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Modelling the temporal dynamics of seismic exposure in Santiago, Chile

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ABSTRACT

Among the three components of seismic risk—hazard, exposure and vulnerability—exposure is the least studied. This paper presents the preliminary results of a study on the temporal dynamics of seismic exposure in the last 25 years for the city of Santiago, Chile. Exposure models with a census-block resolution are built for two different epochs—1992 and 2017—and compared. Results show that the city has grown both horizontally (i.e., expanding) and vertically (i.e., densifying) in the study period. Also, that reinforced concrete is becoming the preferred building material, going from 3% to 17% of the total buildings in the city. Considering the constant update of seismic design regulations in Chile, the formality of construction, the high compliance to codes, and the constant evolution of building practice in Chile, these results imply that the city is evolving into a seismically safer state. This research is the first step towards a time-dependent seismic risk assessment for the city of Santiago. This tool will be used to further explore how urban planning decisions affect the evolution of risk in time.

Keywords: exposure modelling, seismic risk, spatiotemporal dynamics, urban growth

INTRODUCTION

Chile is one of the most exposed countries to natural hazards and one of the most seismically active in the world (*Dilley et al., 2005*; *Scholz, 2002*). Since 1900, 81 earthquakes magnitude M_S 7.0 or larger have been registered in the country (*CSN, 2019*), including the largest earthquake ever recorded in the world, the 1960 Great Earthquake of Valdivia. Moreover, four earthquakes magnitude M_W 8.0 or larger have struck Chile in the past 25 years. The largest of them, the M_W 8.8 Maule earthquake of 2010, killed 575 people, affected 75% of Chile's population, and resulted in an economic loss of approximately $30 billion USD or 18% of Chile's GDP (*de la Llera et al., 2017*). Indeed, earthquakes account for 75% of the combined economic losses associated to disasters since 1990 in the country (*UNISDR, 2015*). With an urbanization rate of almost 90% and more than half of its population concentrated in only three metropolitan areas, it is highly relevant to understand how and why Chilean cities are changing over time. In a seismic risk context, this matter is the domain of exposure modelling.

Exposure can be defined as the set of elements or assets present in a hazard zone, which are potentially subject to losses from hazards (*Pittore et al., 2017*). Among the three components of seismic risk—hazard, exposure and vulnerability—exposure is the least studied (*Pittore et al., 2017*; *Rivera, 2018*; *Santa María et al., 2017*; *Silva et al., 2018*)

Regardless of the level of sophistication and resolution of the exposure models, seismic risk assessment (SRA) traditionally considers exposure as a fixed parameter. However, when risk is assessed for long periods of time—say, 50 or 100 years—this assumption over simplifies the complexity of cities and urban environments

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and the fast dynamism they present in time. Therefore, the alternative of moving towards time-dependent SRA arises. However, this requires looking risk components in a different way. In the case of exposure, that means considering its spatiotemporal dynamics and understanding its impact in SRA. This paper presents the results of a study on the temporal dynamics of seismic exposure in the last 25 years for the city of Santiago, Chile.

The city of Santiago and the Santiago Urban Metropolitan System

The city of Santiago is often referred to as *Gran Santiago* (Greater Santiago). No formal definition of the city and its boundaries exists to the date. Although not formally established, there seems to be a consensus that Greater Santiago's boundary comprises 34 out of the 52 *comunas* of the Metropolitan Region of Santiago (MRS): the 32 *comunas* of the Santiago Province[2], plus Puente Alto and San Bernardo *comunas*. Nevertheless, it is also common to find alternative definitions of Greater Santiago which incorporate others to the 34-*comuna* set based on economic, physical, urban, or other criteria (see e.g., *Galetovic & Poduje, 2006*; *MINVU & INE, 2018*). For this research, the definition adopted for Santiago is that proposed by de Mattos et al. (*2014*). There, the authors acknowledge the functional relationship between some peri-urban *comunas* of the MRS with the core of Greater Santiago. To include a *comuna* into the SUMS, at least 15% of its population must commute from its core to the core of Greater Santiago. This criterion recognizes a functional relationship between the city and the *comuna*, and therefore an economical dependency or interaction (*de Mattos et al., 2014*). Thus, the Santiago Urban Metropolitan System (SUMS) is defined as a set of 47 *comunas* (Fig.1), 13 of them which are peri-urban *comunas* connected with Greater Santiago (*de Mattos et al., 2014*). Using the SUMS to define Santiago also allows observing urban growth by means of both horizontal expansion and vertical densification in parallel (*de Mattos et al., 2014*). This is highly relevant for modelling seismic exposure of Santiago in time and therefore fits the purpose of this research.

