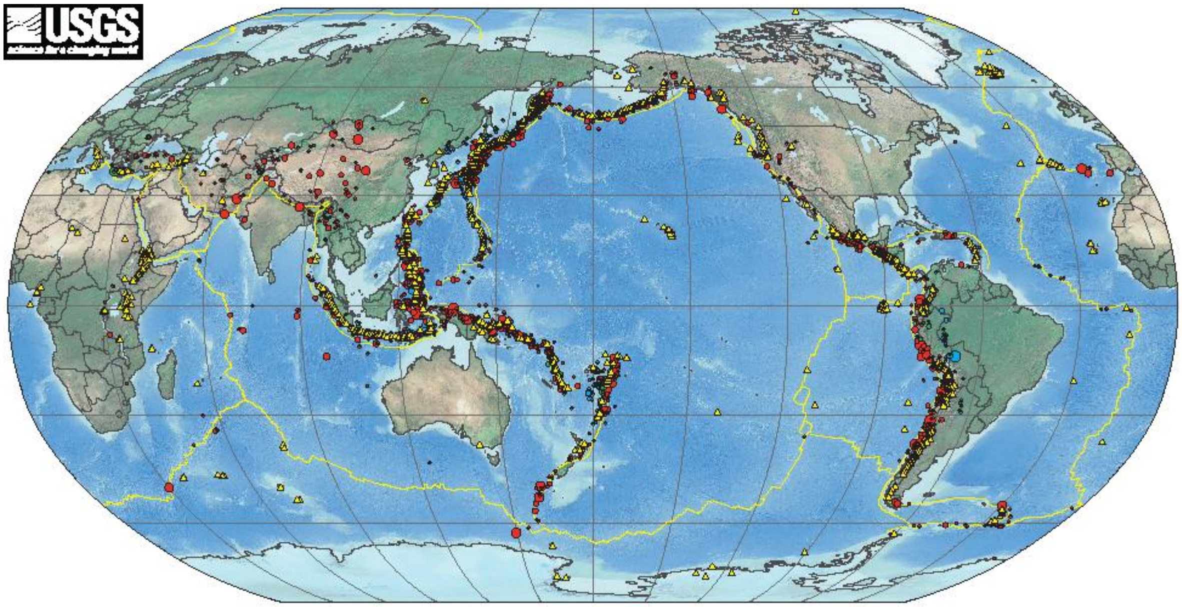

Figure 2.1: World seismicity map from 1900 to 2100 (USGS, 2010).

The strength of an earthquake is usually described in two ways, by its intensity and by its magnitude. *Intensity* is a qualitative or quantitative measure of the severity of seismic ground motion at a specific site. Scales used to measure intensity are for instance the European Macroseismic (EMS-98, developed after the MSK-64[1] scale) and the Modified Mercalli (MM) scale, both of them define 12 grades of intensity and are equivalent. On the other hand, *magnitude* refers to a quantitative measure of the size of an earthquake; it is indirectly related to the energy released and it is not dependent on a specific site (Dowrick, 2009d). The most common magnitude scale used is the Richter scale, where for instance an earthquake of magnitude between 7 and 7.9 is considered as major, being able to cause serious damage (Wikipedia, 2012).

On any given fault within any given region, earthquakes occur at irregular intervals in time, and one of the basic activities in seismology has long been the search for meaningful patterns in the time sequences of earthquake occurrence. The longer the historical record, the better is the overall picture that can be obtained (Dowrick, 2009e).

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[1] Medvedev-Sponheur-Kàrnic

Local geology and local soil conditions have an effect on the severity of ground motion, but there are other possible consequential hazards due to earthquakes, such as liquefaction, landslides, tsunamis, etc (Dowrick, 2009a). Spatial patterns of ground motion can be shown in terms of Modified Mercalli intensity, where intensities have a particular distribution around the epicentral region; these are called isoseismals. The spatial distribution of isoseismal curves will vary at a given site, since it depends on many factors, such as the nature depth and geometry of the source (fault rupture), location of the site in relation to the source, the attenuation characteristics of the wave travel path, local geology at the site, etc (Dowrick, 2009e). An example of isoseismal curves is shown in Figure 2.2 below, for the particular case of the 2010 earthquake in Chile.

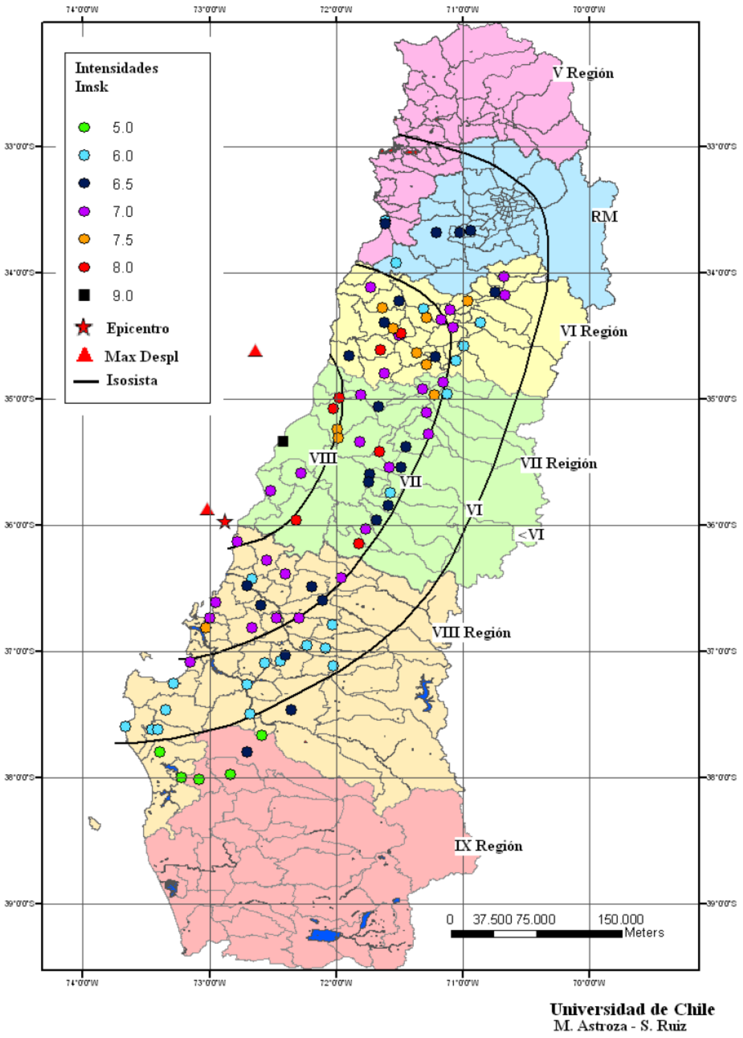

Figure 2.2: Map with Intensities and isoseismal curves for the 2010 earthquake in Chile (Astroza et al., 2010).

For this map MSK intensities have been used, which are considered to be equivalent to Modified Mercalli intensities (Silva, 2011).

2.3.2 Seismic vulnerability assessment

Earthquakes cause losses to the built environment, which why it is important to have models capable of estimating the extent of these losses when facing a potential future earthquake. Two important concepts are introduced in this section to provide a background to seismic vulnerability assessment, these are: seismic hazard and seismic risk.

Seismic hazard refers to any physical phenomenon (e.g. ground shaking, ground failure) associated with an earthquake that may produce adverse effects on human activities. In practice, seismic hazard is often evaluated for given probabilities of occurrence, for example as for ground motions (Dowrick, 2009b). A global seismic hazard map was developed between 1992 and 1998 by the United Nations Global Seismic Hazard Assessment Program (GSHAP) (Giardini et al., 1998); it can be observed in Figure 2.3 below. Seismic maps depict the levels of ground motions that likely will, or will not, be exceeded in specified exposure times. This particular map shows the global seismic hazard as Peak Ground Acceleration (PGA) with a 10% chance of exceedance in 50 years, corresponding to a return period of 475 years[2]. PGA comprises a ground motion parameter that is proportional to force and it is also quite common to be mapped due to its vast use in building codes, which usually specify the horizontal force a building should be able to withstand during an earthquake.

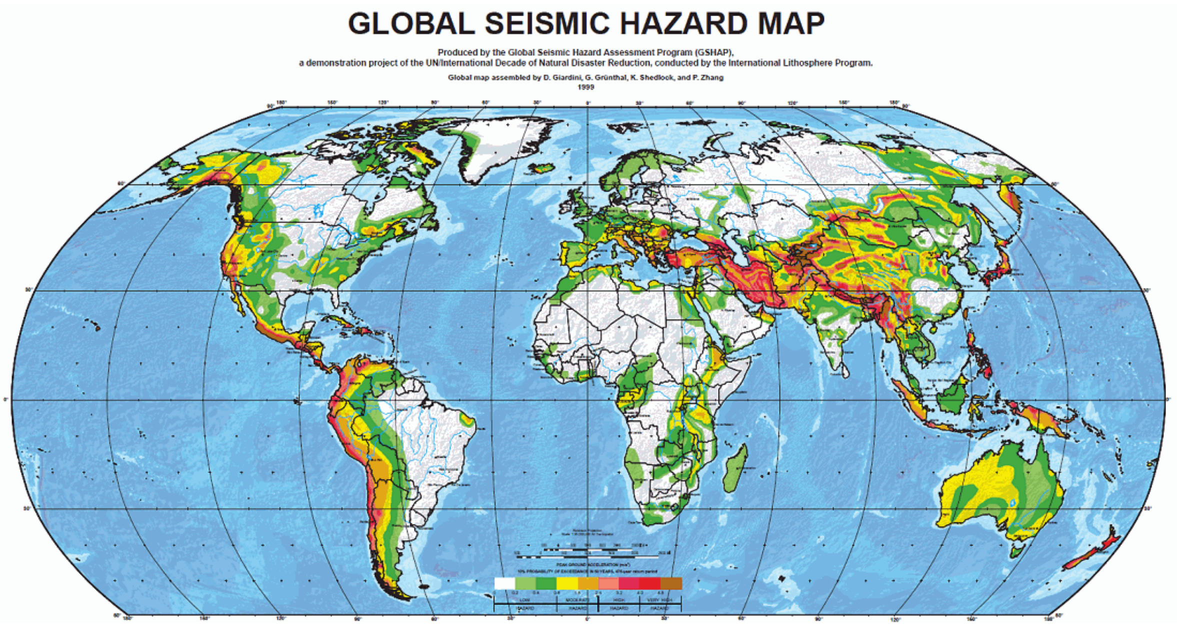

Figure 2.3: Global seismic hazard map (GSHAP). Cooler colors (white, green, yellow and orange) represent lower hazard, warmer colors (pink, red, dark red and dark brown) represent higher hazard (Giardini et al., 1998).

The assessment of seismic hazard is the first step in the evaluation of *seismic risk*, which is the probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at several sites, or in an area, during a specified exposure time (Dowrick, 2009b).

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[2] http://www.seismo.ethz.ch/static/GSHAP/global/global.html

Seismic risk is obtained by combining the seismic hazard with vulnerability factors. Frequent, large earthquakes in remote areas result in high seismic hazard but pose no risk; on the contrary, moderate earthquakes in densely populated areas entail small hazard but high risk (Giardini et al., 1998).

Earthquake vulnerability of the built environment is important for studying the management and minimization of risk in future earthquakes. The main cause for earthquake damage to the built environment is ground shaking; however other consequential hazards, mentioned in section 2.3.1 above, due to earthquakes can play a role when damaging structures. *Vulnerability* is defined as the degree of damage of an item within the built environment to a given strength of shaking (Dowrick, 2009c). The degree of damage can be described qualitatively or quantitatively.

Qualitative measures of vulnerability are designed to evaluate in a simple manner a group of buildings. These measures can describe the performance of different vulnerability classes of construction in a subjective intensity scale, such as the Modified Mercalli (Dowrick, 2009c). Also, different damages grades can be defined and a statistical distribution of damages according to intensity can be established (Dowrick (2009c) and Silva (2011)). The MSK-64 scale defines three vulnerability classes: A, B and C, where A is the most vulnerable, and the EMS-98 scale increases the number of vulnerability classes up to 6 (from A to F) and incorporates the concept of mobility between classes. Then the materials, construction practice, foundation types and other factors can affect the vulnerability class where a construction type is assigned. Damage grades are defined by the MSK-64 or EMS-98 scale, and can be adapted to different built environments. The statistical damage distribution of the MSK-64 and EMS-98 scales, and the damage grades definition, have been adapted to the Chilean built environment (Silva, 2011).

Quantitative measures of vulnerability can be based on an analytical calculation of the response of a specific building to an earthquake, the identification of a typology and the use of a vulnerability indicator for each typology defined, or the identification of certain indicators within a structure that characterize their resistance to earthquakes. Usually the outcome of these quantitative measures is a damage probability matrix, a vulnerability function or a vulnerability index. A damage probability matrix expresses in a discrete form the conditional probability of obtaining a certain damage level due to a certain ground motion of intensity (Calvi et al., 2006). Vulnerability functions are continuous functions expressing the probability of exceeding a given damage state given a function of the earthquake intensity (Calvi et al., 2006). The vulnerability index establishes a relationship between the seismic action and the response, based on certain parameters and their influence on building's vulnerability.

To perform a vulnerability assessment a parameter for ground motion must be chosen in order to correlate ground motion with damage to the buildings. The damage is modeled on a discrete damage scale, such as the MSK, MM and EMS98 scale. The methods proposed for vulnerability assessment in the available literature can be subdivided into empirical, analytical or hybrid (combination of the first two). Empirical vulnerability methods use the damage scale in reconnaissance efforts to produce post-earthquake statistics. In analytical vulnerability methods the damage scale is related to limit-state mechanical properties of the buildings (Calvi et al., 2006).

2.3.3 Seismic activity and built environment in Chile

Chile is one of the most seismically active countries in the world, mostly due to its location on the Pacific Ring of Fire (Leyton et al., 2009). This makes its built environment vulnerable, which is the reason for ensuring appropriate seismic behavior of the structural systems at the built environment, through building codes and practices. The most used structural system for residential systems that contributes to appropriate seismic behavior consists in shear walls, combined with high wall density ratios (Moroni et al., 2004).

Building codes have evolved partly according to the behavior observed over a history of earthquakes; a list of the strong earthquakes occurring in Chile from 1900 on is shown in Table 2.1 below. For instance, masonry buildings with some type of reinforcement have been built since 1930, as a consequence of the first seismic building code imposing reinforcement after poor performance observed at the 1928 earthquake (Moroni et al., 2004). For the 1985 earthquake the reinforced masonry building type showed poor performance, partly explained for the lack of seismic design code until then. The building code that followed this earthquake was updated in 1993 and more rigorous requirements were specified, so since then its construction has decreased due to economic reasons. The hybrid masonry type of housing started being constructed during the 1980s but there is no specific seismic design code for this type (Moroni et al., 2004).

Table 2.1: Historical earthquakes and their magnitudes in Chile (USGS, 2012).

Date	Location	Magnitude	Fatalities
17-08-1906	Valparaiso	8.2	3882
11-11-1922	Chile-Argentina border	8.5	225
01-12-1928	Talca	7.6	225
25-01-1939	Chillán	7.8	28000
06-04-1943	Illapel-Salamanca	8.2	25
21-05-1960	Arauco Península	7.9	-
22-05-1960	Valdivia	9.5	1655
23-02-1965	Taltal	7	1
28-03-1965	La Ligua	7.4	400
09-07-1971	Valparaíso	7.5	90
03-03-1985	Valparaíso (offshore)	7.8	177
30-01-1998	Northern Chile (coast)	7.1	-
18-06-2002	Chile-Argentina border	6.6	-
20-06-2003	Central Chile (coast)	6.8	-
03-05-2004	Bío-Bio	6.6	-
13-06-2005	Tarapacá	7.8	11
14-11-2007	Antofagasta	7.7	2
16-12-2007	Antofagasta	6.7	-
04-02-2008	Tarapacá	6.3	-
13-11-2009	Tarapacá (offshore)	6.5	-
27-02-2010	Bío-Bio (offshore)	8.8	577

3. Methodology and Data

This section introduces the methodology chosen for modeling the residential building stock for Chile. Firstly the general approach for modeling the building stock will be explained, which means that the model does not include the effects of earthquakes. Then, after the system is defined in section 3.2, the methodological approach to include earthquakes in the system is discussed. Section 3.4 introduces the methodological choices for the energy analysis derived from the building stock model. Lastly, section 3.5 outlines the data used in the model and the assumptions behind, and section 3.6 determines the different scenarios to be modeled.

3.1 General approach for modeling building stock with dMFA

The way the building stock has been approached by dynamic MFA in previous research is through the analysis of the floor area and building materials. However in this work we have only worked with floor area, given the lack of data on material intensity for the Chilean dwelling stock. The building stock demand over time or also the floor area in use, S(t), will be given by a relationship between three parameters: population (P), persons per dwelling (P_D) and the average size (area) of a dwelling (A_D), these last two being the lifestyle parameters. Hence, for each year the stock demand will be given by the following expression (Müller, 2006).

$$S(t) = P(t) \cdot \frac{A_D(t)}{P_D(t)} \qquad 2.$$

Given that we know the time series for the population and lifestyle parameters, we can calculate the stock demand over time. This makes possible the calculation of the change in stock demand for each year ($\Delta S/\Delta t$), and since our analysis will be year-based we will have that:

$$\Delta S = S(t) - S(t-1) \qquad 3.$$

Then, the building stock is modeled using MFA, where the main assumption is that mass is conserved, so changes in the stock will be given by the difference between inputs (A_{in}) and outputs (A_{out}).

$$\Delta S(t) = A_{in}(t) - A_{out}(t) \qquad 4.$$

In previous research the quantification of the outflows has been made using a lifetime profile that characterizes the stock. Then the outflows would be given by the probability of a past inflow to be discarded (refer to section 2.1 above). However, for the Chilean stock there is no specific information on lifetime distribution, or on how age cohorts are related to damage due to earthquakes. Hence, in order to simplify the model, the quantification of the outflows will be through a leaching approach, where a constant fraction of the stock leaves the system each year (van der Voet et al., 2002).

$$A_{out}(t) = c \cdot S(t) \qquad 5.$$

The leaching rate "c" is calculated assuming an average lifetime ("L") of dwellings, so it will be given by the following expression (van der Voet et al., 2002).

$$c = \frac{1}{L} \qquad 6.$$

Hence, being able to quantify the change in the stock demand and the outflows, it is possible to calculate the inflows using the general mass balance equation 2 above.

$$A_{in}(t) = \Delta S(t) + A_{out}(t) \qquad 7.$$

Renovation in a building stock model can be treated similarly to demolition activity. Then there would be a share of the stock, defined by a renovation leaching rate, which will undergo renovation. In this work renovation has to variants, it can relate to energy efficiency improvements or to earthquake vulnerability decrease in dwellings. None of these two will affect the total mass balance, since we are assuming that renovation will only improve the energy efficiency or earthquake vulnerability. A schematic representation of the system is shown below in Figure 3.1.

