FIRE RISK ASSESSMENT OF HISTORIC URBAN AGGREGATES: AN APPLICATION TO THE YUNGAY NEIGHBORHOOD IN SANTIAGO, CHILE

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Abstract

Concern for the preservation of historic urban centres has become an issue of international relevance, not only because of their irreplaceable cultural value, but also because of their potential positive role for the sustainable development of countries. Several disasters have shown that historic centres are particularly vulnerable to natural and anthropogenic hazards. The constructive characteristics of buildings and the urban morphology in which they are inserted increase the fragility of their historic fabric and vulnerability in case of disasters. In this context, a comprehensive understanding of vulnerabilities of historic centres is an essential step for the definition and adoption of more effective risk reduction strategies.

This paper presents a fire risk assessment at the urban scale, using the Fire Risk Index (FRI) method. The selected case study corresponds to the historic centre of Yungay, located in Santiago de Chile. The case study is particularly relevant because of the high presence of historic heritage buildings and because between 2016 and 2021 it has been the scene of 21 structural fires, causing irreparable human and heritage losses.

Through the adaptation of the methodology to Chilean fire regulations and urban code, 443 unreinforced masonry buildings were evaluated. Finally, fire risk factors for the ignition, propagation, evacuation and combat phases were identified and mapped through the GIS tool. The results represent a valuable step towards the identification of large-scale risks in Chilean and Latin American historic urban centres, as well as providing the basis for the definition of risk mitigation strategies by decision-makers.

Keywords: Fire risk, Historical urban centres, Fire Risk Index method

1. Introduction

Recent fire events in urban areas, such as the 2020 Almeda Drive (Oregon), the 2014 Great Valparaiso (Chile), and the 2010 Manila (Philippines) are examples of almost complete devastation and irrecoverable losses in economic and heritage terms (Abatzoglou et al., 2021; Florentin et al., 2022; Reszka & Fuentes, 2015). Historic cities and neighborhoods are often more vulnerable to fire risks than new buildings due to: (i) intrinsic features of historic structures such as a high presence of combustible materials, compound vertical and horizontal elements, poor fire protection systems, substandard fire conditions, unplanned expansion, and constant alterations; (ii) the high density and difficult access to resources of the urban environment (e.g. narrow streets, limited fire engine access, shortage of open spaces); and (iii) social drivers as overcrowding of people in buildings, presence of elderly residents, and a deficient management of the government.

The Chilean territory has 146 conservation areas declared as "*Typical Zones*" with a rich cultural and architectural history, all prone to fire risk. During April 12th, 2014, part of the Valparaiso historic quarter and hills, declared a United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage Site (2003), were impacted by a major fire considered the greatest urban fire in Chilean history. The Great Valparaiso Fire caused 15 deaths, injured more than 500 people, destroyed more than 2,900 homes, burned more than 1,000 hectares, and displaced approximately 12,500 people (Reszka & Fuentes, 2015). In 2020, more than 134,000 emergency services were attended by Chilean firefighters, of which approximately 18,500 correspond to structural fires and electrical services (SBI, 2021). About 3,000 claims correspond to fires of electrical origin, equipment and /or electrical appliances in poor condition or overloaded (SBI, 2021).

Preservation of historical heritage is one of the priorities of the Ministry of Culture, Art and Heritage which ratified the "Convention on the Protection of the World Cultural and Natural Heritage" (UNESCO, 1972) in 1980, committing itself safeguarding those assets that present an exceptional interest and that must be preserved as elements of the world heritage for all humanity. Despite the fact that fire hazard is highly prevalent in historical residential housing, no comprehensive studies have been performed about fire risk in historic urban areas such as the Yungay's neighborhood in Santiago, which is the aim of our research. This neighborhood was selected because it has large patrimonial value, high population density, and suffered several modifications in time that make it particularly sensitive to extreme fires. While fire risk of historic urban areas has been widely assessed in Europe, e.g. Portugal (Vicente et al., 2010; Faria et al., 2012; Pais & Santos, 2015; Santana et al., 2007; Granda & Ferreira, 2019a), there are still very few studies in historic centers in Latin American (Granda & Ferreira, 2019b). Consequently, given the large and detailed database of households generated, this provides first archival value, and second, identifies the most critical aggregates of households, architectural types, and urban variables that condition and contribute most to this risk. This paper is only a starting point in a long run effort to assess more comprehensibly the fire vulnerability of aggregate buildings located in the historic centers of old cities. The article focuses on the application of a modified empirical procedure to the Yungay's neighborhood, used as a representative case of other historic quarters of foundational cities located along the central valley of Chile.