The SUMS is divided into four concentric areas (Fig.1): the Historic Centre (HC) which corresponds to the Santiago *comuna*, the First Crown (FC) which comprises the 22 *comunas* around the HC (in bold in footnote 2), the External Crown (EC) comprising 11 *comunas* around the FC (in italic in footnote 2 plus Puente Alto and San Bernardo), and the Extended Peri-urban (EP) comprising the 13 *comunas* in the external ring of the SUMS (Pirque, San José del Maipo, Colina, Lampa, Buin, Calera de Tango, Paine, Curacaví, Talagante, El Monte, Isla de Maipo, Padre Hurtado, and Peñaflor). The remaining 5 *comunas* of the MRS are not included as part of Santiago with this definition and are therefore not considered in this research. From this point onwards, every time Santiago is mentioned, it will refer to the SUMS.

METHODOLOGY

To model the spatiotemporal dynamics of Santiago between 1992 and 2017, two exposure models are built. Next, a discussion and description about the data sources used to build the models is provided. Then, the method followed to generate the exposure models is explained.

Data sources

There is no single aggregated database containing detailed information of the building stock in Chile. Instead, different data is collected and maintained in different formats by different institutions (i.e., local governments, ministries, public services, and institutes). Thus, the fragmentation of the data pertinent to seismic exposure hinders its study and monitoring over time. The use of remote sensing data is promising for generating automatized or semi-automatized exposure models with large coverage for studying exposure in the future (*Pittore et al., 2017*). However, the lack of accurate historic technical data is a problem hindering the study of past states of the city's built environment (*Vergara, 2017*). For this reason, the census is used as the main data source for modelling past and present seismic exposure in Santiago.

[2] Santiago, **Cerrillos**, **Cerro Navia**, **Conchalí**, **El Bosque**, **Estación Central**, *Huechuraba*, **Independencia**, **La Cisterna**, *La Florida*, **La Granja**, **La Pintana**, *La Reina*, *Las Condes*, *Lo Barnechea*, **Lo Espejo**, **Lo Prado**, **Macul**, *Maipú*, **Ñuñoa**, **Pedro Aguirre Cerda**, *Peñalolén*, **Providencia**, *Pudahuel*, *Quilicura*, **Quinta Normal**, **Recoleta**, **Renca**, **San Joaquín**, **San Miguel**, **San Ramón**, and **Vitacura**.

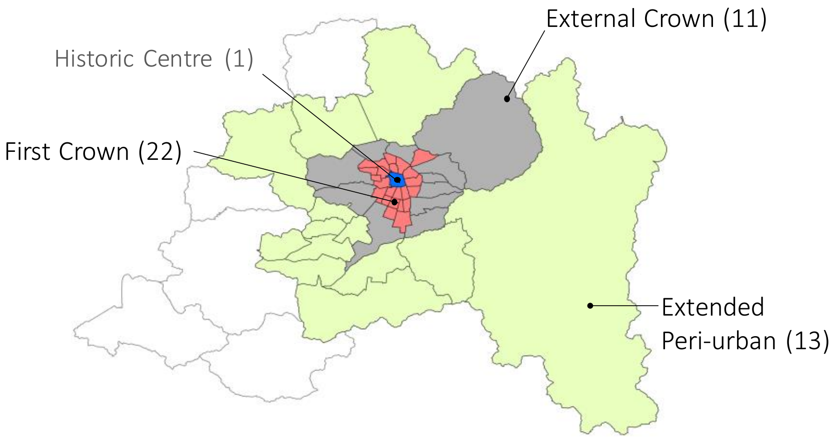

Figure 1. The 52 *comunas* of the Metropolitan Region of Santiago and the four areas of the SUMS. In parenthesis is the number of *comunas* comprising each area

Using census data can be an inefficient approach to model exposure (*Pittore et al., 2017*). However, this data is being collected regardless, providing a reliable and comprehensive input to develop, update, and/or validate exposure models in time. Despite census data limitations, global efforts such as the Global Earthquake Model (GEM) still heavily rely on each country's census data (*Silva et al., 2018*). Furthermore, building typologies in Chile are quite uniform across the country because of the widespread use and enforcement of design and construction standards (*Contrucci, 2008*). Thus, it is relatively straightforward and accurate to recognize the structural system of a dwelling based only on information of its main wall material, which is available from the census (*Santa María et al., 2017*). Hence, the census is chosen as the backbone data for exposure modelling.