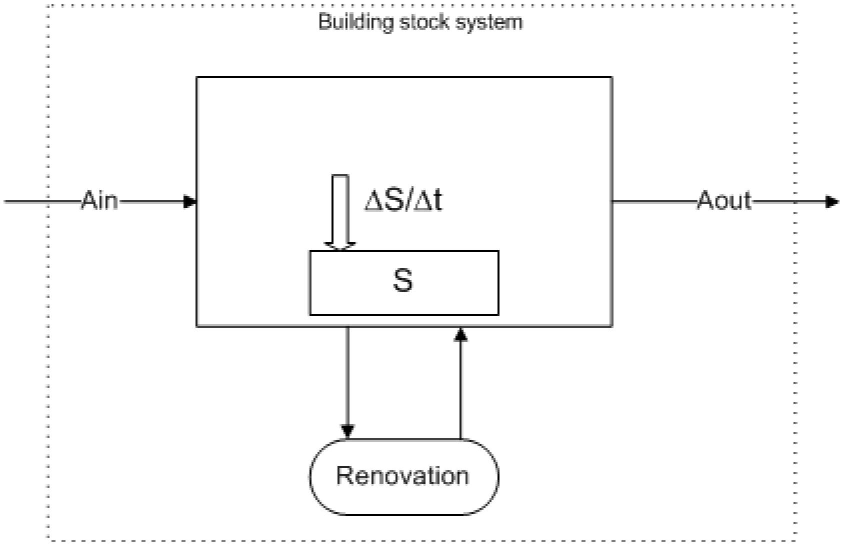

Figure 3.1: Building stock system

3.1.1 Comparison between leaching and lifetime model

The subsection 3.1 above is the explanation on how the building stock model works when considering a leaching approach. This gives the basis to our further model development that will include earthquake activity.

A leaching model is usually appropriate when age is not important and each element in the system has the same probability to be discarded (van der Voet et al., 2002). This of course is not the case for a building stock, since each dwelling has a different probability to be discarded according to its age. This represents a weakness of the model; however the lack of data on age distribution for the Chilean stock prevents for the use to its full extent of the delay model and justifies better the leaching model, where the modeling approach is simpler and the data requirement level is lower (van der Voet et al., 2002). Furthermore, the leaching approach represents a simplified and flexible way of modeling earthquake damage, given that the driving force behind an event like this is not ageing, but leaching (van der Voet et al., 2002).

We aimed to compare the results of both modeling approaches, which are shown in Figure 3.2 and Figure 3.3 below.

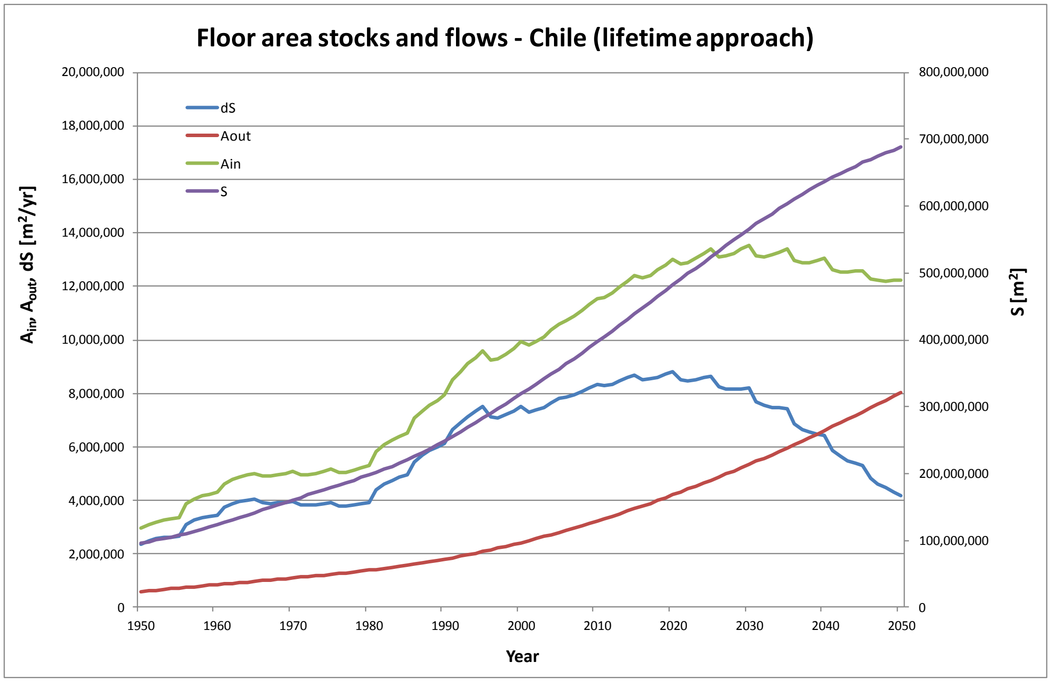

Figure 3.2: Results for the residential building stock modeling using the lifetime approach

The difference between the lifetime approach and the leaching approach when modeling the dwelling stock lies mostly on the flows, not on the stock demand or stock demand change. This is due to the fact that the stock demand (S), and hence the stock demand change (dS), are affected by the lifestyle parameters (A_D and P_D) and population (P), and since we are using the same data series for these, the results are the same for each model.

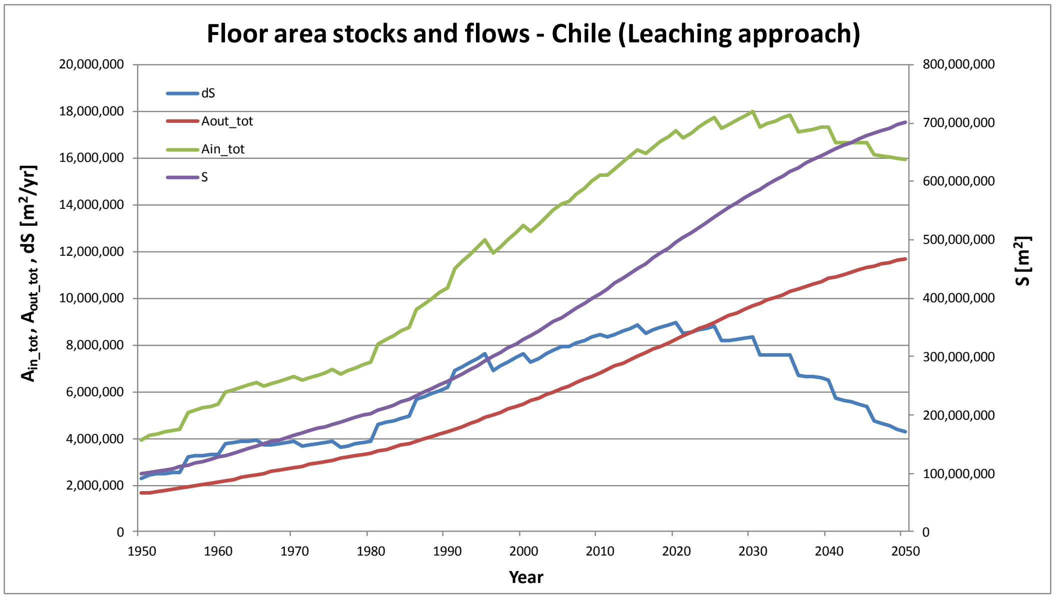

Figure 3.3: Results for the residential building stock modeling using the leaching approach

Regarding the inflows and outflows we can see that the leaching approach predicts the peaks just as the lifetime approach does. The difference is in the magnitude of the flows, where the leaching approach overestimates the magnitude compared to the lifetime approach. This is not surprising, since that firstly the stock is growing over time and secondly by considering a constant leaching rate based on an average lifetime, will imply a higher turnover of the stock, increasing in average the outflows, and hence the inflows.

3.2 System definition

The system in this work will be the residential building stock in Chile, and the timeframe for the analysis is from 1900 to 2100. The building stock is modeled using a dynamic material flow analysis based on floor area in square meters. This model includes, through a leaching approach, the effect of earthquake activity in the system, for both demolition and renovation activities. The operational energy performance of the dwelling stock will also be modeled. Please refer to Figure 3.4 below.

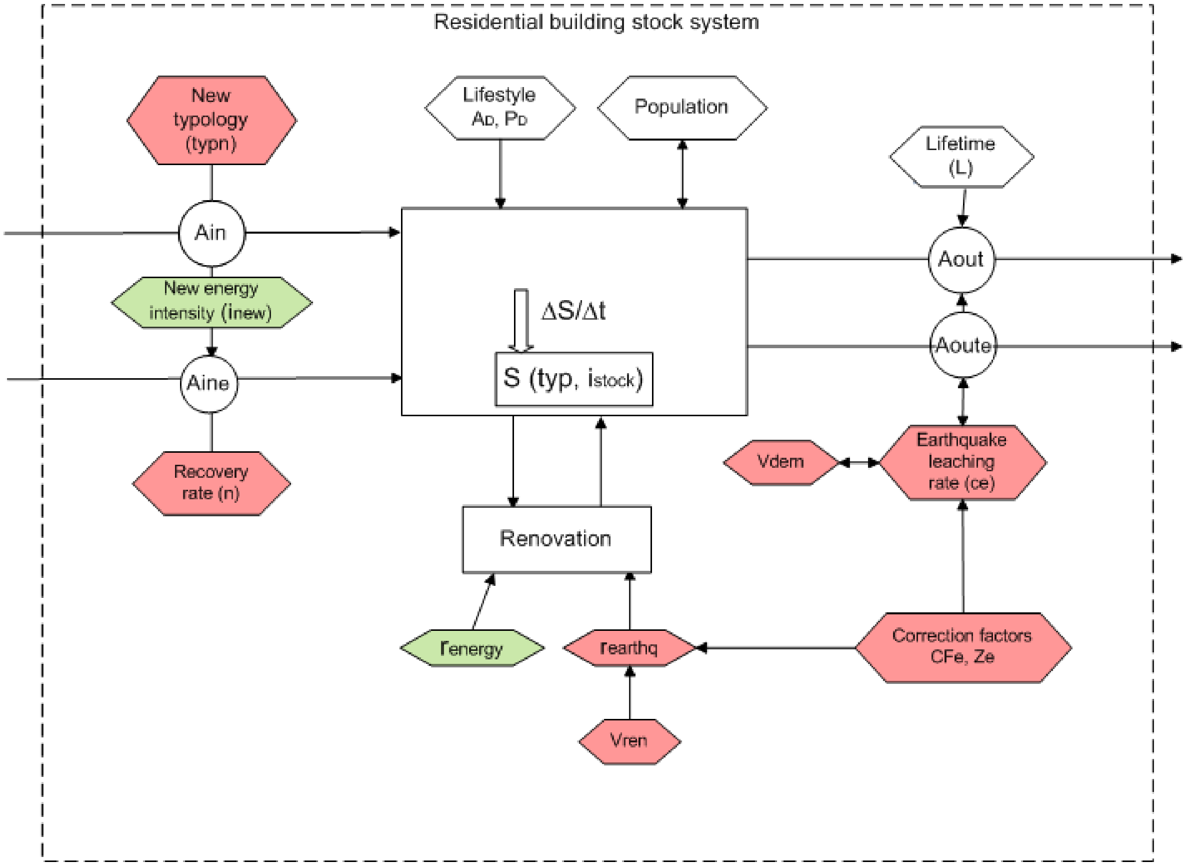

Figure 3.4: System definition of the residential building stock of Chile

The stock demand is calculated using population (P) and lifestyle parameters, floor area per dwelling (A_D) and persons per dwelling (P_D), while *typ* characterizes the typology distribution of the existent stock, according to six different earthquake vulnerability classes. The stock is also characterized by an average energy intensity factor for the operational phase of dwellings, called i_{stock}.

Outflows are determined using a leaching approach, so they depend on the stock and the leaching rate. For normal outflows (A_{out}) the leaching rate (c) will depend on the assumed lifetime (L) of the stock. For earthquake outflows (A_{oute}) the leaching rate (c_e) will be determined by the earthquake demolition matrix (V_{dem}), the zone where the future earthquake is modeled (Z_e) and the correction factor (CF_e). For historical earthquakes though the leaching rate is given.

Normal inflows (A_{in}) are determined using the mass balance, but their typology distribution is defined according to the scenarios implemented, so they are dependent on typ_n. Earthquake inflows (A_{ine}) will depend on earthquake outflows and also on the recovery rate in years (n) for the lost stock. Both of these inflows are characterized by an energy intensity factor (i_{new}), related to the operational energy intensity of the new dwellings.

3.3 Including the effects of earthquakes in the system

The effects of an earthquake in the building stock are related to demolition and renovation. So, after an earthquake there will be a sudden decrease in the stock, given that certain buildings are more vulnerable to earthquakes than others, so those most vulnerable ones will be severely damaged, and hence demolished. Some other fraction will have to undergo through a renovation process that shall restore the building's integrity and could make it more resistant to future earthquakes. Naturally there are renovation activities taking place that will only seek to improve superficial or aesthetical damage, but those are not being taken into consideration in the model.

When accounting for demolition triggered by an earthquake, the event will cause a sudden increase in the outflows, and hence the stock will experience a decrease that is not related to a decrease in the demand. This leads to the definition of an extra outflow (A_{out_e}) and hence inflow (A_{in_e}) due to an earthquake. The extra outflow will be defined by a leaching rate specific for earthquakes "c_e". In this case the leaching model seems to represent better, or more intuitively the effect of an earthquake in the building stock, since the system experiences a leaching that not necessarily has to do with age distribution of the stock, but more with the earthquake vulnerability.

$$A_{out\_e}(t) = c_e \cdot S(t) \tag{8.}$$

The earthquake inflows should replace whatever stock that was demolished due to the event. However, the losses from an earthquake are not recovered instantly. It takes some years, "n", to recover the lost building stock. So in the model we will have that the earthquake outflows will be subdivided into "n" number of years, having "n" equations representing the earthquake inflows.

$$A_{in\_e}(t) = A_{out\_e}(t)/n \tag{9.}$$

$$A_{in\_e}(t+1) = A_{out\_e}(t)/n \tag{10.}$$

…

$$A_{in\_e}(t+n-1) = A_{out\_e}(t)/n \tag{11.}$$

Then the total mass balance will be given by:

$$\frac{\Delta Stock(t)}{\Delta t} = A_{in}(t) + A_{in\_e}(t) - \left[A_{out}(t) + A_{out\_e}(t)\right] \tag{12.}$$

This new variable "Stock" accounts for the physical stock. We differentiate between stock demand and physical stock due to the fact that by including earthquake activity the mass balance is altered, since the stock demand will not reflect necessarily the physical stock, particularly after an earthquake.

3.3.1 Including vulnerability classes into the mass balance and earthquake renovation

The building stock in seismic regions can be characterized by its vulnerability to earthquakes, so it can be possible to subdivide the stock in different vulnerability classes. This allows the integration of future earthquakes into the model and the estimation of their potential damage to the building stock by using a statistical damage distribution table (refer to data and assumptions section below).

The statistical damage distribution table (

Table 3.2) specifies five damage degrees and our final aim is to identify the demolished and renovated share. We have considered that damage degrees 4 and 5 will lead to demolition (which is usually the case, according to Astroza (2012)), and 50% of the share with damage degree 3 will also lead to demolition. This is due to the fact that buildings with damage degree 3 could be repaired, depending on the economic feasibility of it, so given the lack of more precise information we assumed that this should be the case for half of the stock with damage degree 3. As of renovation of damaged buildings we are assuming that the remaining share with damage degree 3 and the share of the stock with damage degrees 1 and 2 will undergo earthquake renovation activity.

Thus, after applying these assumptions based on the information displayed at the damage distribution table, we obtain the share that should go either to demolition or renovation, ending up with two summarized tables that specify, per each earthquake intensity and vulnerability class, the share of the building stock that should go to demolition or renovation (V_{dem} and V_{ren}, respectively). Please refer to these tables in the data section below. The vulnerability matrix for demolition (V_{dem}) helps us determining the leaching rate (c_e) for a possible future earthquake, while the renovation matrix (V_{ren}) will yield the leaching rate for renovation activities (r_e).

Given that it is possible to estimate the outflows from earthquakes by vulnerability class it is convenient to implement the mass balance by typology, which will be defined according to vulnerability classes. In this way we will be able to see the effects of the vulnerability class distribution in the potential damage of the stock given a possible future earthquake. In order to accomplish this we need to be able to describe the stock based on earthquake vulnerability classes, establishing an initial typology distribution. Information on typology distribution regarding vulnerability of the stock is not available as such, so we have made assumptions based on whatever available information there is in order to establish an initial typology distribution for 2008. Results before 2008 will not be displayed according to typologies, since it does not reflect the reality. In practice the Chilean building stock has experienced many changes in its vulnerability classes, given that usually earthquakes act as a trigger for more stringent building codes and practices[3].

The model has been set up for the 2010 earthquake to start triggering changes in the typology distribution. For each year we calculate the stock demand by typology, S_{typ} (row vector with 6 columns representing each vulnerability class, by multiplying the total stock demand by the corresponding typology share distribution ”typ” (row vector with typology distribution, 1x6).

$$S_{typ}(t) = S(t) \cdot typ(t) \qquad 13.$$

Outflows (A_{out_typ}) under normal circumstances (no earthquake) can be calculated for that year using a constant leaching rate for each vulnerability class, given by 1/L. So basically we are assuming that each vulnerability class has the same average lifetime, and that the leaching is equal for each. This yields a row vector as well, with 6 columns.

$$A_{out\_typ}(t) = c \cdot S_{typ}(t) \qquad 14.$$

The change in stock demand (ΔS) is calculated the same way as in equation 2 above, getting a scalar. We sum the rows for the outflow and get the overall outflow (A_{out}), a scalar as well. With these two numbers we are able to calculate the total inflow needed by the system, so we only need to multiply by the typology share (typ_n) in order to estimate the inflows by vulnerability class (row vector as well):

$$A_{in\_typ}(t) = [\Delta S(t) + A_{out}(t)] \cdot typ_n(t) \qquad 15.$$

Making the inflows dependent on the typology distribution gives flexibility when it comes to fix a determined typology for the incoming stock, for instance assuming that either the typology could remain constant and equal to the stock typology or a certain vulnerability class could be phased out due to bad performance after an earthquake. Thus, we can create scenarios for the impact of policies that strengthen building codes or building classes. This will be further discussed in the scenario section.

For the earthquake outflows the damage and hence leaching rate will depend on whether we refer to past or future possible earthquakes. For historical earthquakes included in the model (not every earthquake has been included due to the lack of data on total damage), except the one in 2010, we will assume an overall leaching rate based on the available damage statistics (please refer to data section below). On the other hand, for future earthquakes the leaching rate will be different for each vulnerability class and will be given by the damage distribution table, assuming certain earthquake intensity.

For future earthquakes we will rely on the demolition matrix (V_{dem}) described above. The leaching rate per typology, for a particular earthquake intensity, is given by the corresponding row of V_{dem}.

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[3] Refer to the part of the report where I’ll detail this further (evolution of building codes and relevant historical earthquakes).