The majority of existing methods for fire risk analysis were not developed for cultural heritage assets; rather, they have been devised for new individual buildings, and are inappropriate for the analysis of aggregates of structures that typically form historical urban centers. Different studies (Baquedano Juliá & Ferreira, 2021; Salazar et al., 2021) present extensions of vulnerability indicators for fire risk assessment of cultural heritage, such as: (1) the Gretener method (Kaiser, 1979) in which fire risk is calculated as a ratio between potential hazard (like fire-load density) and protective measures; (2) the Fire Risk Assessment Method for Engineering [FRAME] (FRAME, 2008) that breaks down the risk calculations in three components associated with the building, occupants, and uses; (3) the Fire Risk Index Method for Historical Buildings [FRIM-HB] (Arborea et al., 2014), which is a preventive estimation approach, aimed to identify priorities for protection and preservation of built heritage; (4) the ARICA method (Coelho, 2010), based on the Portuguese code for fire safety, which allows to assess fire risk of individual buildings by a set of fire risk factors; and (5) the Fire Risk Index [FRI] (Ferreira et al., 2016), an adaptation of the original ARICA method to the urban-scale. Considering the relative advantages and disadvantages of these methods, the FRI method was selected herein because of its simplicity and larger accuracy with collected data. Despite its simplicity, the Gretener method was excluded because it does not allow differentiation between large areas and escape routes, ignores conditions of the electrical and gas systems as the eventual absence of fire protection walls, which are all factors that affect fire risk levels of aggregate historic buildings. In the case of the FRIM-HB and ARICA methodologies, both were intended for individual buildings, and hence, their applicability to the larger geographic scale of a neighborhood, as in the analyzed case study, would be unrealistic in terms of time and resources.

Therefore, this research uses the FRI method (Ferreira et al., 2016) to identify recurrent vulnerabilities in terms of the fire evolving stages: ignition, propagation, evacuation and combat for 443 Chilean historic buildings that belong to the Yungay's neighborhood in Santiago, Chile. The first result is a complete database of the architectural, constructive, structural, and urban features considering the 22 fire risk sub-factors of FRI analysis for each of the 443 historic buildings. Furthermore, the FRI method was adapted to specific Fire Safety Conditions of Chilean regulations and to the typological, constructive, and as-built structural characteristics of this heritage, which may be used, at least as a proxy, to extrapolate information to other historic centers in Central and Latin American regions. The modified-FRI-factors presents novel contributions in: (a) the assessment of the fire ignition risk, and the condition of the electrical system by looking at the extension cords and possible overloading of the basic installations together with the analysis of fire propagation risk; (b) categorization of fixed fire loads according to structural typologies and movable fire loads; and (c) categorization according to the building's use.

The results of the application of FRI-modified-form are used to assess the phases of ignition, propagation, evacuation, and combat fire-risk levels, as well as to estimate the fire risk index. To validate the results, fire-risk index results are correlated with the data of historical fires (from 2016 to 2021) to evaluate the ability of the index to identify areas of higher and lower risk. Moreover, the risk level for each of the fire evolution stages were cross-correlated with the urban and architectural layouts in order to identify the most vulnerable configurations. This work starts with a description of the study area, then moves into the fire-risk assessment, and the application and discussion of the results, to end with some of the conclusions. It is a first step and an input for the development of guidelines and recommendations for the conservation of cultural heritage in urban areas exposed to fire-risk by means of disaster risk mitigation measures and emergency plans developed with the participation of better-informed community and local authorities.

2. Study area: Yungay neighborhood

The city of Santiago has a well-defined matrix form configured as a radio-concentric spatial organization, whose shape originates from the historical foundational center, which progressively expanded radially toward the periphery. Historical formation characteristics of this urban structure were stabilized during the 19th century, when a clearly differentiated urbanization process became visible between the densification and monumentalization of the capital city center, and the emergence of new residential peripheries in the outer territory.