There are two drawbacks to using the census for seismic exposure modelling. First, its technical accuracy. The information recorded in the census comes directly from the response of the dwellers. Hence, technical information such as wall or roof covering material can be recorded wrongly. The second and most relevant constraint is that the census records information for dwellings, whereas exposure in seismic risk models requires the number of buildings or structures. Except for detached houses, there is no direct correspondence between the number of dwellings and the number of buildings. To overcome this, and to perform an informed dwelling-to-building aggregation process, supplementary data is used. Next, both main and supplementary data sources are described. Then, the methodology followed to develop the exposure models is presented.

The national census

The national census is performed regularly approximately every 10 years. The institution overseeing the data collection and publication of results is the *Instituto Nacional de Estadísticas* (National Institute of Statistics, INE). The first completely digitalized census is that of 1992 and the full anonymised microdata from then onwards is publicly available by request under Law 20,285 on transparent access to public information. The census accounts for collective buildings (e.g., hotels, motels, institutions, hospitals) and both formal and informal residential buildings. However, collective buildings are only counted but not surveyed (i.e., the form is not applied in collective buildings). Furthermore, mobile dwellings (e.g., tents, house trailers), pedestrians, and homeless people are also counted. In this research, only permanent residential buildings are considered for the exposure model, so collective buildings—which comprise only 0.2% of the total building inventory of the country in 2017—and mobile dwellings are removed from the database.

The census data used for exposure modelling of residential buildings are: (i) number of dwellings at different geographical levels (e.g., national, communal, census block); (ii) technical information of dwellings, namely dwelling type (e.g., house, flat, vernacular construction), main exterior wall material (e.g., RC, masonry, adobe), and main roof covering material (e.g., concrete slab, roof tiles, roof sheets); and (iii) census cartography providing the maps to visualize the data spatially with a GIS software or similar. Next, the three census categories providing technical information of housing are described. These data fields of the are used for modelling the seismic exposure of residential buildings in Santiago in 1992 and 2017.

Dwelling types

For seismic exposure modelling, the most relevant census category is the dwelling type. This is the only data reported directly by the surveyor. All other data fields come from the answers of the dweller. Dwelling type information allows a basic, first-level classification of the exposure. Across censuses, different dwelling type categories have been used and therefore processing is needed to compare data in time. However, the main dwelling types have remained constant, namely house, flat, and room in *conventillo*.[3] Other dwelling type categories include emergency constructions (*mediaguas*), traditional indigenous dwellings, vernacular constructions (e.g., rancho, choza), and self-constructed dwellings.

Main exterior wall material

The second most relevant technical category is the main exterior wall material, which allows a second-level classification of census data about dwellings. With this information, and because of the overall uniformity and formality of the Chilean built environment, it is possible to perform a rough classification of residential buildings. Most common exterior wall materials used in Chile and surveyed in the census are reinforced concrete (RC), clay brick and concrete block masonry, timber, and adobe. Other traditional materials are used for vernacular and informal constructions such as cob, mud, *pirca*, *quincha*, or waste materials.

Main roof covering material

The third technical category is main roof covering material. This information is used for disaggregation of census data in the exposure modelling process (see the Exposure modelling method section).

Supplementary data

Three additional data sources are used to build the exposure models. These are the Edification Statistics Database (ESD), the 2012 census, and the database of social dwellings of the Ministry of Housing and Urbanism (MINVU). The ESD integrates the information from the *Formulario Único de Estadísticas de Edificación* (Unique Form of Edification Statistics, UFES). The UFES is presented to the corresponding municipality—local government—when applying for a construction permit. Once the permit is granted, the information of each construction permit, corresponding each to a construction project, is incorporated in the ESD by INE, institution managing and maintaining the database. The ESD used in this research comprises the construction permits issued between January 2002, when the database was implemented, and July 2014.