The overall share of the stock that will be demolished for 2010 for instance can be calculated using the following expression:

$$\left(S_{typ}(2010) \cdot V_{dem}(int = VIII)'\right) \Big/ \sum_{typ=1}^{6} S_{typ}(2010) \qquad 16.$$

So, for the 2010 earthquake, the overall stock facing severe damage and hence demolition would have been 14%, while in reality only 3.6% of the total stock did. This difference is mainly due to two reasons: an earthquake does not affect the total stock due to geographical reasons[4] and the damage distribution table has not been designed to represent the country's stock. Then it is necessary to correct for these facts, so we define two factors, a geographical correction factor (Z_e) and another factor to calibrate the magnitude of the earthquake damages to the stock (CF_e), taking into account the latest earthquake in 2010. Then the leaching rate by typology for a future earthquake will be:

$$c_{e\_typ}(t, int) = Z_e \cdot CF_e \cdot V_{dem}(int) \qquad 17.$$

Having a calibrated leaching rate per typology (c_{e_typ}) the outflows for when there is an earthquake can be calculated for each typology as stated by the equation 18 below.

$$A_{out\_e\_typ}(t) = c_{e\_typ}(t, int) \cdot S_{typ}(t) \qquad 18.$$

As pointed out before, the inflows that replace earthquake outflows should replace the overall amount of lost stock. The main question is with which typology distribution the lost stock will be replaced. We have considered as baseline scenario the case where the typology does not change. However, this is not what happens in reality, given that earthquakes have historically had an effect on building codes and construction policies, improving the vulnerability of the building stock. In alternative scenarios dwellings destroyed by earthquakes shall be replaced by less vulnerable ones. In practice, this means that the total inflow from earthquake losses would still be equal to the outflow, but the magnitude of each vulnerability class will be different from the magnitude of the outflows. Moreover, as it was discussed before, the reconstruction process is assumed to take 3 years, so the earthquake inflows will be distributed evenly through this time frame.

After calculating all the flows for a particular year we can base on the mass balance to recalculate the typology share. This is done by using the basic mass balance equation (12), considering that all variables are expressed as row vectors, hence per vulnerability class.

$$Stock_{typ}(t) = A_{in\_typ}(t) + A_{in\_e\_typ}(t) - A_{out\_typ}(t) - A_{out\_e\_typ}(t) + Stock_{typ}(t-1) \qquad 19.$$

This calculation of *Stock(t)* will yield a different value from the actual stock demand "S", particularly for the years where there's an earthquake. This is due to the fact that the stock demand only considers in its calculation the lifestyle parameters and the population, so

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[4] This can be further explained in another section of the report.

earthquake activity is not included, unless we would were to change for instance the input data of people per dwelling. We have chosen not to change the lifestyle parameters, because that would give a wrong message to the model, that given the occurrence of an earthquake, the stock demand decreases, while it's only the physical stock that decreases.

In order to calculate the typology share for present year we establish a mass balance for each vulnerability class, calculating as well the total stock corresponding to that year (row summing for $\mathrm{Stock}_{\mathrm{typ}}$). Then we divide the stock of each vulnerability class (for *i* from 1 to 6, representing vulnerability classes A to F, respectively) by the total stock to get the typology share. We will have a vector as a result called "typ" and each row will represent the typology share. Column summing this vector yields 1.

$$typ_i(t) = \frac{Stock_{typ=i}(t)}{\sum_{typ=1}^{6} Stock_{typ}(t)} \qquad 20.$$

This typology distribution will be assigned for the coming year as well (t+1).

3.3.2 Renovation due to earthquakes and normal renovation

As explained in the section above the share of the building stock that needs renovation after an earthquake will be given by using the matrix $\mathrm{V}_{\mathrm{ren}}$. Renovation in this case implies an improvement in the vulnerability class. In this matrix, for a given earthquake intensity, there is an associated share of the stock of each vulnerability class that is supposed to undergo renovation. The renovation leaching rate, $\mathrm{r}_{\mathrm{e\_typ}}$, will be given by the share delivered by the renovation matrix multiplied by the correction factors used for the demolition rate.

$$r_{e\_typ}(t, int) = Z_e \cdot CF_e \cdot V_{ren}(int) \qquad 21.$$

Normal renovation to improve the vulnerability class of buildings is also considered. In this case it is assumed that each class will be subjected to a constant renovation activity determined by a share "r", which is equal to the energy renovation leaching rate described in section 3.4 below. Only we assume that there is no creation of less vulnerable classes, so the fraction of vulnerability class F is not subjected to renovation.

$$r_{normal\_typ} = [r \quad r \quad r \quad r \quad r \quad 0] \qquad 22.$$

So, the total leaching rate for renovation purposes would be given by the sum of the renovation leaching rates described above. Which rate we consider will depend on the scenarios. Please refer to section 3.6 below.

$$r_{vuln\_typ} = r_{e\_typ} + r_{normal\_typ} \qquad 23.$$

This leaching rate will not affect the total mass balance, but only the typology distribution or the amount of stock in each typology. Hence, after having calculated the typology distribution "*typ*" explained in the previous section we can use this renovation leaching rate to modify the stock for each typology. Being the physical stock for a particular year a row vector composed by $\mathrm{Stock}_{\mathrm{A}}$ to

Stock$_F$, and considering a renovation rate for each vulnerability class, from re$_A$ to re$_F$, we will have that a stock will be:

$$Stock(t) = \begin{array}{|c|}\hline Stock_A(t)\cdot(1-r_{e_A}) \\ \hline Stock_B(t)\cdot\left(1-r_{e_B}\right)+Stock_A(t)\cdot r_{e_A} \\ \hline Stock_C(t)\cdot\left(1-r_{e_C}\right)+Stock_B(t)\cdot r_{e_B} \\ \hline Stock_D(t)\cdot\left(1-r_{e_D}\right)+Stock_C(t)\cdot r_{e_C} \\ \hline Stock_E(t)\cdot\left(1-r_{e_E}\right)+Stock_D(t)\cdot r_{e_D} \\ \hline Stock_F(t)+Stock_E(t)\cdot r_{e_E} \\ \hline \end{array} \qquad 24.$$

In this particular case we are assuming that by renovating, there will be a shift in vulnerability class to the next upper level. However, even if there should be a share of the vulnerability class "F" that needs to undergo renovation, we assume that this renovation will not shift vulnerability class. In practice this would involve the creation of a new class. Moreover, class F is quite resistant regarding renovation damages, showing only damages for an earthquake of intensity X, which is quite high.

3.4 Energy

The energy performance will be modeled for the operational phase of the building stock. This will be based in the mass balance for the building stock explained in the previous section. The stock will be characterized by an overall energy intensity factor (i$_{stock}$) while new incoming stock will be characterized by another energy intensity factor (i$_{new}$), both in kWh/m^2/yr. The main purpose of defining a different energy intensity factor for inflows is to model the effect on energy policies to the overall energy performance of the stock. This will be further discussed in the scenario section.

As mentioned above, the energy part will be based on the mass balance of the building stock. For each year we have that:

$$Stock(t) = A_{in\_tot}(t) - A_{out\_tot}(t) + Stock(t-1) \qquad 25.$$

A$_{in\_tot}$ represents the sum of normal and earthquake inflows and A$_{out\_tot}$ the sum of normal and earthquake outflows. This equation allows us to establish for each year the share of inflows, outflows and previous year stock. We do this dividing this equation by *Stock*(t).

$$1 = \frac{A_{in\_tot}(t)}{Stock(t)} - \frac{A_{out\_tot}(t)}{Stock(t)} + \frac{Stock(t-1)}{Stock(t)} \qquad 26.$$

Then we can characterize the energy intensity of the stock in a particular year using the percentage contribution of each of the flows and the existent stock. This means that the share of the outflow and the previous year stock will be characterized by the average energy intensity factor of the previous year, while the share of inflows will be characterized by i_{new}, the intensity of the new incoming stock. So the energy intensity of the stock in a year t will be:

$$i_{stock}(t) = i_{new}(t) \cdot \frac{A_{in\_tot}(t)}{Stock(t)} + i_{stock}(t-1) \cdot \left(\frac{Stock(t-1)}{Stock(t)} - \frac{A_{out\_tot}(t)}{Stock(t)} \right) \qquad 27.$$

Due to the lack of more precise historical information we will model with an initial value for the energy intensity factor for the existent stock by 2009. This value is obtained from a study on energy efficiency of the Chilean stock (CChC, 2010). Hence, having this initial value will allow us to calculate the overall energy intensity factor for the stock when changes are introduced in new incoming stock. This and the choices regarding the energy intensity for the new construction is further discussed in the scenario section below.

Renovation for increased energy efficiency will be treated with the leaching approach as well, hence having a leaching rate that will represent a part of the stock undergoing renovation. There is no data available on energy efficiency renovation rates for the existent stock, so we will have to make assumptions on it (refer to data and assumptions section below). However, the main intention for including renovation rates, even if we have little information regarding them, is to analyze the effect of energy efficiency measures in the existent stock. The renovation rate will have a direct impact on the energy intensity factor that was calculated in equation 24 above, so we basically will modify that calculation using a renovation leaching rate "r" and assuming that this renovated share will adopt a renovation energy intensity factor (i_{ren}).

$$i_{stock}(t) = i_{stock}(t) \cdot [1-r] + i_{ren}(t) \cdot r \qquad 28.$$

The renovation intensity factor for each year "i_{ren}(t)" will be given by the average between the energy intensity of the stock and the energy intensity for new incoming stock, assuming that there is regulatory standard on new construction. So for each year the energy intensity factor for renovation will be calculated as followed:

$$i_{ren}(t) = \frac{i_{stock}(t) + i_{new}(t)}{2} \qquad 29.$$

The overall energy consumption (E) in kWh/yr will be calculated using the same principle as equation 24 above:

$$E(t) = i_{new}(t) \cdot A_{in\_tot}(t) + i_{stock}(t-1) \cdot [Stock(t-1) - A_{out\_tot}(t)] \qquad 30.$$

This approach that characterizes the outflows with the overall average energy intensity factor is a simplification of the energy analysis, since in practice the outflows have not necessarily the same energy intensity level as the average for the stock. But given the lack of information on the energy characterization of the outflows we have assumed this.

3.5 Data and assumptions

3.5.1 Stock demand

For the calculation of the stock demand (S) described in equation 1 we have used the same data series used in the project work (Gallardo, 2011), these are floor area per dwelling (A_D), persons per dwelling (P_D) and population (P). A short explanation on how these data series were obtained is discussed in this section. A detailed explanation has been provided in the project work, but we will discuss shortly the chosen data series for the underlying parameters.

The population for Chile was available from 1950 to 2050. We have also considered certain extreme values (INE, 2012), 3 million by 1900 and 1 million in 1850, and fit a spline curve to obtain a smooth historical development. Trends from the data series from 1950 to 2050 were the basis to the future development of the population, also fitting the data to a spline curve. We can see a slight tendency to decrease after 2050, which is not too far from a likely development, since in a medium scenario the population projection by a study from CEPAL shows a similar trend (CEPAL, 2007). See Figure 3.5 below.

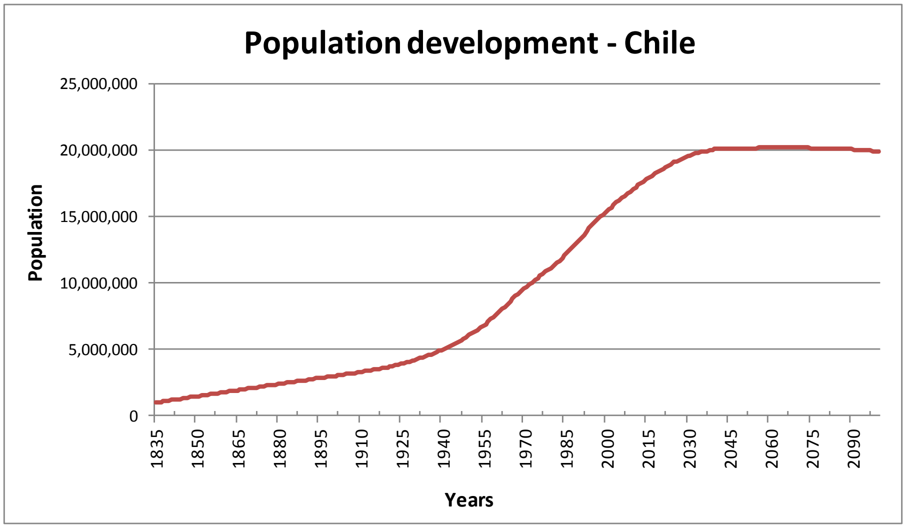


Figure 3.5: Population development for Chile.

The average floor area for a dwelling (A_D) data is the one with most uncertainty, due to the lack of information on dwelling sizes for the Chilean stock and the rough assumptions made to estimate them. With available information on total demand development and new construction permits it was possible to estimate the development of the size of dwellings from 1992 to 2013. Then assuming stabilization values for the past and the future the development was approximated, this is shown in below. This comprises a very concise explanation of how the development of this parameter was estimated, for more details please refer to the project work (Gallardo, 2011).

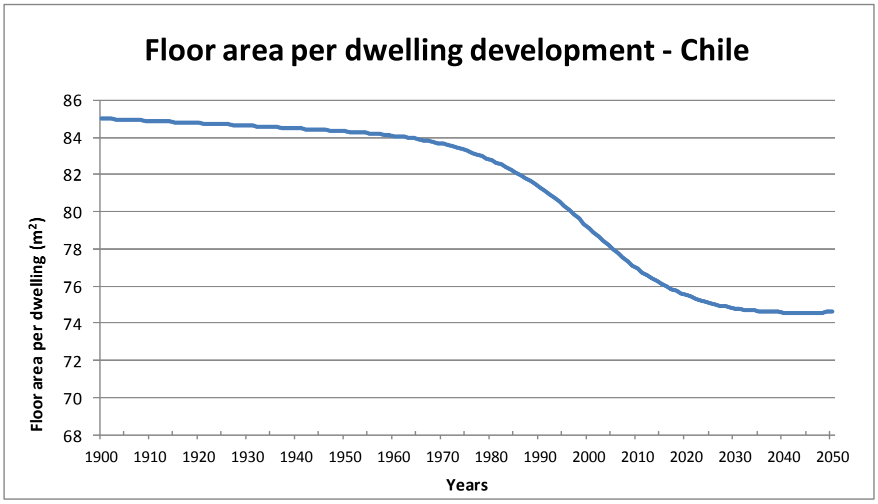


Figure 3.6: Floor area per dwelling, Chile.

These trends show quite a different development compared to a developed country such as Norway (Bergsdal et al., 2007) and might differ from the reality. However when estimating the service level of floor area per capita, calculated as the ratio between floor area per dwelling and persons per dwelling, we can see that this shows an increasing trend, making sense for a country that has not yet reached developed countries service levels.

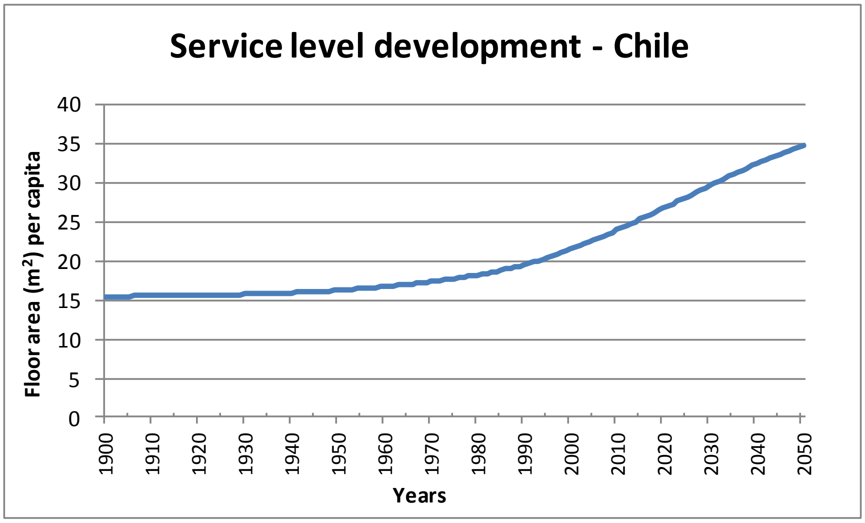


Figure 3.7: Floor area per capita, Chile.

The development of the persons per dwelling parameter was available for 5 years (INE, 2012) and extreme values were assumed to show similar levels to the Norwegian dwelling stock (Bergsdal et al., 2007), with a level by 1900 and 2100 of 5.5 and 2 persons per dwelling, respectively. With these data a spline curve was fit in order to get the long term development shown in Figure 3.8 below.

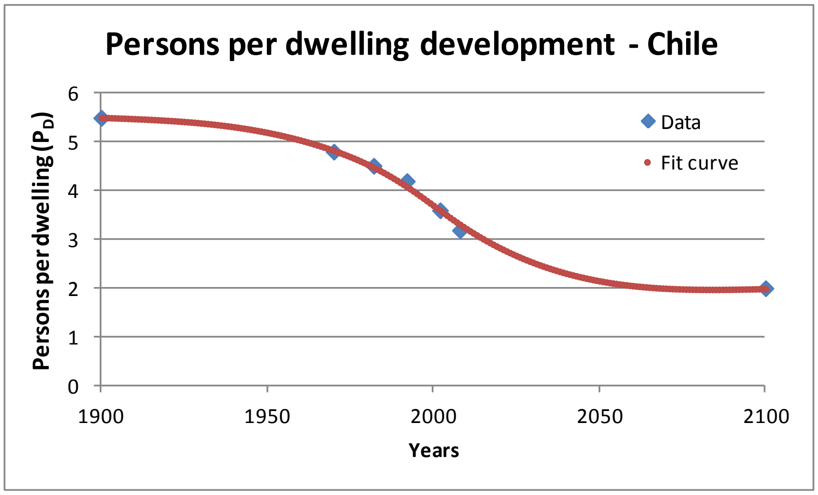


Figure 3.8: Development of the service level in persons per dwelling (P_D) for Chile.

3.5.2 Demolition (leaching) rate

The average lifetime (L) for the stock has been considered to be 60 years (Torres, 2011). This determines the normal leaching rate (c). On the other hand, the earthquake leaching rate data can be explained differently for historical earthquakes (up to 2010) and future possible earthquakes. For historical earthquakes we only consider three major earthquakes for which information on overall damage was documented. These are the 1960, 1985 and 2010 earthquakes and there is available data on the amount of buildings that were destroyed. Then, using the population and persons per dwelling for each of those years we calculate the estimated number of dwellings, which allow us to calculate an estimated share of the destroyed stock.

Table 3.1: Historical earthquakes and damage caused in dwellings, Chile.

Year	Magnitude	Destroyed dwellings	N° Dwellings	Destroyed share (%)
2010	8.8	190,359	5,307,378	3.6%
1985	7.8	42,653	2,765,446	1.5%
1960	9.5	169,250	1,516,249	11.2%

The recovery rate after an earthquake, “n”, will be 3 years. This has been based on the reconstruction period after the 2010 earthquake, for which the authorities have reported that the reconstruction should finish by June 2013 (Mercurio, 2012).

Regarding future possible earthquakes, the leaching rate is determined using a damage distribution table. In particular we use a statistical damage distribution table that was developed for Chile with the intention to define seismic zones.

Table 3.2: Statistical damage distribution table for Chile (Silva, 2011).