Located in the south-west area of the historic foundational center, the Yungay quarter (neighborhood) forms an urban continuity with other quarters of the city, the Brasil, Portales Park, and Concha y Toro, which generate a protected area of about 120 hectares (Figure 1).

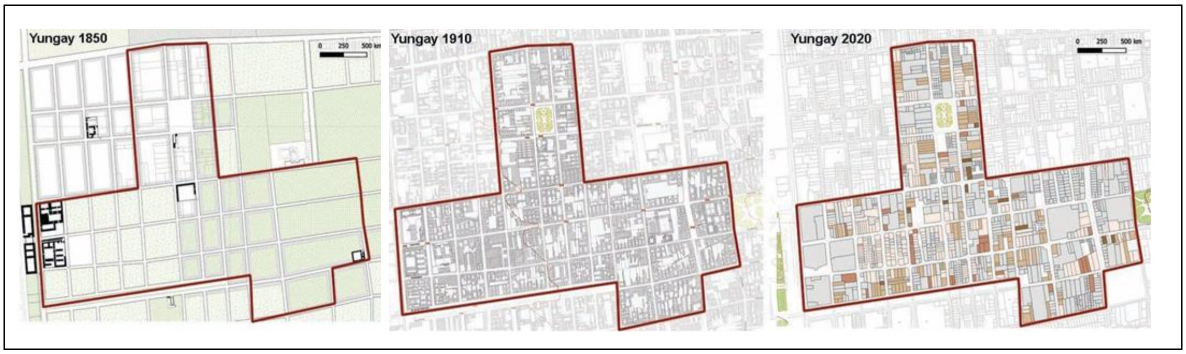

Figure 1: Schematic growth urban process of the Yungay neighborhood between 1850 and 2020

The neighborhood, a *Villa* distant and autonomous from the city center, was a project designed in 1839 on the agricultural land of *Quinta de los Portales* as a new residential periphery, originated from the urbanization and construction of one-story adobe houses arranged on the lots around inner courtyards. Today it is recognized as a consolidated physical structure and urban landscape. During the second half of the 19th century and the first decades of the 20th century, *Villa Yungay* was not only morphologically and typologically consolidated, but also integrated and connected as a neighborhood to the entire central downtown area of the Santiago commune. Around 1929, with the arrival of architect and engineer Karl Brunner, and his proposal to modernize the city of Santiago, a review process of the existing urban blocks began, deriving from the criticism that modern urbanism raised about the efficiency of the macro compact urban blocks (i.e., closed urban block [C]). However, as a consequence of the operational difficulties of the application of the *Official Urbanization Plan of the Santiago Commune*—due to the modification of the line and the opening of interior streets, the lack of incentives for private development in its densification and renovation, and the high costs of expropriation—the sector remained unchanged during the 50 years that the plan was in effect (Rosas et al., 2015). In 1989 the *Official Urbanization Plan of the Santiago Commune* was revoked with the objective to impose a dynamic speculative growth by typological substitution of low-rise housing attached to the block module, for new high-rise buildings composed of blocks and isolated towers attached to the lot and absent from the rules of the block. In this urban context, the affected neighbors reacted against the destruction of this consolidated quarter, being declared a Typical Zone. The Yungay neighbourhood is now considered one of the most representative historical zones of Santiago as evidenced by the declaration of *Typical Zone* (Decree No. 43, 2009).

Due to the constant growth and reuse of this urban area (Figure 1: Schematic growth urban process of the Yungay neighborhood between 1850 and 2020

), the Yungay quarter is now composed of heterogeneous urban blocks considering an architectural, constructive, and structural point of view. As for the great part of historical centers and neighbourhoods in Chile, the Yungay's urban shape is the result of an accelerated and dispersed growth process characterized by demolitions, modifications, alterations and reconstructions to the urban plot (Bramerini & Castenetto, 2014) due to the new dynamics of urbanization, and damage caused by several past earthquakes and fires. As discussed in the next sections, the alterations of the urban blocks have important direct and indirect impacts on the structural response, fire risk, and socio-demographic vulnerabilities of **single buildings**, making them more or less vulnerable.