The 2012 census was declared invalid after several audits found important mistakes in the design, implementation, and processing of the census which lead to a national omission rate of at least 9.3% (*INE, 2014*). However, it still provides high coverage (ca. 90%) of housing in Chile and it can be used as a supplementary source to model exposure.

MINVU manages and updates a cadastre of social dwellings projects built in the country under its sponsorship and/or subsidy. These projects are a combination of houses and apartment buildings and conform to a narrow group of architectural and structural typologies. Access to the database is open and available at the webpage of the Chilean Geospatial Data Infrastructure (IDE Chile).

Details on how supplementary data is used for exposure modelling can be found in Rivera (*2018*). Overall, supplementary data is used to back up exposure modelling decisions such as disaggregating building typologies surveyed together in the census and aggregating dwelling counts into buildings counts to generate the final exposure models (see the Exposure modelling method section).

Exposure modelling method

The method followed to build the exposure models of Santiago comprises eight steps (Fig.2). In essence, the method allows going from dwelling counts from the raw census data to building counts of different fragility typologies (FT) which are defined to represent Santiago's built environment. For this purpose, data is classified first into census classes (CC), an intermediate set of categories which allows sorting and managing the data (see Fig.3).

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[3] A *conventillo* is a large, old house with several rooms which are rented to different families who share common facilities such as bathroom, toilet, and kitchen.

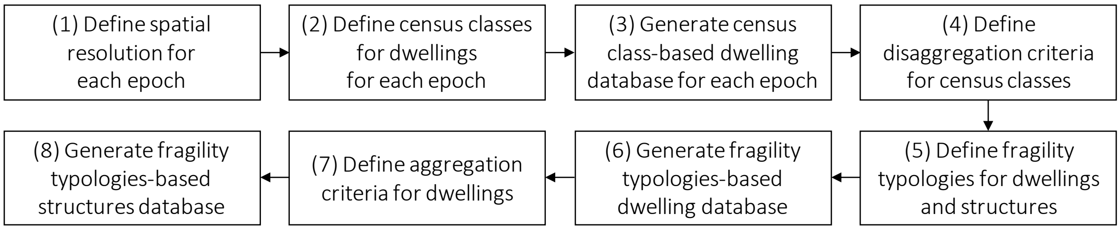

Figure 2. The eight-steps methodology to model Santiago's exposure from census data

First, the spatial resolution of each model is defined as the smallest level of data aggregation. Due to data availability, *manzana censal* (census block) resolution is used for 1992 and *zona censal* (census zone) resolution is used for 2017. Thus, Santiago is divided into 37,195 census blocks in 1992 and 2,223 census zones in 2017.

Second, the categories to classify the raw census data, i.e., the CC, are defined (see Fig.3). CC are epoch-specific and apply only for dwellings. CC are defined in two levels. The first level corresponds to dwelling type (categories in italic in Fig.3), and the second level to the main exterior wall material. With this, thirteen CC for dwellings are defined for 1992 and fourteen for 2017 (see Fig.3 for an example).

Third, a database is produced for each epoch by classifying the census data into the defined CC. The first version of the exposure models are thus CC-based dwelling databases where each row corresponds to a spatial unit (i.e., a census block or zone) and each column represents a different CC. Then, the database contains 37,195 rows and 13 columns in 1992 and 2,223 rows and 14 columns in 2017.

Fourth, the criteria for disaggregating the CC data are set. This is necessary because there are several CC grouping more than one types of dwellings. For example, the *Brick/RC/block house dwelling* CC in 1992 groups RC and masonry houses despite the fact that they correspond to different FT in the final model (see Fig.3). In such cases it is necessary to set the criteria to disaggregate CC data into the FT categories. To establish the disaggregation criteria of CC data, assumptions are made using the main and supplementary data sources. For example, data of main roof covering material is used. In *Brick/RC/block house* dwellings, if the roof is an RC slab, then the dwelling is classified as an RC house dwelling; else, as a masonry house dwelling (see details in *Rivera, 2018*).

Fifth, the categories to classify the CC disaggregated data, i.e., the FT, are defined. FT are common to all epochs and representative of Santiago's residential built environment. Thus, the set of FT is unique and its definition allows studying the temporal dynamics of exposure. FT are defined in two levels: again, the first level refers to dwelling type, and the second to the main exterior wall material (see Fig.3). A total of fifteen FT are defined for Santiago: six different FT for house dwellings (RC, masonry, timber, panel, adobe, and *quincha*), two for flat dwellings (RC and masonry), four for room dwellings (masonry, timber, adobe, and *quincha*), one for *mediagua*, one for vernacular, and one for self-construction dwellings.