	Type A		Type B		Type C		Type D		Type E		Type F	
Intensity	**%**	**Damage degree**	**%**	**Damage degree**	**%**	**Damage degree**	**%**	**Damage degree**	**%**	**Damage degree**	**%**	**Damage degree**
5	5 95	1 0	5 95	1 0								
6	5 50 45	2 1 0	5 50 45	2 1 0	5 95	1 0						
7	5 50 35 10	4 3 2 1	5 50 35 10	4 3 2 1	5 50 45	2 1 0	5 95	1 0				
8	5 50 35 10	5 4 3 2	5 50 35 10	4 3 2 1	5 50 35 10	3 2 1 0	5 50 45	2 1 0				
9	50 35 15	5 4 3	5 50 35 10	5 4 3 2	5 50 35 10	4 3 2 1	5 50 35 10	3 2 1 0	5 50 45	2 1 0		
10	75 25	5 4	50 35 15	5 4 3	5 50 35 10	5 4 3 2	5 50 35 10	4 3 2 1	5 50 35 10	3 2 1 0	5 50 45	2 1 0
11	100	5	75 25	5 4	50 35 15	5 4 3	5 50 35 10	5 4 3 2	5 50 35 10	4 3 2 1	5 50 35 10	3 2 1 0
12	100	5	100	5	75 25	5 4	75 25	5 4	75 25	5 4	75 25	5 4

In a statistical damage distribution table, such as the one above, for each earthquake intensity (V to XII) and each to XII) and each vulnerability type (A to F, being A the most vulnerable one) there is a damage grade (from 0 to 5) grade (from 0 to 5) assigned to a percentage of the sample; thus indicating the typical statistical behavior of the behavior of the buildings according to their typology. Damage grades are defined in

Table 3.3 below; these have been modified to fit the Chilean case (Silva, 2011).

Table 3.3: Damage degrees for buildings experiencing earthquakes, Chile.

0	No damage
1	Slight damage (minor damages in plaster)
2	Moderate damage (horizontal cracks in ceilings and chimneys, vertical cracks in wall corners without separation, fine cracks under ceiling levels of walls)
3	Heavy damage (fall of roof or parts of chimneys, vertical cracks in wall corners with separation, indicating collapse, diagonal cracks under ceiling levels of walls)
4	Destruction (fall of a wall or part of it)
5	Total collapse of buildings (fall of more than one wall)

This particular damage distribution table above has been developed for a Chilean building sample, which was based on a previous version that included only three vulnerability classes (A to C) and was developed for determining seismic intensity after the 1985 earthquake. Even if the damage distribution table has been developed for a much older share of the stock it still represents quite recent valuable information for modeling the overall effects of earthquakes in the building stock and provided that we can apply a correction factor to the overall damage would give results at least in a realistic order of magnitude.

The vulnerability matrix for demolition and renovation (V_{dem} and V_{ren}, respectively) obtained from the damage degree table is detailed below in Table 3.4.

Table 3.4: Vulnerability matrices, for demolition and renovation activity.

V_dem

	Vulnerability class					
Int	**A**	**B**	**C**	**D**	**E**	**F**
V	0%	0%	0%	0%	0%	0%
VI	0%	0%	0%	0%	0%	0%
VII	30%	30%	0%	0%	0%	0%
VIII	73%	30%	3%	0%	0%	0%
IX	93%	73%	30%	3%	0%	0%
X	100%	93%	73%	30%	3%	0%
XI	100%	100%	93%	73%	30%	3%
XII	100%	100%	100%	100%	100%	100%

V_ren

	Vulnerability class					
Int	**A**	**B**	**C**	**D**	**E**	**F**
V	5%	5%	0%	0%	0%	0%
VI	55%	55%	5%	0%	0%	0%
VII	70%	70%	55%	5%	0%	0%
VIII	28%	70%	88%	55%	0%	0%
IX	8%	28%	70%	88%	55%	0%
X	0%	8%	28%	70%	88%	55%
XI	0%	0%	8%	28%	70%	88%
XII	0%	0%	0%	0%	0%	0%

As mentioned in section 3.3.1 and 3.3.2 there are two correction factors applied to the leaching rate per typology obtained from V_{dem} and V_{ren}, a geographical correction factor (Z_e) and another factor to calibrate the magnitude of the earthquake damages to the stock (CF_e). This correction has been based on the last big earthquake in 2010, and has been calibrated for the amount of destroyed stock. The same correction factors are used for the damaged share of the stock, in order to simplify the analysis.

The geographical correction factor will be determined by three earthquake-geographical zones defined based on the percentage of the stock they represent: northern (23.3%), central-southern (70.5%) and southern (6.2%). This has been assumed using the definition of 7 thermal zones and their share of the stock by 2008 (CChC, 2010). We know that the 2010 earthquake led to the destruction of 3.6% of the building stock and considering that it was of intensity VIII and took place in the central-southern zone, we obtain that CF_e amounts to 0.365.

3.5.3 Typology distribution

An important variable that helps modeling the effect of earthquakes in the building stock is the typology distribution, which has been defined in this work as the subdivision of the stock into different earthquake vulnerability classes, from A, the most vulnerable, to F, the least vulnerable. Again, there is no precise information on the quantity of buildings belonging to each class, so we have made certain assumptions to estimate these numbers.

First we have considered 5 building types that have been used in the literature for categorizing building structures that are important when defining their vulnerability. In particular we have based on housing reports developed specifically for Chile by the World Housing Encyclopedia. In these reports housing types are described within ten categories: general information, architectural features, socio-economic issues, structural features, evaluation of seismic features, past earthquake damage, building materials, construction economics, insurance and seismic strengthening. We have considered as well specific literature on performance of masonry housing types in Chile (Moroni et al., 2004). Therefore the structural types considered for the Chilean stock are: masonry (Moroni et al., 2004 and Moroni et al. (2002c)), steel structural wall (Arze, 2002), reinforced concrete (RC) wall (Moroni and Gómez, 2002), adobe and wood. Masonry buildings are subdivided into three different types: confined, reinforced and hybrid. We have estimated the share of these structural types from the building stock. This is summarized in the table below.

Table 3.5: Structural types distribution for the residential Chilean stock, by 2009.

1	Masonry	53.7%
	Confined	17.9%
	Reinforced	17.9%
	Hybrid	17.9%
2	Steel structural wall	3.0%
3	RC structural wall	12.0%
4	Adobe	4.8%
5	Wood	26.5%
	Total	**100.0%**

The share of RC structural wall (12%), adobe (4.8%) and wood (26.5%) dwellings is taken directly from an estimation of the building typology developed for a study called "Final uses of energy and energy conservation supply curve in the residential building sector of Chile" (CChC, 2010). This study was characterizing the stock by 2008. The 3rd report of the World Housing Encyclopedia estimated that the share of steel structural wall dwellings was around 2% of the stock. Since this report was from 2002 and we are basing on the 2008 estimations of typology at the energy report mentioned above, we have decided to round this percentage up to 3%. Lastly, the remaining share of the stock will be assigned to masonry buildings, which accounts for 53.7% of the stock. This is not such a strong assumption, since for instance at the energy report (ME, 2010) they say that 48.8% of the buildings are brick based, which we can assume to be masonry structural type. Moreover, they estimate the share of masonry concrete buildings to be 7.3%. This adds up to 56.1 in total, so it is not too different from our 53.7%. A major issue on data availability though is regarding the share of the three different types of masonry buildings. We have assumed that it distributes equally for each type. This is a very strong assumption, and probably does not reflect the reality, but unfortunately better information regarding this was not available.

Hence, with the composition of the stock by structural type, we can assign these into a vulnerability class, according to available information. So, all Adobe and half of hybrid masonry buildings will be assigned to vulnerability class A. Adobe houses are classified as vulnerability class A by the definition of classes at the development of the damage distribution table for the Chilean case (Silva, 2011). Hybrid masonry buildings have been addressed by Moroni et al. (2002c) in the 8th housing report of the World Housing Encyclopedia, where they have been rated to be class A and C, so we have assumed that half of the stock is class A and the other half is class C. Their low rating in vulnerability is mainly due to the fact that the seismic design code (by 2002) does not address this building type and specifications have been issued only for 1 and 2 story dwellings, while this structural type is mainly used for dwelling up to 4 stories high (Moroni et al., 2002c).

Vulnerability class B will be composed by only half of wood buildings. This is a strong assumption, since there is no evidence available regarding vulnerability performance on these building types. Furthermore, half of reinforced and hybrid masonry buildings and the other half of wood buildings are assigned to class C. Reinforced masonry buildings are classified as class C and E by the 5th report of the World Housing Encyclopedia (Moroni et al., 2002a).

Class D is composed by half of confined masonry buildings. This structural type was assigned to classes D and F by the 7th report of the World Housing Encyclopedia (Moroni et al., 2002b). Vulnerability class E is composed by the other half of confined and reinforced masonry structural types and half of steel and RC structural wall buildings. These two last structural types have been assigned vulnerability classes E and F in the World Housing Encyclopedia, 3rd and 4th reports, respectively (Moroni and Gómez, 2002, Arze, 2002). Consequently, the other half of steel and RC structural wall buildings will compose vulnerability class F.

Table 3.6: Typology distribution for the residential Chilean stock, by 2009.

Vulnerability class	Share
A	13.8%
B	13.3%
C	31.2%
D	9.0%
E	25.4%
F	7.5%

3.5.4 Energy

The energy analysis will be based in available historical information on distributed energy to the residential sector, from 1997 to 2009 (CNE, 2009). From 2010 on we will make assumptions that will define our scenarios. The energy distributed to the residential sector will be considered as energy consumed in the operational phase of dwellings. Technically there are distribution losses, but in order to simplify the analysis we have decided not to include them. So, this total energy consumption for this time span will be translated into an energy intensity factor by dividing it by the stock demand for the corresponding years.

Regarding the energy intensity factor for new construction, for modeling the baseline scenario and scenarios 1a, 1b, 2a and 2b a constant number for the energy intensity of new construction is considered. We have the historical series of the energy consumption and hence the energy intensity of the stock (calculated by the division between energy consumption and stock demand). Also the stock demand (S) for 1997 and 2009 and the cumulative new construction between 1997 and 2009 ($A_{in\_tot\_cum}$) are known, so we can estimate the energy consumption of the old stock and hence the consumption of the new stock. The energy consumption of the old share of the stock will be given by the multiplication of the energy intensity of the stock calculated for year 1997 by the amount of "old stock" still standing in 2009, which is given by subtracting the total stock in 2009 and the new construction accumulated between 1997 and 2009.

$$E_{old\_stock}(2009) = i_{stock}(1997) \cdot [S(2009) - A_{in\_tot\_cum}(2009)] \quad 31.$$

Then the energy consumption of the accumulated new stock ($E_{cum\_new\_stock}$) will be calculated by subtracting the total energy consumption of year 2009 and the previously calculated energy of the "old stock" (E_{old_stock}).

$$E_{cum\_new\_stock}(2009) = E(2009) - E_{old\_stock}(2009) \quad 32.$$

Finally, the energy intensity for the new stock (i_{new}) will be calculated dividing the energy consumption of the new stock ($E_{cum\_new\_stock}$) by the amount of accumulated new construction ($A_{in\_tot\_cum}$). Please refer to Table 2.1 below.

Table 3.7: Summary of data available and calculation of the energy intensity of the new stock based on historical data.

Year	Stock (m^2)	E (kWh)	i_{stock} (kWh/m^2)	Cumulative New construction (m^2)	Energy consumption (kWh)		i_{new} (kWh/m^2)
					Old stock	Cum. new stock	
1997	306,962,111	5.26E+10	171.22	-	-	-	-
2009	399,859,248	6.01E+10	150.39	176,351,548	3.83E+10	2.19E+10	124

The 2009 value (124 kWh/m^2) will be our assumed energy intensity factor for new construction for the model, from 2010 on.

On the other hand, for scenarios 3, 4 and 5 the energy intensity of the new construction will be based on a target to achieve zero energy dwellings by 2040; hence new dwellings by 2040 should have an intensity factor of zero kWh/m^2. A spline curve has been fitted to these assumptions, so the development of the intensity factor for new construction is as Figure 3.9 below illustrates.

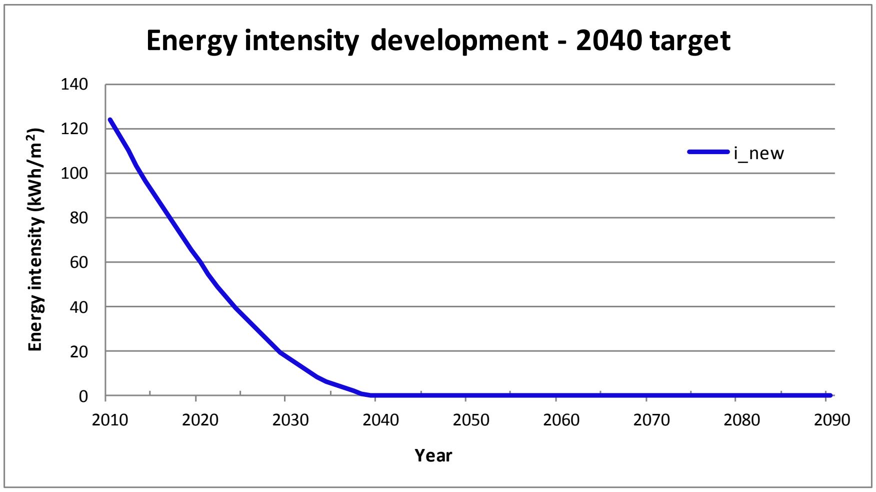


Figure 3.9: Energy intensity for new construction based on a 100% reduction target (zero energy dwellings) by 2040.

The way renovation is addressed in the energy model considers an energy intensity factor (iren) and a renovation leaching rate (r). The energy intensity factor is an outcome of the model, because it depends on the energy intensity of the stock. The renovation leaching rate is a share of the stock that undergoes renovation and has been set up as a constant 1% rate.

3.6 Scenarios

For all the scenarios two possible future earthquakes will be included in the model, in years 2035 and 2060, and with the same seismic intensity as the one in 2010 (VIII in the MSK-64 scale). Building less vulnerable structures and renovating existent structures affect the typology distribution of the stock and hence its overall vulnerability towards earthquake damage. Moreover, the stock turnover itself, together with energy efficiency measures on the existent or incoming stock affect its overall energy standard. Based on this various scenarios have been proposed with different assumptions regarding the effect of earthquakes in the typology distribution and the effects of energy standards, both in new construction or renovated dwellings. The main aim for these scenarios is to enable the comparison on how different policy options affect the damage caused by potential future earthquakes as well as the average energy standard of the dwelling stock.

It is worth to note that the tool used to model was Matlab, and the Matlab codes can be found in Annex II.

Baseline scenario

- The typology distribution remains unchanged, assuming that no policy measures are taken for the improvement of the vulnerability in the stock. All demolished dwellings (outflows) are replaced by dwellings of the same typology. Implicitly, this scenario assumes as well that the damaged dwellings that need renovation are renovated but keeping their same vulnerability class.
- The energy intensity factor for new construction is constant, based on a reference value from 2010 on. Please refer to the data and assumptions section.

Scenario 1a – "*Patching policy*"

- Policy measures are only implemented for improving the vulnerability of the demolished share of the stock due to an earthquake. In practice this means that the typology distribution will only change for earthquake inflows (A_{in_e}), where the lost stock of a certain typology will be replaced by the next upper vulnerability class.
- The baseline scenario assumptions are used for the energy intensity factor.

Scenario 1b – "*Strengthening policy*"

- Policy measures are implemented for improving the vulnerability of the demolished share of the stock due to an earthquake and as well the new construction. In practice earthquake inflows will replace the lost stock, but moving vulnerability to the next upper level (decreasing it), as in scenario 1a above. On the other hand, normal inflows will include the phase out of the weakest vulnerability classes progressively after earthquakes; so classes A, B and C will be phased out from normal inflows after the 2010, 2035 and 2060 earthquakes, respectively. So in this case the inflows that were supposed to go into these classes will go instead to the next upper vulnerability class, B, C and D, respectively.

- The baseline scenario assumptions are used for the energy intensity factor.

Scenario 2a – "strengthening and renovation"

- The same policy measures will be considered for normal and earthquake inflows as in scenario 1b, assuming strengthening approach, but it will also include a patching policy on earthquake renovation (r_e). This means that there will be a vulnerability class shift (to the next upper level) for the share of the stock that needs renovation after being partially damaged in an earthquake.

- The baseline scenario assumptions are used for the energy intensity factor.

Scenario 2b – "strengthening and constant renovation"

- The same policy measures will be considered as in scenario 2a but also a constant renovation rate for improving the vulnerability of the stock will be considered. This means that there will be a constant share of the stock each year that will undergo renovation, shifting its vulnerability class to the next upper level.

- The baseline scenario assumptions are used for the energy intensity factor.

Scenario 3 – "energy efficient new construction"

- The typology distribution remains unchanged, assuming that no policy measures are taken for the improvement of the vulnerability of the stock, as in the baseline scenario.

- Energy efficiency measures are introduced from 2010 on, consisting in the gradual decrease of the energy intensity factor for new construction until a 100% reduction.

Scenario 4 – "energy efficient new construction and renovation"

- The typology distribution remains unchanged, assuming that no policy measures are taken for the improvement of the vulnerability of the stock, as in the baseline scenario.

- Same energy efficiency standards are applied to new construction as in scenario 3, but a policy on renovation for energy efficiency on the existent stock is considered, from year 2010 onwards. The renovated share will be considered constant at 1% and the energy intensity of the renovated share of the stock will be calculated as the average between the energy intensity of the stock and the energy intensity of the new construction.

Scenario 5 – “combined scenario”

- The same policy measures regarding vulnerability as in scenario 2b are considered.
- The same policy measures regarding energy efficiency and renovation as in scenario 4 are considered.

4. Results

The results are shown firstly for the total stocks and flows (section 4.1) for the building stock model including earthquake activity. Section 4.2 shows the results of the scenarios, particularly for the typology distribution of the stock and the consequential overall demolition rate for the scenarios and each modeled earthquake. The results of energy performance of the stock are introduced in section 4.3, showing for the different scenarios the energy intensity factor development and the overall energy use. In the last section (4.4) the results for the sensitivity analysis are presented.

4.1 Leaching approach including earthquake activity: results for the total stock and flows

The results of the total flows, stock demand and stock demand change for the residential building stock in Chile are shown in Figure 4.1 below. We can see the sudden increase in the outflows due to earthquakes and the consequent increase in the inflows but spread over a longer time span, in this case three years. The stock demand (S) and the change in stock demand (dS) develop independently from the flows.