2.1. Urban layout analysis

The first Typical Zone of the Yungay's quarter presents a regular plot of orthogonal streets and 43 rectangular urban blocks of different dimensions with a territorial extension greater than 370 hectares and a total of 1,229 structural units. The largest urban blocks (~85m wide and 180-195m long) are located in the north area (up in Figure 2), between the San Pablo and Cathedral streets, while the smaller blocks (~85m wide and 85-125m long) are in the south area, between Catedral and Portales streets. As detected in (Rosas & Parcerisa, 2017), the Yungay neighbourhood has permanent features (e.g. street and façade are the same, the private is developed inside the house, and the tendency to the horizontality of the heights), and parcelled and metric structures of the lots that constitute compact urban blocks, giving identity and character to this extensive and heterogenous urban area.

In the Typical Zone, four main traditional construction typologies are identified: (a) 30% of buildings are adobe masonry with mud mortar, and wooden roof and floors (Pager construction type A1, according to Jaiswal & D'Ayala, 2011 taxonomy); (b) 11% is unreinforced brick masonry with lime mortar (Pager construction type UFB3, Jaiswal & D'Ayala, 2011); (c) 5% is *adobillo* structures, timber frame with shaped earthen blocks (about 15 x 60 x 10cm); and (d) 11% of *clay-brick partitions* are wooden frames with infill walls made of brick masonry. A total of 62% of these structures is one-storey, 34% is two-stories, and the 4% is three or four-stories.

According to morphological features of the urban area, i.e. shape and composition of the blocks, three types of urban blocks are identified (Saavedra & Starkman, 2000) as shown in **Figure 2 (a) and (b)**: (i) closed [C]; (ii) penetrated [P]; and (iii) divided [D]. Each block combines different sizes: (a) a small lot [S] has 6-9m wide façades and 8-25m long transverse walls; (b) a large lot [L] has 7-15m wide façades and 25-40-60m long transverse walls; and (c) a deep lot [D] has facades 7-15m wide and 25-40-60m long transverse walls.

Figure 2: (a) Matrix Yungay urban structure: block types in columns (closed, penetrated, divided); and lot types in rows (small, large and small lots, and deep and small lots); (b) Yungay urban structure compound by block types (closed, penetrated, divided); and lot types (small, large and small lots, and deep and small lots); and (c) photos of block types (closed, penetrated, divided).

The *closed block* [C] (Figure 2b) has façades contiguously arranged and with a direct building access from the public area. They are characterized by heterogeneous Structural Units (SUs) of different ages, with or without continuity, and with an elongated rectangular-shape, i.e.: (a) diachronic (built in different historical context) and (b) synchronic (built in the same historical context). The adjacent SUs are interconnected by wall-to-wall and roof-to-wall connections, depending on their evolutionary process. The Yungay's neighborhood has 29 closed blocks corresponding to the 67% of blocks. *The penetrated blocks* [P] derive from a closed block alteration due to the introduction of *Cités*. *Cités* correspond to a group of aggregate dwellings (land occupation between 70-90%) that fragments a single deep lot with several houses organized around one central or lateral alley of width 1.5m to 6m. This architectural typology emerged in the 20th century in response to housing problems with the intention of applying new modern ideas of hygiene and to densify the existing areas instead of building new ones. Currently, the neighbourhood has 8 penetrated blocks and 10 *Cités* (Figure 2Figure 5: b), of which five are deep-small lots [P/D+S] and three are large-small parcels [P/L+S]. The *divided blocks* [D] are formed by the division caused by one or two complete streets. There are 4 divided blocks as shown in Figure 2b; one is a deep-small parcel [D/D+S] and three are small lots [D/S].

2.2. Structural unit [SU] typologies

The most common lot types are: (1) *deep rectangular* lots of courtyard houses (7-8 x 50m, 12 x 45m, 15 x 60m and 16 x 40m), generally part of the original block layout; (2) large *rectangular or square* lots, destined to equipment such as schools, churches, convents and hospitals covering an area corresponding to the entire urban block (as for blocks 9, 20, 29, 30 and 31 with dimensions ≅ 82 x 110m, Figure 2b), or intended for new reinforced concrete (RC) residential structures erected after demolition (e.g., blocks 15, 16, 35, 40, with dimensions 42 x 120m, 70 x 70m, Figure 2b); and (3) *small* SUs (6x8m, 9x20m and 15x21m), resulting from the increase in land price and density during the 19th and 20th centuries, as shown in blocks 18, 22, 23, 24, and 35 (Figure 2b).