Sixth, a second database is produced for each epoch by classifying the disaggregated CC data into the defined FT. The second version of the exposure models are FT-based dwelling databases where each row corresponds to a spatial unit and each column represents a different FT. Then, the database contains fifteen columns in every epoch. For example, in 1992, dwellings in the *Brick/RC/block flat dwelling* CC are first disaggregated into *brick/block flats* and *RC flats*, and then classified into the *Masonry flat* and *RC flat* FT, respectively.

Seventh, the dwelling-to-structure aggregation criteria are defined for each FT and for each comuna of Santiago. Aggregation allows an estimate to be made of the number of structures per FT for each spatial unit per epoch from the FT dwellings data produced in the previous step. For dwellings in the *mediagua*, vernacular, and self-construction FT, the aggregation parameter is 1, meaning that for these FT one dwelling corresponds to one structure. House dwellings are aggregated into *detached*, *semi-detached*, or *continuous house* structures for RC, masonry, timber, panel, adobe, and *quincha*. Flat dwellings are aggregated into *apartment building* structures for RC and masonry. Room dwellings are aggregated into *conventillo* structures for masonry, timber, adobe, and *quincha*. The value of the parameter (i.e., how many dwellings of certain FT are considered to constitute a structure of that FT) is calculated using supplementary data (see details in *Rivera, 2018*).

Finally, the eighth step consists on producing a final database for each epoch by aggregating dwellings into structures for each FT. The exposure models are FT-based structure databases where each row corresponds to a spatial unit and each column represents a different FT. Thus, the final database contains fifteen columns in every epoch, one for each FT.

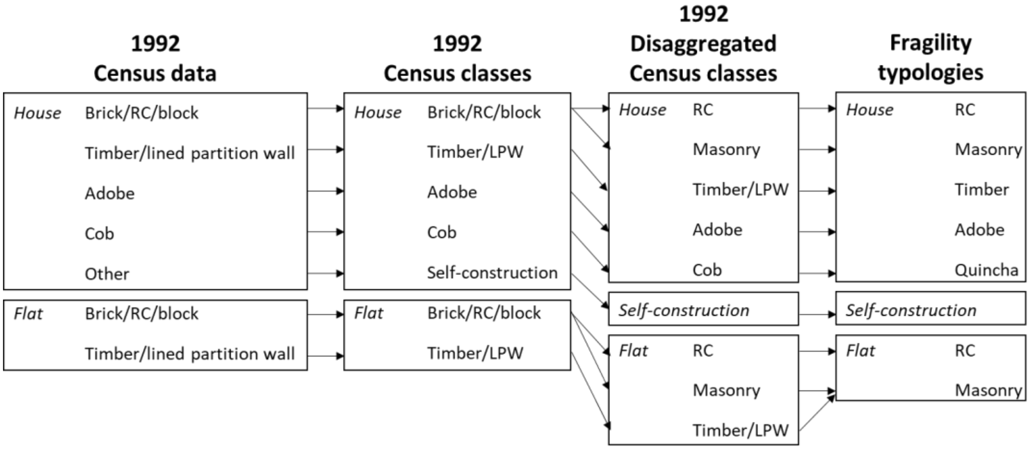

Figure 3. An example of how data changes throughout the exposure modelling process. Only categories associated to house and flat dwellings are shown

RESULTS

An overview of the 1992 and 2017 censuses and exposure models shows an increase of total population, dwellings, and structures (Table 1). Noteworthy is the fact that while population has grown 35% in the study period, dwellings do so in 75%, and structures in 38%. A larger increase in the number of dwellings as compared to number of structures indicates densification through vertical expansion (Table 1).