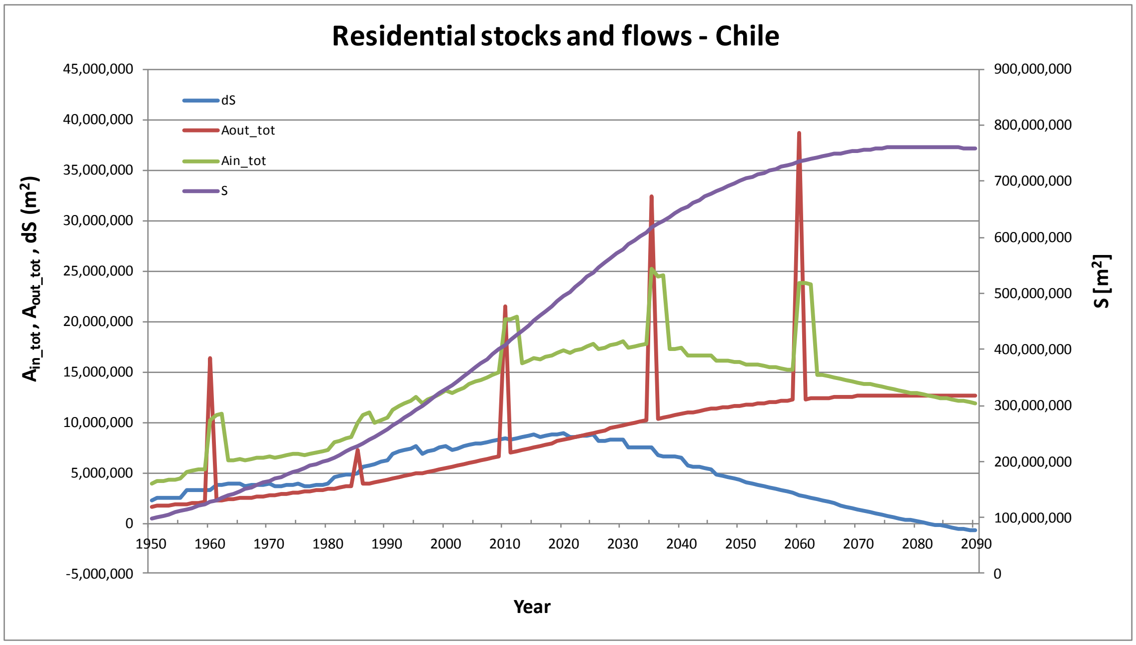


Figure 4.1: Results of the building stock model including earthquakes, residential Chilean stock.

The difference between stock demand and physical stock can be seen in Figure 4.2 below, where the effect of earthquakes included in the model (years 1960, 1985, 2010, 2035 and 2060) in the physical (or standing) stock are appreciated.

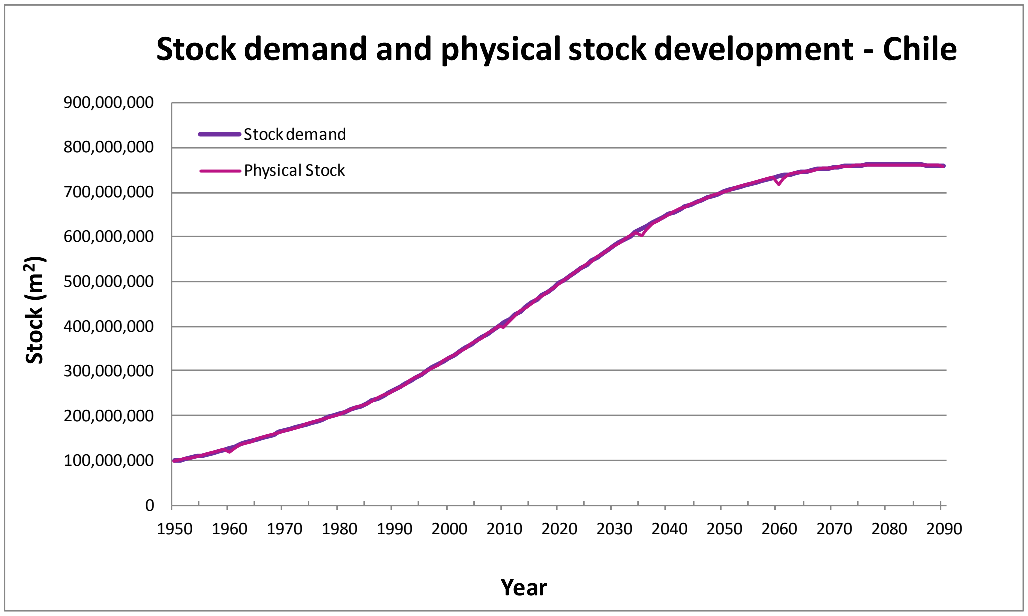


Figure 4.2: Development of the stock demand versus the physical stock.

When there is an earthquake the physical stock experiences a momentarily decrease until it reaches again the stock demand trend. A very slight decrease in the stock can be seen in the figure for historical earthquakes, while future earthquakes have a more noticeable effect. However, the most destructive earthquake was the one in 1960, destroying 11.16% of the stock (Table 3.1).

4.2 Results from scenarios considering typology distribution

The main purpose for using a typology distribution based on different earthquake vulnerability classes in the building stock model is to see how this distribution is affected when an earthquake occurs. As consequence of this it is possible to assess the effect of possible future earthquakes into the overall demolition rate.

The baseline scenario does not consider any change in typology distribution, so all the outflows due to earthquake demolition shall be replaced by the same typologies that were destroyed, maintaining the same typology distribution of the stock over time. Naturally, due to the demolition rate affecting differently to vulnerability classes, there will be a temporary change in the typology distribution the year the earthquake occurs and the time span of the reconstruction but after this, the typology distribution returns to the same as before the earthquake. To see the development of the stock typologies, please refer to Annex I.

By observing the share of the stock from each typology we can see the evolution of the typology distribution for each scenario, and each year where an earthquake was modeled. The results from the scenarios can be compared to the baseline scenario, and also scenarios 3 and 4, which have also assumed constant typology. Please refer to Figure 4.3 below.

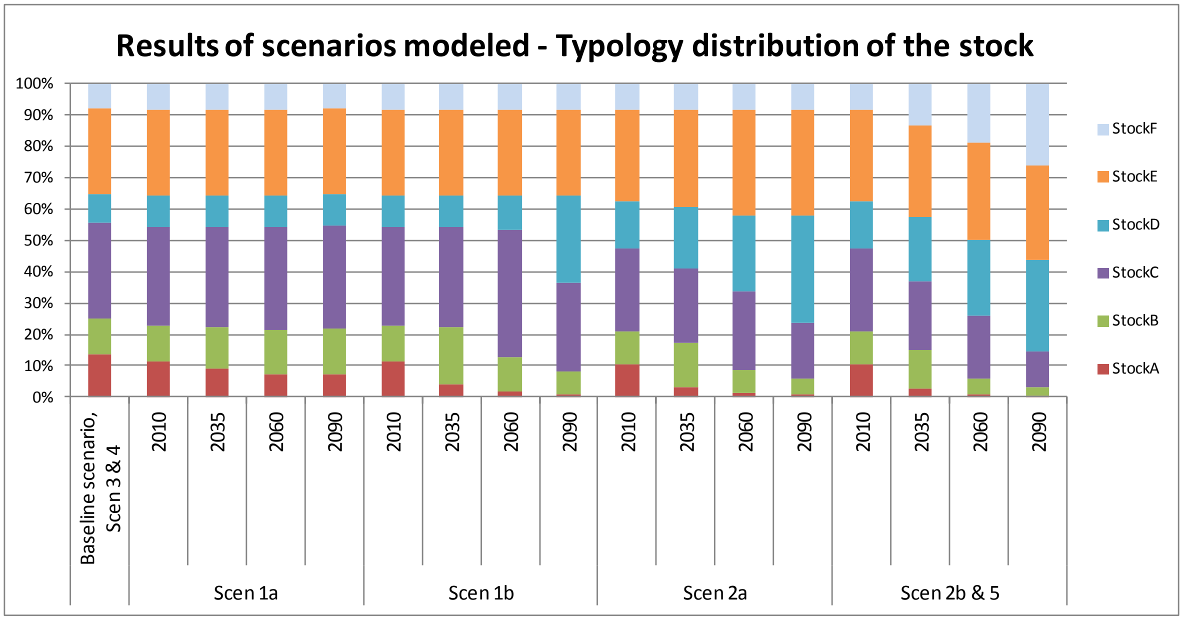


Figure 4.3: Typology distribution for scenarios modeled (baseline, 1a, 1b, 2a, 2b, 3, 4 and 5)

The patching policy (scenario 1a) will not decrease significantly the share of the three lower vulnerability classes (A, B and C), while the patching & strengthening policy (scenario 1b) has a progressive and long term effect on the share of the most vulnerable class A, reaching a level of 1% by 2090. The share of the other lower vulnerability classes B and C are decreased only in the long term, because there is a momentary increase first in the shares of class B (year 2035) and then in class C (year 2060). This is due to the fact that when phasing out a vulnerability class the stock demand for this class is replaced by the next upper, or less vulnerable, class. However, when looking at the strengthening & renovation policy (scenario 2a) results we can see that this transitory increase in classes are less evident, specially for class C. This is a positive result of the renovation activity due to earthquakes.

In these three scenarios discussed above we can see that even if the three lower vulnerable classes comprise a lower share of the stock in the long term, still the three higher vulnerability classes, except class D, do not increase much their share. This is mainly due to the fact that the earthquake modeled comprises damage only in classes A, B and C; so the strengthening will only involve decreasing vulnerability up to class D when reconstructing and renovating. However, when considering normal renovation for decreasing the vulnerability of the stock, which is the strengthening & constant renovation policy (scenario 2b), we can see that the effect of this measure is quite relevant for increasing the share of the less vulnerable classes, D, E and F.

Different typology distribution developments for different scenarios lead to different stock vulnerabilities. Hence, the effect of potential policy approaches in building codes or practices can be compared by assessing the overall demolition rate (or leaching rate, c_e) due to potential future earthquakes. Table 4.1 below shows the earthquake demolition rate caused by the 2010 and the modeled future earthquakes.

Table 4.1: Demolition (leaching) rate (%) due to earthquakes yielded by the model.

Year	Baseline, 3rd and 4rd scenarios	Scenario 1a *Patching policy*	Scenario 1b *Strengthening policy*	Scenario 2a *Strengthening & renovation*	Scenarios 2b and 5 *Strengthening & constant renovation*
2010	3.6%	3.60%	3.60%	3.60%	3.60%
2035	3.6%	3.26%	2.57%	2.34%	2.03%
2060	3.6%	2.96%	1.59%	1.27%	0.90%

From this table we can see that changing building policies after an earthquake will lead to a future decreased leaching rate, due to a progressive decrease in the stock vulnerability. Scenario 1a describes a *patching policy* that only replaces the lost stock due to earthquakes with an improvement in the vulnerability class. This scenario makes little difference in the earthquake demolition rate for future earthquakes, decreasing it (relative to the baseline scenario) only by 9% and 17% for the simulated 2035 and 2060 earthquakes, respectively. However, when introducing a *strengthening policy* (scenario 1b), meaning that after an earthquake the weakest vulnerability class shall be phased out from normal inflows and earthquake losses will be replaced by an upper vulnerability class, the leaching rate is reduced more drastically, particularly for the second future earthquake, decreasing by 56% (down to 1.59%) compared to baseline scenario. These two scenarios, 1a and 1b, involve policy measures that affect the inflows; however there is a share of the building stock that suffered moderate damage and hence needs to undergo renovation after an earthquake. Renovation of the partially damaged stock will shift this share into the next upper vulnerability class. This will have a slight effect on the leaching rate, when compared to scenario 1b. However, when including constant renovation to improve vulnerability of the stock the effects on the overall demolition rate are significant, decreasing it down to 0.9% for the 2060 earthquake, or by 75% compared to the baseline scenario.

The share of the stock that is subjected to renovation is depicted in Table 4.2 below.

Table 4.2: Renovation rate (%) for improving typology

Year	Scenario 2a *Strengthening & renovation*	Scenarios 2b and 5 *Strengthening & constant renovation*
2010	11.2%	11.2%
2035	11.5%	11.8%
2060	11.4%	10.7%

We can see that the renovation level for 2035 is higher for scenarios 2b and 5 than for scenario 2a. This is due to the constant renovation share together with the fact that by 2035 the share of the lower vulnerability classes is still high. However, for the second modeled earthquake in 2060 we can see already that the renovation rate is lower for scenarios 2b and 5 than for scenario 2a. This evidences the effect of a constant renovation of the stock, to improve its vulnerability.

4.3 Results on the energy performance of the stock

For analyzing the energy performance of the stock we look into the total operational energy (TWh/year) of the stock and also the overall energy intensity of the stock (kWh/m^2). Two scenarios are introduced to be compared with the baseline and scenarios 1 and 2. Scenario 3 considers only energy efficiency measures for new construction "*energy efficiency (EE) standard*", and scenario 4 includes energy efficiency measures for new construction as well as for existent stock, through renovation "*energy efficiency (EE) standard and renovation*". Scenario 5 is also shown in these results and it comprises a combined scenario where typology changes are introduced due to earthquake activity and energy efficiency measures, for new construction and existent stock, are taken in the building stock. Figure 4.4 below shows the energy intensity development of the stock for these scenarios, as well as the energy intensity of the renovated share of the stock.

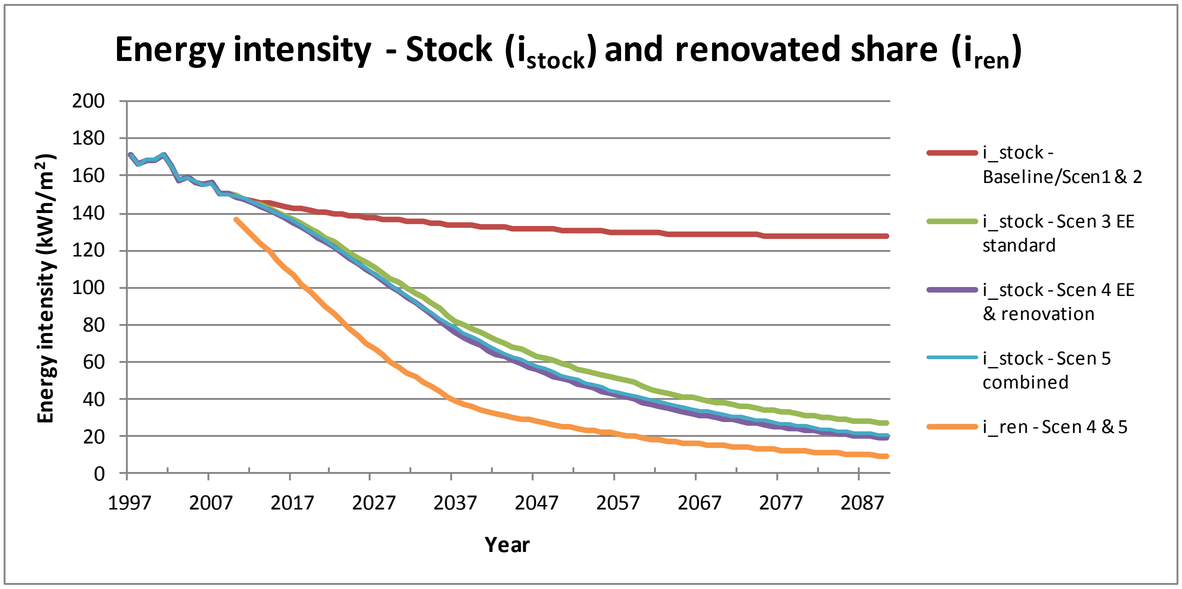


Figure 4.4: Energy intensity development of the stock for scenarios modeled, and energy intensity for renovated share, for scenarios 4 and 5.

Total operational energy consumption of the residential building stock for the different scenarios is shown in Figure 4.5 below. In every scenario, except the baseline scenario, the energy consumption has a peak at year 2018, after which it starts decreasing. The effects of the earthquakes are seen as a decrease of the total energy consumption, mainly due to the fact that the physical stock is momentarily reduced.

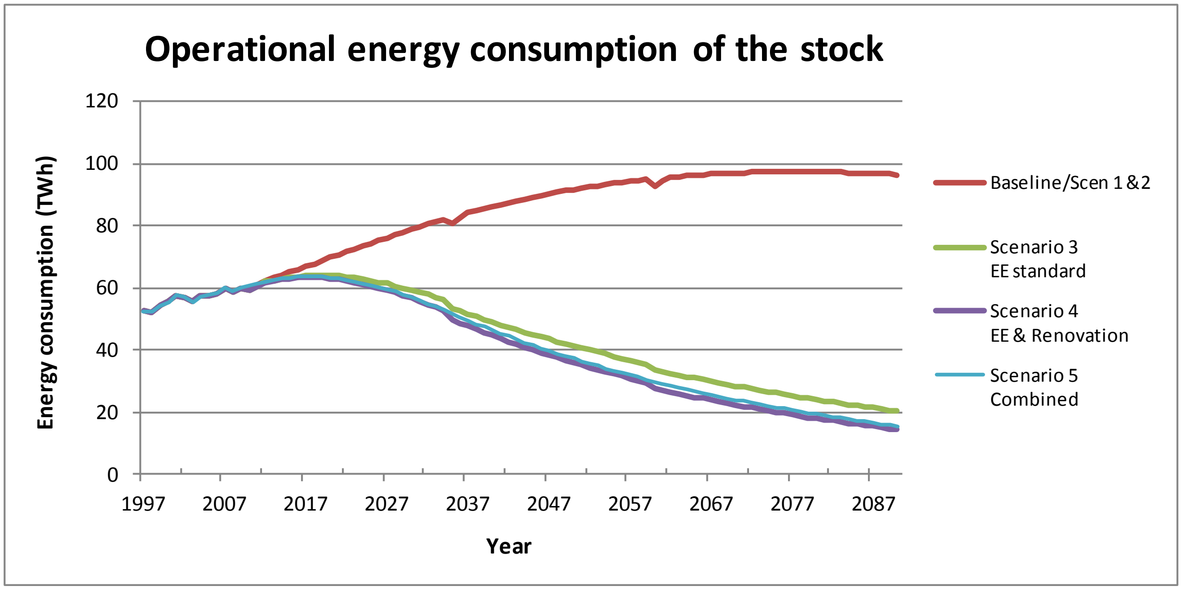


Figure 4.5: Energy consumption of the stock for modeled scenarios.

So, by assuming a gradual energy standard imposed in new construction from 2010 on we can see the effects of energy efficiency regulation and the evolution of the system in the long term. For scenario 3 the total energy consumption of the stock reaches a level of 20.3 TWh by 2090 and the energy intensity factor stabilizes to a level of 26.8 kWh/m^2. When including energy renovation in the system (scenario 4) the development is similar, but reaching lower levels in the energy consumption and intensity factor, 14.4 TWh and a 18.9 kWh/m^2 by 2090, respectively. The energy intensity of the renovated dwellings reaches a level around 9.5 kWh/m^2. Renovation activity considers that the energy intensity factor will depend on the current energy of the stock and the energy intensity set by the standards for new construction, being the average of these two numbers. This assumes that as the stock reaches better energy efficiency standards, the level of energy intensity reached by renovating the stock will also improve.

Scenario 5 shows constantly slightly higher values for energy intensity and total energy consumption compared to scenario 4. The only difference between these two scenarios is that scenario 4 is not considering typology distribution changes. The higher turnover rate of the stock due to earthquake activity caused by weak policy measures regarding vulnerability makes the energy performance of the stock slightly better than when the stock is less vulnerable to earthquakes.

4.4 Sensitivity analysis

A sensitivity analysis was performed for the lifetime, earthquake intensity and the energy target. The lifetime was increased to 100 years and we show the results from the total stocks and flows in Figure 4.6 below. We can see that the difference with the results with the lower lifetime (60 years) in Figure 4.1 lie on the flows only, having lower magnitudes throughout the period analyzed. The effect of an earthquake is of the same magnitude (equal demolition rate), but their relative importance to the magnitude of the outflows is higher.

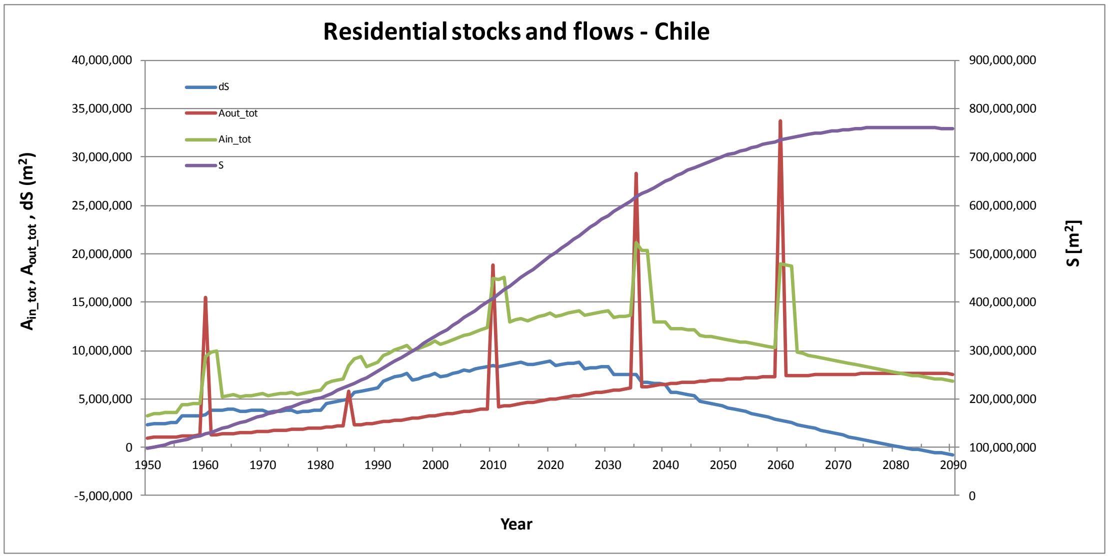


Figure 4.6: Results for the building stock model (including earthquakes) with lifetime of 100 years, residential Chilean stock.

The earthquake intensity for the future possible earthquakes was increased to intensities IX and X and the effects on the overall demolition rate can be observed in Table 4.3 below. The difference in intensity generates the increase by 116% on the demolition rate when increased by one unit, compared to the baseline scenario (intensity VIII).

Table 4.3: Demolition (leaching) rates due to earthquakes of different intensities for the baseline scenario.

Year	Baseline scenario	Baseline scenario (Intensity IX)	Baseline scenario (Intensity X)
2010	3.6%	3.6%	3.6%
2035	3.6%	7.8%	12.8%
2060	3.6%	7.8%	12.8%

Ultimately, the energy intensity target for new construction was extended to reach zero energy standards by 2050 instead of 2040. Please refer to Figure 4.7 below.

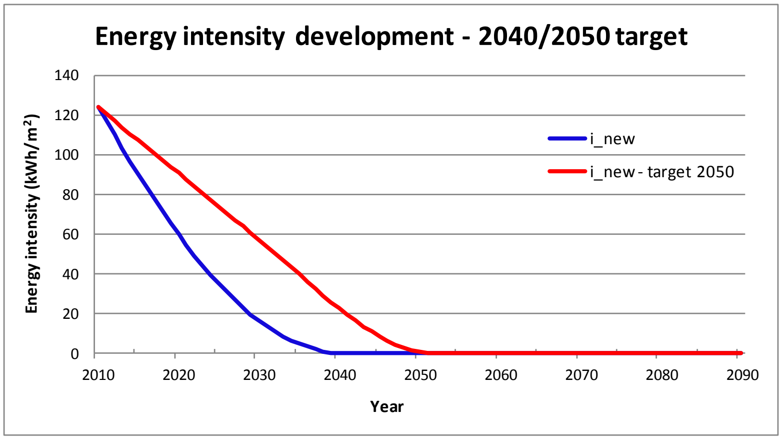
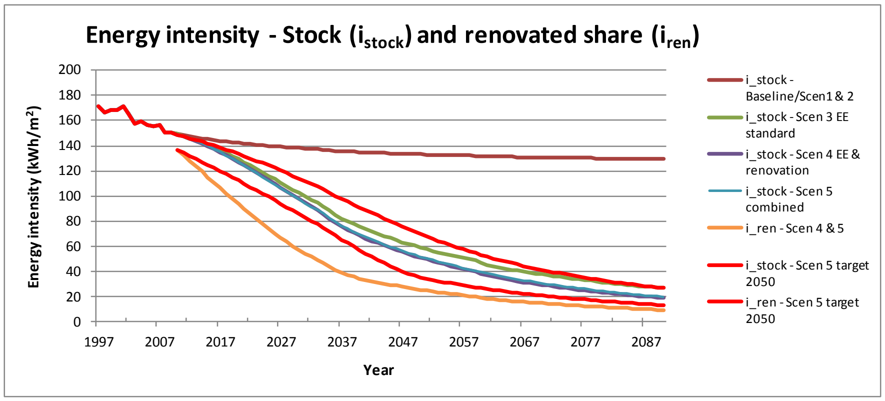


Figure 4.7: Energy intensity development for zero energy dwelling's target on new construction, by 2040 and 2050.

This sensitivity analysis was run for the combined scenario (n°5) and the results are shown in Figure 4.8. Here we can see that the energy intensity development of the stock for this scenario is consistently higher than any other scenario during the modeled period. The energy consumption shows a similar pattern, having a higher and delayed peak of consumption by 2025, accounting for 67 TWh that year.



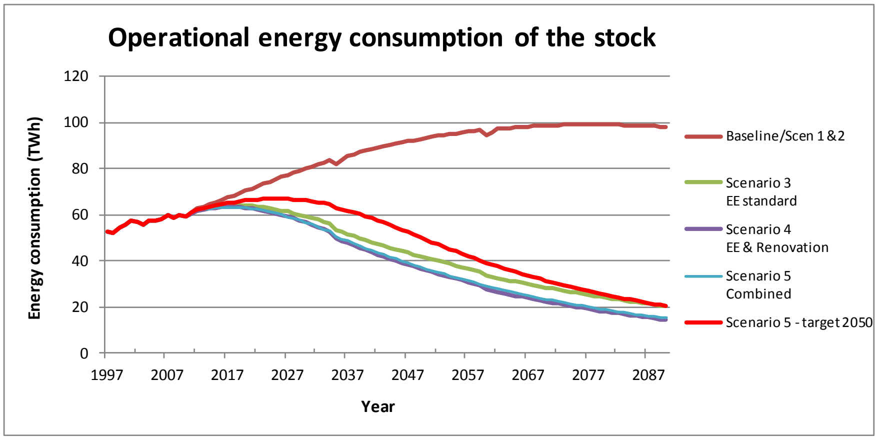


Figure 4.8: Results for energy intensity and energy consumption when delaying the target for zero energy dwellings by 10 years (2050), for scenario 5.

5. Discussion

In the results for the total stock and flows of the system (refer to Figure 4.1) we see that the system is mainly driven by the stock demand. For instance, the effects of earthquakes in the system are characterized by the sudden increase in outflows and therefore inflows, and also by the decrease in the physical stock (Figure 4.2). However, the trends for these variables follow the same trends as the situation without earthquakes, when comparing with Figure 3.3. Hence, the physical stock returns to follow the stock demand trend and the outflows follow the same development pattern, except for the years with earthquakes. This is mainly due to the strong influence the stock demand has on the model, since outflows and hence inflows depend on the stock demand calculated for each year. Similarly, when changing the lifetime, for instance expanding it to 100 years, the effects are only noticed in a lower magnitude of the flows over the studied period.

It is worth to question the fact that the stock demand remains unchanged despite earthquakes. One would think that the development of the stock demand could be affected by the constant occurrence of earthquakes, preventing for instance the persons per dwelling parameter to reach the level of a developed country. Technically after an earthquake the amount of persons per dwelling increases (see Figure 5.1 below), due to the fact that suddenly the stock decreases and the same amount of people are sharing a lower housing level. As the system recovers by reconstructing the lost stock the level of persons per dwelling comes back to its normal development. In our model we are implicitly assuming that the amount of persons per dwelling will reach a developed country level in the long term anyway, such as the one in Norway. This is the stock demand in the long term will not be affected by earthquake activity. However in practice, the stock demand might develop towards a lower level, due to the economic burden that earthquakes bring in a developing country, making it unable to reach the same living standards as a non-seismic developed country would. This could be due to a development towards a lower service level either in persons per dwelling (increasing its magnitude in the long term) or in area per dwelling (decreasing its magnitude).

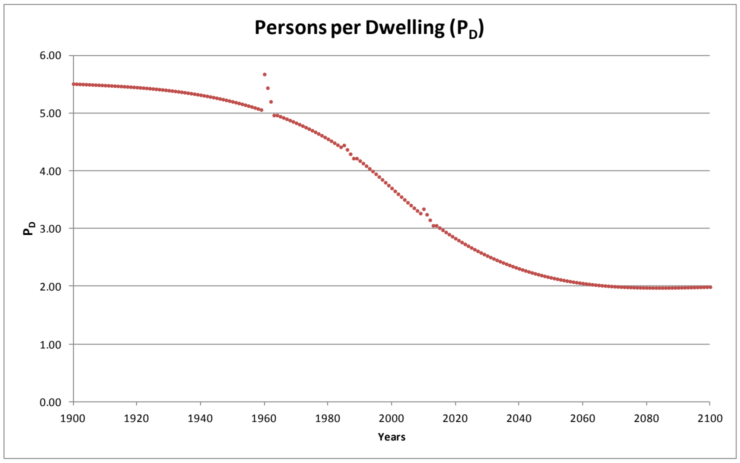


Figure 5.1: Effect of earthquakes on the service level (persons per dwelling, P_D).

Even if in practice the service level changes in the system after experiencing and earthquake we chose not to include it in the model this way. This is because the way the building stock is modeled the lifestyle parameters drive the stock demand, so a sudden increase in, for instance, persons per dwelling is interpreted as a decrease in the demand of stock. This is the reason behind choosing to introduce the effects of earthquakes through an increase in the outflows, so we can relate the effect of an earthquake to a transitory decrease on the physical stock.

As we could see from the discussion above, the lack of information on how earthquakes affect lifestyle parameters in the long term constrains the analysis to the assumed development of the overall stock demand. The damage on a building stock due to earthquakes can be explained by analyzing on how vulnerable the stock is to seismic activity, through a vulnerability assessment. The building stock is composed by several construction types that can be classified into different vulnerability classes, and this knowledge can contribute determining how much destruction an earthquake can cause in a system. Then, even if the system is mainly governed by the stock demand, the effect of the typology distribution on the performance of the stock undergoing seismic activity is an interesting fact to study in a systematic way.

Vulnerability of the built environment can be measured through many different methods, some of which can be applicable to a systematic type of assessment like the present work and others are too specific to be applied in the system level, requiring for instance extensive information on structural parameters. We have chosen to work with a qualitative method for estimating the vulnerability of the stock, which is based on a statistical damage distribution table. This method was chosen due to the fact that statistical damage distribution tables and have been adapted to the Chilean case already, so even if this corresponds to a table developed for the stock after the 1985 earthquake it represents more or less the Chilean reality. Moreover, there was data available on the vulnerability rating for certain structural types build in Chile, which could allow us for a gross estimate of the typology distribution of the Chilean building stock.

Different policy approaches on building codes and practices after earthquakes will have different effects on the overall demolition rate due to an earthquake. A less vulnerable stock is characterized by a typology distribution with a lower share of the most vulnerable structures, A, B and C. The policy approach that delivers the best performance results, for the earthquake modeled, is the one that comprises strengthening, renovation after earthquakes and normal renovation for improving structures' vulnerability (scenario 2b). However, the assumption on the feasibility of upgrading every vulnerability class (except the F one) through renovation might not be too realistic. But in the light of no better available information, we have assumed quite optimistic scenarios.

There is clearly a difference between applying patching and strengthening types of policy in the demolition rates for future earthquakes, so the inclusion of stringent building codes has a great effect when they are enforced on normal inflows. However, even if the most vulnerable classes are phased out progressively from the inflows, the demolition rate is still quite high compared to when constant renovation is enforced. This reflects on the importance of the standing stock on the vulnerability to earthquakes.

A weakness of the estimation of future demolition (leaching) rates due to earthquakes lies on the statistical damage distribution table. In practice the damage distribution table is used to estimate the intensity of an earthquake given the observed damages in the affected region. This particular table we are using has been developed for determining seismic intensity after the 1985 earthquake, so it might not fully represent the reality on earthquake vulnerability of the current or future stock. This is mainly due to the fact that many changes have taken place in the building stock after the 1985 earthquake, most likely strengthening it. Nevertheless, it still represents recent valuable information for modeling the overall effects of earthquakes in the building stock, at least in a realistic order of magnitude. This provided that a correction factor can be applied to the overall damage. The damage distribution table does not reflect the reality of the vulnerability of the total stock and besides, an earthquake does not affect simultaneously the whole stock with the same intensity (please refer to Figure 2.2 for the distribution of intensities in the last earthquake in Chile, 2010). These two reasons justify the application of a correction factor, and the fact that it is based on the 2010 earthquake is roughly correcting for the year the damage distribution table was developed. Although, for future possible earthquakes with different intensities than the one in 2010 it might not represent the most appropriate correction, leading to an overestimation of the damaged and demolished stock. We can see this effect when performing the sensitivity analysis on intensity (section 4.4), where the demolition rate more than doubles when the intensity increases from VIII (MM8) to IX (MM9), and almost triplicates when the intensity raises to MM10. Nonetheless, intensity MM11 carries quite a lot of speculation, given that so far intensities higher than MM10 have not been observed (Dowrick, 2009c).

A positive feature of the use of the damage distribution table is that it defines certain types of vulnerability classes, which gives the loss estimation method more flexibility, instead of fixing the damage to a specific structural type. Being able to link vulnerability classes to certain structural types, the importance then relies on the proper classification of the stock into each vulnerability class. Here again strong assumptions have been made in order to characterize the stock into the different vulnerability classes. The uncertainty lies firstly on the estimation of the composition of the stock by structural types (masonry, adobe, wood and steel or reinforced concrete structural wall) and secondly on the share of each structural type that is assigned to a vulnerability class. Within the composition of the stock by structural types the most uncertain one is the composition of the different masonry building types.

Regarding the energy modeling of the stock, the approach used is very simplified, but it is enough to analyze the trends of the stock when introducing energy efficiency standards. We see (Figure 4.4) that the historical decreasing trends on energy intensity could be further continued if energy efficiency standards are imposed in new construction. The continuation with current energy intensity levels (baseline scenario) for new stock makes a big difference on the energy consumption in the long term, when comparing with the scenarios that include energy efficiency standards (Figure 4.5). The baseline scenario (and scenarios 1 and 2) would lead to saturation in the total energy consumption by around year 2070, while with the other scenarios comprising energy efficiency measures this saturation would occur much earlier, around year 2018. Even if this occurs in an optimistic scenario it is still quite delayed compared to the energy consumption of the Norwegian dwelling stock, which already shown saturation in its energy consumption around year 2000. Delaying the target of zero energy dwellings 10 years causes a delay of 7 years in the saturation of the consumption, and a higher level of energy consumption than the other scenarios. The level of energy consumption still decreases over time to reach the level reached initially by the scenario 3 (only energy efficiency standard, no renovation), but with a constant higher energy intensity level.

With renovation there is a lower level of energy intensity reached, but its effect could be higher if a higher share of the existent stock undergoes renovation. Due to lack of information on renovation levels we have set the renovation rate at 1% of the stock for every year. Calculating the amount of square meters equivalent to 30 years of renovation activity at this rate (2011-2041) we get that 25% of the stock would have been renovated by 2041. As pointed out above, there is no benchmark for the renovation level in the Chilean dwelling stock, but comparing to the renovation levels (50%) at the Norwegian dwelling stock mentioned in Sartori et al. (2008) 25% seems like a reasonable target for renovation at a developing country.

Even if there is a decreasing trend in the long term when introducing an energy efficiency target and/or renovation measures, the energy consumption experiences saturation, or a peak, in year 2018. A way to avoid this is to introduce sudden energy efficiency measures. Please refer to Figure 5.2 below, which represents the case of a sudden measure in energy intensity of new construction together with a gradual measure on renovation activity.

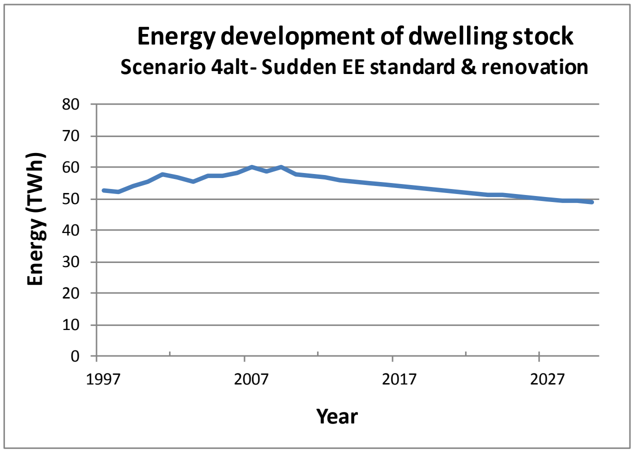


Figure 5.2: Alternative scenario for energy efficiency standard (sudden measure from 2010 on) and renovation (same as scenario 4)

The results from the energy model have shown that combining policy measures concerning vulnerability and energy standards do not make much difference in energy performance of the stock. As a matter of fact, by implementing policy measures on vulnerability, and hence making the stock more earthquake resistant, the effects of energy standards are slightly worse than when no strengthening policies are taken. This result is not surprising due to the higher turnover rate when the built environment is not strengthened for ground motion purposes. However, if each vulnerability class could be described as well by an energy intensity factor, then a better characterization of the stock in energy terms could be achieved, and the effects of earthquakes on the energy performance of the building stock could be analyzed in a more detailed way. Unfortunately data linking the energy performance of each vulnerability class is not available.

6. Conclusions

In this study the residential building stock for Chile has been modeled through a dynamic Material Flow Analysis, based on floor area. The approach was based on the methodology defined by Müller (2006) on the stock in use being the physical link between resource demand (input) and waste generation (output), but a leaching approach was chosen for modeling the outflows, instead of a lifetime approach. Earthquake activity was included in the model as an extra leaching rate and two possible future earthquakes have been modeled. The effects of earthquakes have been analyzed through the typology distribution of the stock based on vulnerability classes. Moreover, the overall energy performance of the stock was modeled, in terms of energy intensity of the stock and energy consumption.