Table 1. Summary of the 1992 and 2017 censuses (population and dwellings) and exposure models (structures) per internal (HC+FC) or external (EC+EP) region of Santiago

	Total		**HC + FC**		**EC + EP**	
	1992	*2017*	*1992*	*2017*	*1992*	*2017*
People	5,145,350	6,940,109	57%	44%	43%	56%
Dwellings	1,200,832	2,090,848	58%	47%	42%	53%
Structures	742,590	1,025,695	55%	37%	45%	63%

Although the total population and structures in Santiago increases overall, the growth is explained mainly in the two external areas of the city, the EC and EP. Instead, the total structures in the centre of the city, i.e., in the HC and FC, remain essentially stable (Fig.4). Whereas 57% of the population lived in the HC and FC in 1992, only 44% live there in 2017. It is seen that these areas concentrate 55% of the structures of the city in 1992, but only 37% by 2017. Rapidly growing, the EP goes from 8 to 12% of the population and from 10 to 18% of the structures in the same period.

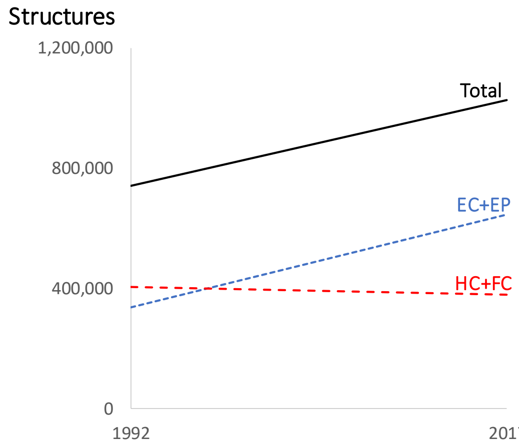

Figure 4. The External Crown (EC) and Extended Periurban (EP) explain most of the growth of structures in time in Santiago. The Historic Centre (HC) and First Crown (FC) stay essentially constant

The exposure models also show that houses are by far the predominant first-level structure typology (Table 2). On average in the study period, they represent 82% of the total structures, while apartment buildings only account for 3%. Together, *conventillos*, *mediaguas*, vernacular, and self-constructed structures represent 15% in 1992 but rapidly decrease to only 4% of the total in 2017. Note that in the EP practically there are no apartment buildings (Table 2). This typology increases its share of the total when moving towards the centre of Santiago, reaching an average maximum of 8% in the HC. With houses and apartment buildings representing 85 and 96% of the total structures in each epoch, the focus is put in these two first-level typologies onwards.

Table 2. Percentage of first-level typologies out of total structures in time per area of Santiago

	Houses (%)		**Ap. Buildings (%)**		**Other typologies (%)**	
	1992	*2017*	*1992*	*2017*	*1992*	*2017*
HC	82	84	7	8	11	8
FC	82	94	3	3	15	3
EC	83	96	1	2	16	2
EP	82	96	0	0	18	4
Average	82	93	3	3	15	4

A second result from the exposure models is that the city is growing both horizontally and vertically, i.e., by expansion and densification. The parallel occurrence of these phenomena has been reported by others (*Contrucci, 2008*; *de Mattos et al., 2014*; *Vergara, 2017*). However, this paper provides updated evidence of this, showing that expansion is predominant in the exterior of the city (EC and EP) while densification is more intensive in the centre (HC and FC). Regarding expansion, the exposure models show that the total number of houses is increasing in time, with most of this type of growth occurring in the external part of the city, i.e., in the EC and EP. Regarding densification, the censuses show that the proportion of total house dwellings for each epoch has decreased with time in every area of Santiago except for the EP (Fig.5, left). Noteworthy is the case of the HC, where house numbers decrease by over two thirds in 25 years. Instead, flats are on the rise for every area of the city; the share of flat dwellings from the total has doubled in the HC, FC, and EC (see Fig.5, left). Since the number of flats is small in the EP, the proportions are distorted, and the curve should be disregarded. The trends observed for structures are different than those for dwellings (Fig.5, right). For houses, although a rise can be observed in every area, the differences between 1992 and 2017 are smaller than those for dwellings, with an average of 10% and a maximum of 15% in the EP. Also, the proportion of structures that are apartment buildings remains relatively constant in time, despite the important increase of dwellings reported earlier. Thus, proportionally more flat dwellings and a constant share of apartment building structures means a densification of the building stock. While densification is more intensive in the centre of the city (i.e., HC and FC), the EC also densifies but with lower heights.