Results for the total stock and flows show the strong dependence of the model to the stock demand, where the effects of earthquakes are observed in a momentary decrease of the physical stock, but the system is still driven by the stock demand calculated with a normal development of the underlying parameters. It is worth questioning if a dwelling stock subjected to seismic activity could develop in the long term towards reaching service levels observed in non-seismic developed countries, due to the economic burden that constant damage or destruction of the built environment brings. This comprises an interesting question that could be further explored in the relationship that governs stock demand.

By applying a qualitative vulnerability assessment method it was possible to model the effects of typology distribution on the overall demolition and renovation rate for possible future earthquakes. Policies focusing on strengthening and renovating the building stock, hence making it less vulnerable to earthquakes, have a large positive effect on overall demolition rates. On the other hand, patching types of policies have little effect when it comes to making the stock less vulnerable. Weaknesses of the model lie on the fact that the damage distribution table was adapted to reflect damages for a certain building sample after the 1985 earthquake and that a correction factor was used to calibrate overall demolition and renovation rate based on the 2010 earthquake. A sensitivity analysis showed that this might be causing an overestimation on the demolished share of future earthquakes, especially when modeling for higher intensities. Moreover, there is also quite a lot uncertainty involved in the typology distribution, given that usually information on the building stock composition is not as detailed in order to classify structures into vulnerable types.

Uncertainty and model weaknesses aside, the approach used for modeling the Chilean stock allows for a systematic view on the effects earthquakes cause to the built environment. The results of the model can show the consequences of applying different policies aiming at decreasing the vulnerability of the stock, which is useful when assessing the overall risk of the built environment to seismic activity, and moreover when aiming at mitigating possible future risks.

Regarding the energy consumption of the stock the system has not reached saturation yet, and the timing for this will be strongly influenced by the energy intensity development of the stock.

The more the delay of implementing energy efficiency and renovation measures, the later the saturation level will be reached. This peak in energy consumption though can be avoided by introducing sudden measures in energy efficiency, but this does not represent a very realistic possibility.

The combined effect of policies for decreasing the vulnerability of the dwelling stock and policies concerning energy efficiency could be further explored if each vulnerability class could be described by an energy intensity factor. In practice, it might occur that lower vulnerability classes dwellings show for instance poorer energy performance, considering that these dwellings might most likely be owned by lower income population. This at the same time might imply that due to lower income the energy consumption is lower as well due to economic constraints. This would require of course a more detailed analysis of the consumption of energy by end use and by end user. Further research in this front would be interest, especially when assessing a developing country, where there is still a big gap regarding service levels and hence opportunities for leapfrogging.

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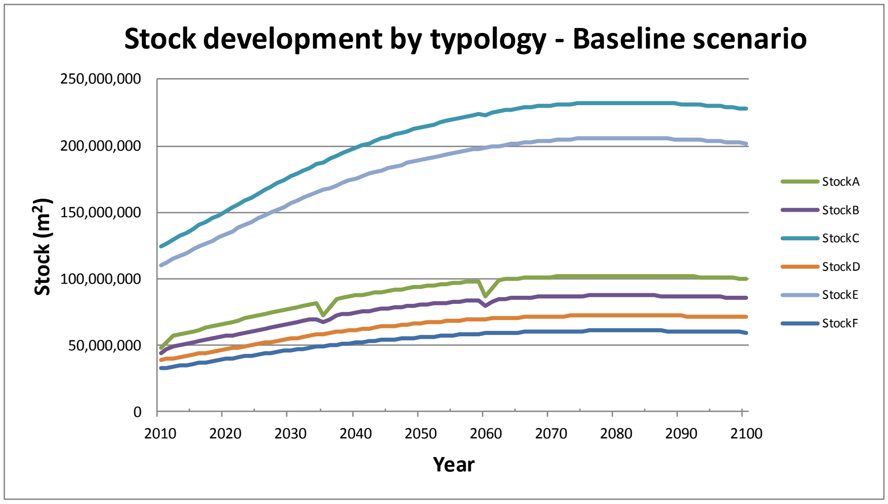
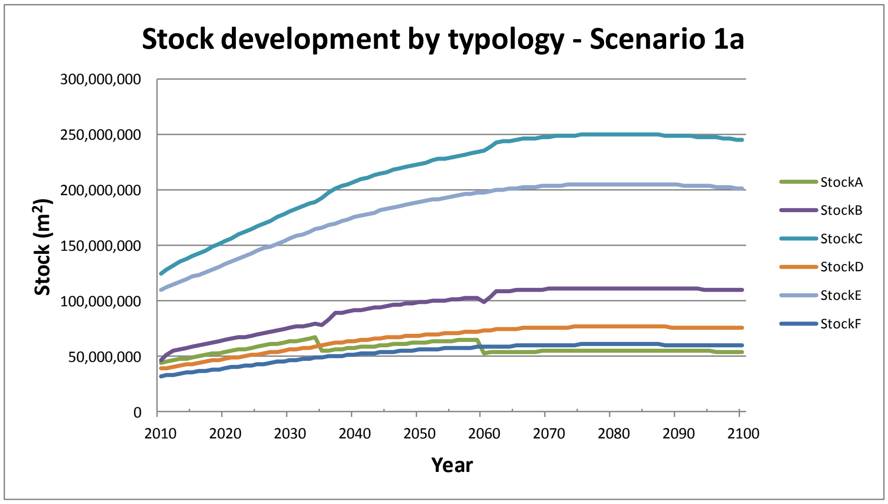
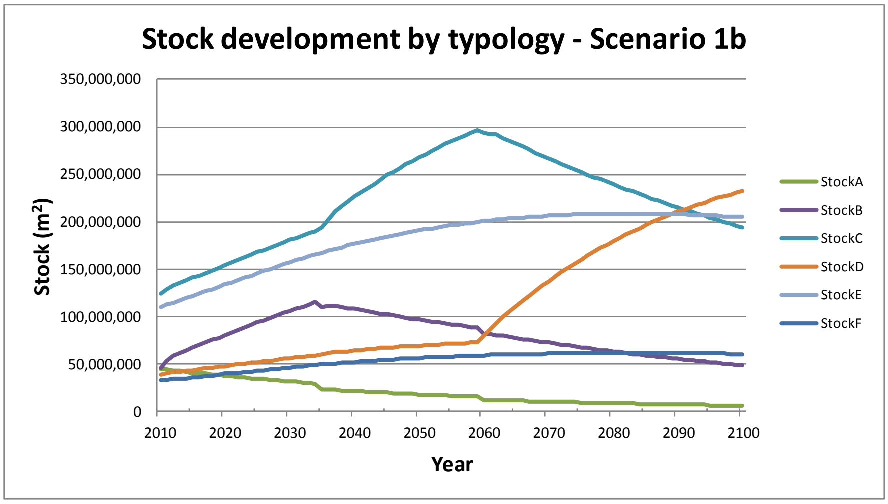
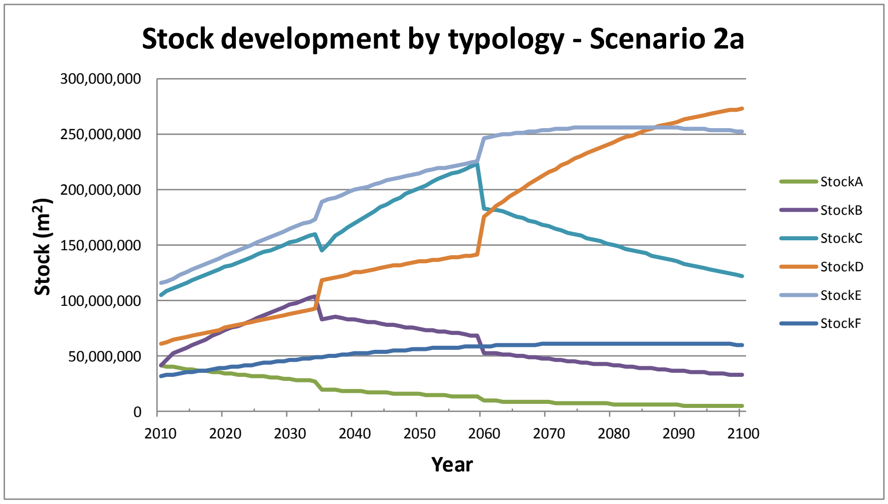
Annex I

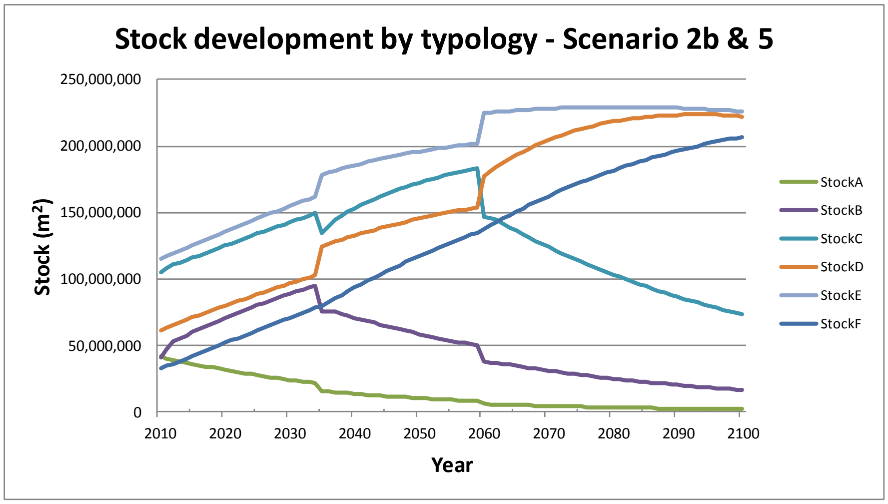
Results for the stock development in different modeled scenarios.








Stock development by typology - Scenario 2a
300,000,000
250,000,000
200,000,000
150,000,000
100,000,000
50,000,000
0
Stock (m²)
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
StockA
StockB
StockC
StockD
StockE
StockF


Stock development by typology - Scenario 2b & 5
250,000,000
200,000,000
150,000,000
100,000,000
50,000,000
0
Stock (m²)
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
StockA
StockB
StockC
StockD
StockE
StockF

Annex II

Matlab codes for different scenarios. The first 88 lines are the same for each code.

```
clear all

% --- READING DATA ---
% Time (years)
t = xlsread('Leaching10-parameters','Primary data','B6:B306');

% Population
P = xlsread('Leaching10-parameters','Primary data','K6:K306');

% Persons per dwelling
Pd = xlsread('Leaching10-parameters','Primary data','I6:I306');

% Area per dwelling
Ad = xlsread('Leaching10-parameters','Primary data','C6:C306');

% Typology (vulnerability class) contribution (%) - snapshot for a given
year.
types = xlsread('Leaching10-parameters','Typology','C3:C8');

% Statistical damage distribution table
V_matrix = xlsread('Leaching10-parameters','Typology','C14:N53');

% Leaching rate from historical earthquakes
ce_h = xlsread('Leaching10-parameters','Primary data','O6:O306');

% Thermal zones share of the stock (%) - snapshot for a given year.
t_zones = xlsread('Leaching10-parameters','Typology','F3:F9');

% Earthquake zones share of the stock (%) - snapshot for a given year.
e_zones = xlsread('Leaching10-parameters','Typology','I3:I6');


% --- VULNERABILITY ---
% Turning the vulnerability distribution matrix into a matrix with the
share to be demolished and renovated
dem = zeros(40,6);
ren = zeros(40,6);
b=2;
    for i=1:40          % 8 intensities, 5 damage degrees = 40 rows
      for j=1:6         % Typology (vulnerability class)
        if V_matrix(i,b*(j-1)+2) == 3       % Assuming half of buildings
with damage degree 3 are demolished
        dem(i,j) = 0.5*V_matrix(i,b*(j-1)+1)/100;
        end
        if V_matrix(i,b*(j-1)+2) > 3        % Damage degree 4 and 5 cause
demolition.
        dem(i,j) = V_matrix(i,b*(j-1)+1)/100;
        else
            if V_matrix(i,b*(j-1)+2) == 3   % Assuming half of buildings
with damage degree 3 are renovated
```

```
            ren(i,j) = 0.5*V_matrix(i,b*(j-1)+1)/100;
            else
            if V_matrix(i,b*(j-1)+2) > 0    % Damage degree from 1 to 2
are renovated.
            ren(i,j) = V_matrix(i,b*(j-1)+1)/100;
            end
            end
        end
      end
    end

 V_dem=zeros(8,6);      % Percentage of the "sample" that is demolished,
according to intensity and vulnerability class.
 V_ren=zeros(8,6);      % Idem but for renovation
 s=5;
for i=1:8
    for j=1:6
    V_dem(i,j)=sum(dem(s*(i-1)+1:s*i,j),1);
    V_ren(i,j)=sum(ren(s*(i-1)+1:s*i,j),1);
    end
end


% --- LEACHING RATES ---
L = 60;                 % Lifetime of dwellings
c = zeros(1,6); % Leaching fraction (normal circumstances, no earthquake)
for i=1:6
    c(:,i)=1/L;           % Constant leaching according to the lifetime,
each typology leaches equally.
end

ce = zeros(length(t),6);     % Earthquake leaching rate matrix, 6
vulnerability classes.
ce_tot = zeros(length(t),1); % Overall earthquake leaching rate, for
future earthquakes.
for i=1:length(t)
    if ce_h(i,:)>0
        ce(i,:)=ce_h(i,:);     % Assuming it leaches equally for each
vulnerability class (historical earthquakes only)
    else
    end
end

Ze = input('Please enter earthquake zone (1,2 or 3):');             %
Share of the stock prone to earthquake damage.
cfe = 0.365;                                                        %
Calibration factor for a similar earthquake as 2010 (considering region
2)
```

Baseline Scenario – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                    % Stock ("S") demand over time
S_matrix = zeros(length(t),6);    % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;    % Initial value for the stocks.
dS_matrix = zeros(length(t),6);   % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);           % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);          % Extra leaching due to earthquakes
I = zeros(length(t),6);           % Normal inflow
Ie = zeros(length(t),6);          % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));       % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);       % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);

r = 0.01;                        % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
R = zeros(length(t),6);           % Renovation matrix, normal
circumstances.
Re = zeros(length(t),6);          % Renovation matrix, due to earthquake.
re = zeros(length(t),6);          % Renovation share, due to earthquake.
re2 = zeros(length(t),6);         % Renovation share, due to earthquake.
re1 = zeros(1,6);

for i=2:length(t)
    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

   I(i,:) = typ(:,i).*(dS(i,:)+sum(O(i,:),2));    % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)
    if i==211 || i==236 || i==261
        if i==211
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);
```

```
     % All dwellings demolished by the earthquake are replaced by
dwellings of the same typology
     Ie(i,:) = Oe(i,:)./3;
     Ie(i+1,:) = Oe(i,:)./3;
     Ie(i+2,:) = Oe(i,:)./3;
    else
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        
        Ie(i,:)= Oe(i,:)./3;    % Assuming it takes three years to
recover
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
        else
        end
    end
    
    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';
    
end

I_t = I+Ie;
O_t = O+Oe;
R_t = R+Re;

% --- ENERGY ---
i_n = xlsread('Leaching10-parameters','Energy','C3');      % Energy
intensity of new buildings - 2020 target
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.

for l=1:length(t)
    if l>210                    % Chosen year (2013) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n*sum(I_t(l,:),2)/sum(Stock(l,:),2) - i_stock(l-
1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-1,:)*sum(Stock(l-
1,:),2)/sum(Stock(l,:),2);
    else
    end
end

E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```

Scenario 1a – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                  % Stock ("S") demand over time

S_matrix = zeros(length(t),6);  % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;  % Initial value for the stocks.
dS_matrix = zeros(length(t),6); % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);         % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);        % Extra leaching due to earthquakes
I = zeros(length(t),6);         % Normal inflow
Ie = zeros(length(t),6);        % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));     % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);     % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);

R = zeros(length(t),6);         % Renovation matrix, normal
circumstances.
Re = zeros(length(t),6);        % Renovation matrix, due to earthquake.
re = zeros(length(t),6);        % Renovation share, due to earthquake.
re2 = zeros(length(t),6);       % Renovation share, due to earthquake.
r = 0.01;                      % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
re1 = zeros(1,6);
% re1 = [r/6 r/6 r/6 r/6 r/6 0];  % Renovation rate for decreasing
earthquake vulnerability


for i=2:length(t)

    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

   I(i,:) = typ(:,i).*(dS(i,:)+sum(O(i,:),2));   % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)

    if i==211 || i==236 || i==261
        if i==211
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
```

```
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);

     % Typology distribution changes only for earthquake inflows (Ain_e)
     Ie(i,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
     Ie(i+1,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
     Ie(i+2,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
    else
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);

        Ie(i,:)= Oe(i,:)./3;    % Assuming it takes three years to
recover
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
        else
        end
    end

    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

end

I_t = I+Ie;
O_t = O+Oe;
R_t = R+Re;


% --- ENERGY ---
i_n = xlsread('Leaching10-parameters','Energy','C3');      % Energy
intensity of new buildings - 2020 target
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.

for l=1:length(t)
    if l>210                    % Chosen year (2013) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n*sum(I_t(l,:),2)/sum(Stock(l,:),2) - i_stock(l-
1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-1,:)*sum(Stock(l-
1,:),2)/sum(Stock(l,:),2);
    else
    end
end
```

```
E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```

Scenario 1b – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                   % Stock ("S") demand over time

S_matrix = zeros(length(t),6);  % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;  % Initial value for the stocks.
dS_matrix = zeros(length(t),6); % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);          % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);         % Extra leaching due to earthquakes
I = zeros(length(t),6);          % Normal inflow
Ie = zeros(length(t),6);         % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));      % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);      % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);

R = zeros(length(t),6);          % Renovation matrix, normal
circumstances.
Re = zeros(length(t),6);         % Renovation matrix, due to earthquake.
re = zeros(length(t),6);         % Renovation share, due to earthquake.
re2 = zeros(length(t),6);        % Renovation share, due to earthquake.
r = 0.01;                       % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
re1 = zeros(1,6);
% re1 = [r/6 r/6 r/6 r/6 r/6 0];  % Renovation rate for decreasing
earthquake vulnerability


for i=2:length(t)

    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

    % Typology distribution changes for normal inflows (Ain)
```

```
    if i<212
        typ_n(:,i) = typ(:,i);
    else
        if i<237
            typ_n(:,i) = typ(:,212)-[typ(1,212) -typ(1,212) 0 0 0 0]';
% Class "A" is phased out from the input, all that share goes to the
closer next class, that'd be "B".
        else
            if i<261
                typ_n(:,i) = typ(:,237)-[typ(1,237) -
typ(1,237)+typ(2,237) -typ(2,237) 0 0 0]';   % Class "B" is phased out
from inflows.
            else
                typ_n(:,i) = typ(:,261)-[typ(1,261) -
typ(1,261)+typ(2,261) -typ(2,261)+typ(3,261) -typ(3,261) 0 0]';  % Class
"C" is phased out from inflows.
            end
        end
    end
   I(i,:) = typ_n(:,i).*(dS(i,:)+sum(O(i,:),2));   % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)


    if i==211 || i==236 || i==261
        if i==211
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);

     % Typology distribution changes for earthquake inflows (Ain_e)
     Ie(i,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;    % Assuming it takes
three years to recover
     Ie(i+1,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
     Ie(i+2,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
    else
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);

        Ie(i,:)= Oe(i,:)./3;    % Assuming it takes three years to
recover
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
```

```
        else
        end
    end

    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

end

I_t = I+Ie;
O_t = O+Oe;
R_t = R+Re;


% --- ENERGY ---
i_n = xlsread('Leaching10-parameters','Energy','C3');      % Energy
intensity of new buildings - 2020 target
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.

for l=1:length(t)
    if l>210                     % Chosen year (2013) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n*sum(I_t(l,:),2)/sum(Stock(l,:),2) - i_stock(l-
1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-1,:)*sum(Stock(l-
1,:),2)/sum(Stock(l,:),2);
    else
    end
end

E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```

Scenario 2a – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                   % Stock ("S") demand over time

S_matrix = zeros(length(t),6);   % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;   % Initial value for the stocks.
dS_matrix = zeros(length(t),6);  % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);          % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);         % Extra leaching due to earthquakes
```

```
I = zeros(length(t),6);          % Normal inflow
Ie = zeros(length(t),6);         % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));      % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);      % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);

R = zeros(length(t),6);          % Renovation matrix, normal
circumstances.
Re = zeros(length(t),6);         % Renovation matrix, due to earthquake.
re = zeros(length(t)+1,6);         % Renovation share, due to earthquake.
re2 = zeros(length(t)+1,6);        % Renovation share, due to earthquake.
r = 0.01;                       % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
re1 = zeros(1,6);
ren_share = zeros(length(t),1);


for i=2:length(t)

    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

    % Typology distribution changes for normal inflows (Ain)
    if i<212
        typ_n(:,i) = typ(:,i);
    else
        if i<237
            typ_n(:,i) = typ(:,212)-[typ(1,212) -typ(1,212) 0 0 0 0]';
% Class "A" is phased out from the input, all that share goes to the
closer next class, that'd be "B".
        else
            if i<261
                typ_n(:,i) = typ(:,237)-[typ(1,237) -
typ(1,237)+typ(2,237) -typ(2,237) 0 0 0]';    % Class "B" is phased out
from inflows.
            else
                typ_n(:,i) = typ(:,261)-[typ(1,261) -
typ(1,261)+typ(2,261) -typ(2,261)+typ(3,261) -typ(3,261) 0 0]';  % Class
"C" is phased out from inflows.
            end
        end
    end
   I(i,:) = typ_n(:,i).*(dS(i,:)+sum(O(i,:),2));    % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)

    if i==211 || i==236 || i==261
        if i==211
```

```
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);
        ren_share(i,:) = sum(Re(i,:),2)/sum(S_matrix(i,:),2);



     % Typology distribution changes for earthquake inflows (Ain_e)
     Ie(i,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;    % Assuming it takes
three years to recover
     Ie(i+1,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
     Ie(i+2,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
    else
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);

        Ie(i,:)= Oe(i,:)./3;    % Assuming it takes three years to
recover
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
        else
        end
    end

    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

    % Renovation due to earthquakes changes the typology distribution
    re(i,:) = re1(:,:)+re2(i,:);

    Stock_alt = [0 Stock(i,1) Stock(i,2) Stock(i,3) Stock(i,4)
Stock(i,5)];
    re_alt = [0 re(i,1) re(i,2) re(i,3) re(i,4) re(i,5)];

    Stock(i,:) = Stock(i,:).*(ones(1,6)-re(i,:))+Stock_alt.*re_alt;
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

end

I_t = I+Ie;
O_t = O+Oe;
```

```
R_t = R+Re;


% --- ENERGY ---
i_n = xlsread('Leaching10-parameters','Energy','C3');       % Energy
intensity of new buildings - 2020 target
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.

for l=1:length(t)
    if l>210                    % Chosen year (2013) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n*sum(I_t(l,:),2)/sum(Stock(l,:),2) - i_stock(l-
1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-1,:)*sum(Stock(l-
1,:),2)/sum(Stock(l,:),2);
    else
    end
end

E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```

Scenario 2b – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                  % Stock ("S") demand over time

S_matrix = zeros(length(t),6);  % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;  % Initial value for the stocks.
dS_matrix = zeros(length(t),6); % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);         % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);        % Extra leaching due to earthquakes
I = zeros(length(t),6);         % Normal inflow
Ie = zeros(length(t),6);        % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));     % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);     % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);
```

```
R = zeros(length(t),6);         % Renovation matrix, normal
circumstances.
Re = zeros(length(t),6);        % Renovation matrix, due to earthquake.
re = zeros(length(t)+1,6);        % Renovation share, due to earthquake.
re2 = zeros(length(t)+1,6);       % Renovation share, due to earthquake.
r = 0.01;                      % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
ren_share = zeros(length(t),1);

for i=2:length(t)

    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

    % Typology distribution changes for normal inflows (Ain)
    if i<212
        typ_n(:,i) = typ(:,i);
        re1 = zeros(1,6);
    else
        re1 = [r r r r r 0];
        if i<237
            typ_n(:,i) = typ(:,212)-[typ(1,212) -typ(1,212) 0 0 0 0]';
% Class "A" is phased out from the input, all that share goes to the
closer next class, that'd be "B".
        else
            if i<261
                typ_n(:,i) = typ(:,237)-[typ(1,237) -
typ(1,237)+typ(2,237) -typ(2,237) 0 0 0]';   % Class "B" is phased out
from inflows.
            else
                typ_n(:,i) = typ(:,261)-[typ(1,261) -
typ(1,261)+typ(2,261) -typ(2,261)+typ(3,261) -typ(3,261) 0 0]';  % Class
"C" is phased out from inflows.
            end
        end
    end
   I(i,:) = typ_n(:,i).*(dS(i,:)+sum(O(i,:),2));   % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)

    if i==211 || i==236 || i==261
        if i==211
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
```

```
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);
        ren_share(i,:) = sum(Re(i,:),2)/sum(S_matrix(i,:),2);

     % Typology distribution changes for earthquake inflows (Ain_e)
     Ie(i,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;    % Assuming it takes
three years to recover
     Ie(i+1,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
     Ie(i+2,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
    else
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);
        ren_share(i,:) = sum(Re(i,:),2)/sum(S_matrix(i,:),2);
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);

        Ie(i,:)= Oe(i,:)./3;    % Assuming it takes three years to
recover
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
        else
        end
    end

    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

    % Renovation due to earthquakes changes the typology distribution
    re(i,:) = re1(:,:)+re2(i,:);

    Stock_alt = [0 Stock(i,1) Stock(i,2) Stock(i,3) Stock(i,4)
Stock(i,5)];
    re_alt = [0 re(i,1) re(i,2) re(i,3) re(i,4) re(i,5)];

    Stock(i,:) = Stock(i,:).*(ones(1,6)-re(i,:))+Stock_alt.*re_alt;
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

end

I_t = I+Ie;
O_t = O+Oe;
R_t = R+Re;


% --- ENERGY ---
i_n = xlsread('Leaching10-parameters','Energy','C3');      % Energy
intensity of new buildings - 2020 target
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.

for l=1:length(t)
```

```
    if l>210                    % Chosen year (2013) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n*sum(I_t(l,:),2)/sum(Stock(l,:),2) - i_stock(l-
1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-1,:)*sum(Stock(l-
1,:),2)/sum(Stock(l,:),2);
    else
    end
end

E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```

Scenario 3 – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                  % Stock ("S") demand over time

S_matrix = zeros(length(t),6);  % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;  % Initial value for the stocks.
dS_matrix = zeros(length(t),6); % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);         % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);        % Extra leaching due to earthquakes
I = zeros(length(t),6);         % Normal inflow
Ie = zeros(length(t),6);        % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));     % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);     % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);

R = zeros(length(t),6);         % Renovation matrix, normal
circumstances.
r = 0.01;                      % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
Re = zeros(length(t),6);        % Renovation matrix, due to earthquake.
re = zeros(length(t),6);        % Renovation share, due to earthquake.
re2 = zeros(length(t),6);       % Renovation share, due to earthquake.
re1 = zeros(1,6);
% re1 = [r/6 r/6 r/6 r/6 r/6 0];  % Renovation rate for decreasing
earthquake vulnerability
```

```
for i=2:length(t)

    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

   I(i,:) = typ(:,i).*(dS(i,:)+sum(O(i,:),2));   % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)

    if i==211 || i==236 || i==261
        if i==211
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);

     % Dwellings demolished earthquakes are replaced by dwellings of the
same typology (same as baseline scenario)
     Ie(i,:) = Oe(i,:)./3;
     Ie(i+1,:) = Oe(i,:)./3;
     Ie(i+2,:) = Oe(i,:)./3;
    else
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);

        Ie(i,:)= Oe(i,:)./3;    % Assuming it takes three years to
recover
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
        else
        end
    end

    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

end

I_t = I+Ie;
O_t = O+Oe;
R_t = R+Re;
```

```
% --- ENERGY ---
i_n = zeros(length(t),1);
i_n(211:length(t),:) = xlsread('Leaching10-
parameters','Energy','D21:D111');       % Energy intensity of new
buildings - 2020 target
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.

for l=1:length(t)
    if l>210                    % Chosen year (2013) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n(l,:)*sum(I_t(l,:),2)/sum(Stock(l,:),2) -
i_stock(l-1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-
1,:)*sum(Stock(l-1,:),2)/sum(Stock(l,:),2);
    else
    end
end

E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n(m,:)*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```

Scenario 4 – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                  % Stock ("S") demand over time

S_matrix = zeros(length(t),6);  % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;  % Initial value for the stocks.
dS_matrix = zeros(length(t),6); % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);         % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);        % Extra leaching due to earthquakes
I = zeros(length(t),6);         % Normal inflow
Ie = zeros(length(t),6);        % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));     % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);     % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);
```

```
R = zeros(length(t),6);         % Renovation matrix, normal
circumstances.
r = 0.01;                       % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
Re = zeros(length(t),6);        % Renovation matrix, due to earthquake.
re = zeros(length(t),6);        % Renovation share, due to earthquake.
re2 = zeros(length(t),6);       % Renovation share, due to earthquake.
re1 = zeros(1,6);


for i=2:length(t)

    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

   I(i,:) = typ(:,i).*(dS(i,:)+sum(O(i,:),2));   % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)

    if i==211 || i==236 || i==261
        if i==211
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);

     % Dwellings demolished earthquakes are replaced by dwellings of the
same typology
     Ie(i,:) = Oe(i,:)./3;
     Ie(i+1,:) = Oe(i,:)./3;
     Ie(i+2,:) = Oe(i,:)./3;
    else
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);

        Ie(i,:)= Oe(i,:)./3;
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
        else
        end
    end

    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
```

```
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

   end

I_t = I+Ie;
O_t = O+Oe;
R_t = R+Re;


% --- ENERGY ---
i_n = zeros(length(t),1);
i_n(211:length(t),:) = xlsread('Leaching10-
parameters','Energy','D21:D111');      % Energy intensity of new
buildings - 2020 target
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.
i_ren = zeros(length(t),1);
ratio = zeros(length(t),3);


for l=2:length(t)
    if l>210                    % Chosen year (2010) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n(l,:)*sum(I_t(l,:),2)/sum(Stock(l,:),2) -
i_stock(l-1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-
1,:)*sum(Stock(l-1,:),2)/sum(Stock(l,:),2);
       i_ren(l,:) = (i_n(l,:)+i_stock(l,:))/2;
       i_stock(l,:) = i_stock(l,:)*(1-r)+r*i_ren(l,:);
       ratio(l,1) = sum(I_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,2) = sum(O_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,3) = sum(Stock(l-1,:),2)/sum(Stock(l,:),2);
    else
       ratio(l,1) = sum(I_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,2) = sum(O_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,3) = sum(Stock(l-1,:),2)/sum(Stock(l,:),2);
    end
end

E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n(m,:)*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```

Scenario 5 – Code

```
% --- STOCK AND FLOWS ---
S = P./Pd.*Ad;                  % Stock ("S") demand over time

S_matrix = zeros(length(t),6);  % Stocks corresponding to each typology.
S_matrix(1,:) = S(1,:).*types;  % Initial value for the stocks.
dS_matrix = zeros(length(t),6); % Change in stocks by typology.
dS = zeros(length(t),1);
O = zeros(length(t),6);         % Normal outflow (leaching), no
earthquake.
Oe = zeros(length(t),6);        % Extra leaching due to earthquakes
I = zeros(length(t),6);         % Normal inflow
Ie = zeros(length(t),6);        % Inflow replacing earthquake losses
typ = zeros(6,length(t));
typ_n = zeros(6,length(t));     % Typology share for new incoming flows
(particularly after earthquakes)
typ(:,1) = types;
typ(:,2) = types;
Stock = zeros(length(t),6);     % Stock (physical, instead of stock
demand) development
Stock(1,:) = S_matrix(1,:);

R = zeros(length(t),6);         % Renovation matrix, normal
circumstances.
r = 0.01;                       % Renovation rate for energy efficiency
purposes, randomly chosen, for now.
Re = zeros(length(t),6);        % Renovation matrix, due to earthquake.
re = zeros(length(t),6);        % Renovation share, due to earthquake.
re2 = zeros(length(t),6);       % Renovation share, due to earthquake.
ren_share = zeros(length(t),1);


for i=2:length(t)

    S_matrix(i,:) = S(i,:).*typ(:,i);
    O(i,:) = c.*S_matrix(i,:);
    R(i,:) = r.*S_matrix(i,:);
    dS(i,:) = S(i,:)-S(i-1,:);

    % Typology distribution changes for normal inflows (Ain)
    if i<212
        typ_n(:,i) = typ(:,i);
        re1 = zeros(1,6);
    else
        re1 = [r r r r r 0];
        if i<237
            typ_n(:,i) = typ(:,212)-[typ(1,212) -typ(1,212) 0 0 0 0]';
% Class "A" is phased out from the input, all that share goes to the
closer next class, that'd be "B".
        else
            if i<261
                typ_n(:,i) = typ(:,237)-[typ(1,237) -
typ(1,237)+typ(2,237) -typ(2,237) 0 0 0]';   % Class "B" is phased out
from inflows.
```

```
            else
                typ_n(:,i) = typ(:,261)-[typ(1,261) -
typ(1,261)+typ(2,261) -typ(2,261)+typ(3,261) -typ(3,261) 0 0]';  % Class
"C" is phased out from inflows.
            end
        end
    end

   I(i,:) = typ_n(:,i).*(dS(i,:)+sum(O(i,:),2));    % The total demand for
new buildings is expressed as a total number, and the typology of the new
buildings will be determined after each earthquake (change in building
codes)

    if i==211 || i==236 || i==261
        if i==211
            int = 4;
        else
            int = input('Please enter earthquake intensity (3(VII),
4(VIII), 5(IX), 6(X), 7(XI) or 8(XII)):');
        end
        ce(i,:) = e_zones(Ze,:).*cfe.*V_dem(int,:); % Future earthquake
leaching rate, for 2035 and 2060.
        Oe(i,:) = ce(i,:).*S_matrix(i,:);
        ce_tot(i,:) = sum(Oe(i,:),2)/sum(S_matrix(i,:),2);
        re2(i,:) = e_zones(Ze,:).*cfe.*V_ren(int,:); % Future earthquake
renovation rate, for 2035 and 2060.
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);
        ren_share(i,:) = sum(Re(i,:),2)/sum(S_matrix(i,:),2);

     % Typology distribution changes for earthquake inflows (Ain_e)
     Ie(i,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;    % Assuming it takes
three years to recover
     Ie(i+1,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;
     Ie(i+2,:) = (Oe(i,:)+[-Oe(i,1) Oe(i,1)-Oe(i,2) Oe(i,2)-Oe(i,3)
Oe(i,3)-Oe(i,4) Oe(i,4)-Oe(i,5) Oe(i,5)])./3;

    else
        Re(i,:) = (re1(:,:)+re2(i,:)).*S_matrix(i,:);
        ren_share(i,:) = sum(Re(i,:),2)/sum(S_matrix(i,:),2);
        if ce(i,:)>0
        Oe(i,:) = ce(i,:).*S_matrix(i,:);

        Ie(i,:)= Oe(i,:)./3;    % Assuming it takes three years to
recover
        Ie(i+1,:)= Oe(i,:)./3;
        Ie(i+2,:)= Oe(i,:)./3;
        else
        end
    end

    % Calculation of typology for the coming year
    Stock(i,:) = I(i,:)+Ie(i,:)-O(i,:)-Oe(i,:)+Stock(i-1,:);
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';
```

```
    % Effect of renovation on typology
    re(i,:) = re1(:,:)+re2(i,:);

    Stock_alt = [0 Stock(i,1) Stock(i,2) Stock(i,3) Stock(i,4)
Stock(i,5)];
    re_alt = [0 re(i,1) re(i,2) re(i,3) re(i,4) re(i,5)];

    Stock(i,:) = Stock(i,:).*(ones(1,6)-re(i,:))+Stock_alt.*re_alt;
    typ(:,i) = (Stock(i,:)./sum(Stock(i,:),2))';
    typ(:,i+1) = (Stock(i,:)./sum(Stock(i,:),2))';

end

I_t = I+Ie;
O_t = O+Oe;
R_t = R+Re;

% --- ENERGY ---
i_n = zeros(length(t),1);
i_n(211:length(t),:) = xlsread('Leaching10-
parameters','Energy','D21:D111');      % Energy intensity of new
buildings - 2020 target
i_ren = zeros(length(t),1);
i_stock = zeros(length(t),1);
i_stock(198:210,:) = xlsread('Leaching10-parameters','Energy','C8:C20');
% Historical values for the stock energy intensity.
ratio = zeros(length(t),3);

for l=2:length(t)
    if l>210                    % Chosen year (2013) for EE regulation
taking force on new buildings.
       i_stock(l,:) = i_n(l,:)*sum(I_t(l,:),2)/sum(Stock(l,:),2) -
i_stock(l-1,:)*sum(O_t(l,:),2)/sum(Stock(l,:),2) + i_stock(l-
1,:)*sum(Stock(l-1,:),2)/sum(Stock(l,:),2);
       ratio(l,1) = sum(I_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,2) = sum(O_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,3) = sum(Stock(l-1,:),2)/sum(Stock(l,:),2);
       i_ren(l,:) = (i_n(l,:)+i_stock(l,:))/2;
       i_stock(l,:) = i_stock(l,:)*(1-r)+r*i_ren(l,:);
    else
       ratio(l,1) = sum(I_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,2) = sum(O_t(l,:),2)/sum(Stock(l,:),2);
       ratio(l,3) = sum(Stock(l-1,:),2)/sum(Stock(l,:),2);
    end
end

E = zeros(length(t),1);
for m=2:length(t)
    if m<211
        E(m,:)=i_stock(m,:)*sum(Stock(m,:),2)*10^-9;
    else
        E(m,:)=i_n(m,:)*sum(I_t(m,:),2)*10^-9 - i_stock(m-
1,:)*sum(O_t(m,:),2)*10^-9 + i_stock(m-1,:)*sum(Stock(m-1,:),2)*10^-9;
    end
end
```