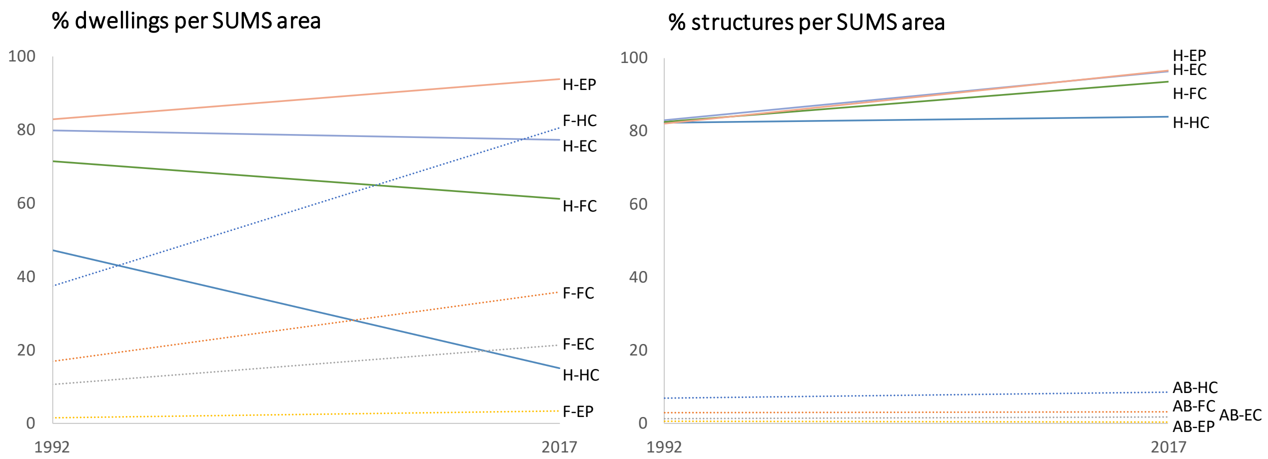

Figure 5. Percentage of total dwellings (left) and structures (right) in each SUMS area. Solid lines represent house dwellings and structures (H-); dashed lines represent flat dwellings (F-) and apartment buildings structures (AB-)

The third result from the exposure models is that Santiago is evolving into a city predominantly made of RC. Whereas 9% of the total dwellings and 3% of the total structures in Santiago are of RC in 1992, these numbers increased to 33 and 17% in 2017, respectively (Table 3). The most dramatic change is for houses, going from ~2% to ~11% of the total dwellings, and from ~3% to ~17% of the total structures of the city in 25 years (Table 3). Instead, flat dwellings tripled in the study period, but apartment buildings (structures) remain under 1% of the total structures of the city (Table 3). This again is due to the densification of the buildings in Chile, meaning more dwellings in a similar number of structures. The models also show that the trend of increasing use of RC for residential buildings is transversal to the city and not a concentrated phenomenon in either the centre or the periphery of the city.

Table 3. Number and percentage of RC out the total dwellings and structures in Santiago in time

	1992		2017	
	(num)	*(%)*	*(num)*	*(%)*
Total dwellings	1,200,832	100	2,090,848	100
RC house dwellings	22,739	1.9	225,877	10.8
RC flat dwellings	87,701	7.3	457,861	21.9
Total structures	742,590	100	1,025,695	100
RC houses	19,699	2.7	169,974	16.6
RC apt. buildings	4,052	0.6	6,205	0.6

CONCLUSIONS

The exposure models support three main ideas: (i) Santiago's residential exposure is increasing in the study period, (ii) it is growing both horizontally and vertically, and (iii) it is doing it mainly by building with RC. This situation presents a challenge to Chilean earthquake engineering and building practice: if new buildings are designed and built properly, the expansion of the city together with the renewal of the older building stock will lead to a safer, more resilient built environment. However, if new knowledge and evidence about Chile's seismic hazard are not incorporated into codes and practice, a major threat for Santiago's seismic resilience exists.

The main contribution of this research is the assessment of seismic exposure considering its spatiotemporal dynamics. A new method to develop exposure models for Chile is proposed. To test the method, the seismic exposure of Santiago is modelled for two different epochs. These models can be used as inputs for SRA and thus study the evolution of seismic risk in Santiago. Thus, this research constitutes a first step towards a time-dependent SRA for the city of Santiago. This tool will be used to further explore how urban planning decisions affect the evolution of risk in time.

Note that the models are meant to be representative at the city level despite having a finer resolution (i.e., census block or zone). This also acknowledges the limitations of census data for a high-definition exposure model which would be required to, for example, assess seismic risk in a census block within a specific *comuna*.

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