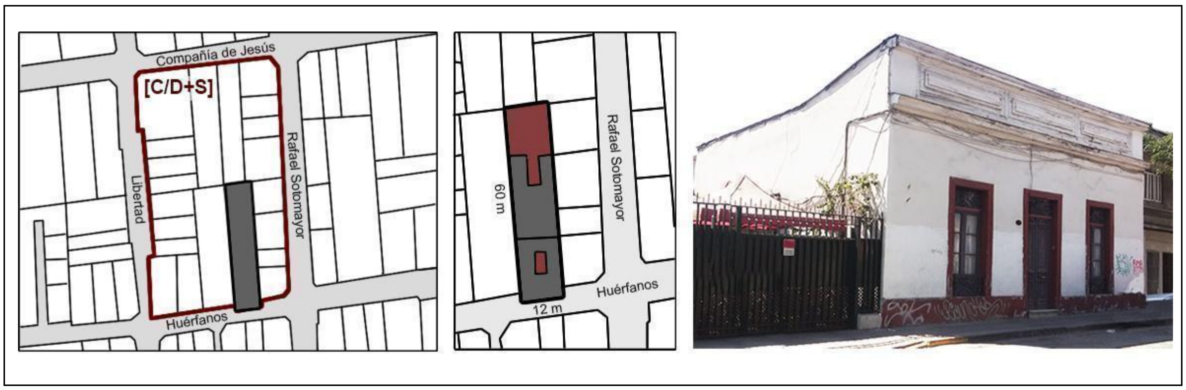

Figure 3: Example of colonial derivation style: Huèrfanos 2729, in a closed block (n° 25) with deep and small lots.

According to Palazzi et al., 2022, 60% of Yungay's SUs are ordinary buildings with continuous one- or (rarely) two-storey façades with an elongated plan aspect ratio that includes a backyard—with north-south and east-west orientations—a shed-roof with mono-pitch wooden traditional trusses, and a flat ceiling. The general distribution is defined in Palazzi et al (2022) as Colonial Derivation style (CD) including popular classicism and republican architectures (Figure 3). The well-done interlocking of the masonry between the main and adjacent façades, and the façade and the orthogonal walls, shows that CD dwellings had synchronic growth. Nevertheless, the original in-plane and in-height alignments are, in some cases, altered by urban growth processes which generated remodelling in the internal spaces, enlargements, and addition of a new storey, causing structural discontinuities. These alterations have direct implications on the seismic and fire vulnerabilities of historical SUs. New insufficiently spaced aligned openings, for example, can enhance the spread of fire between floors depending on the distance between the two or more overlapping windows and/or doors. Exterior walls built in unreinforced masonry have good fire behaviour; however, this performance can be compromised due to a poor conservation state.

Between the mid-19th to the early 20th-century, the Classical style (CL&Va) was introduced (Figure 4). New multi-storey buildings in Neoclassical, Neo-Baroque, and other eclectic stylistic expressions were built in mixed techniques with adobe and brick masonry, adobe and wood, and brick-wooden walls. This style completely overcame colonial influence, changing the physiognomy of the neighborhood. About 40% of the historical buildings in this neighborhood are CL&Va 2-storey structures (rarely 3-stories), which are a variant of the colonial continuous-façade typology with an elongated rectangular layout 10-12m wide and 50-60m long, oriented north-south or east-west with one or two back-yards, a gable-roof with timber king-post trusses with a collar tie, and a timber flat ceiling. Two constructive typologies of CL&Va can be identified: (i) CL&Va_T1 resulting from the addition of a story above the original roof level (including mezzanines). Their first floor was built in adobe or brick masonry, and the second one is characterized by mixed techniques (*tabique*, wood structure with oak piers of 15x15cm and adobe in tambourine, or *adobillo,* defined by timber piers with earthen blocks about 15x60x10cm; and (ii) CL&Va_T2, which are buildings belonging to urban aggregates built at the same time and with homogeneous construction techniques. Generally, this is the case of *Cités* built with clay-brick masonry (wall thickness ~0.7m), where each aggregate structural unit has a good lateral bond between adjacent and orthogonal walls.

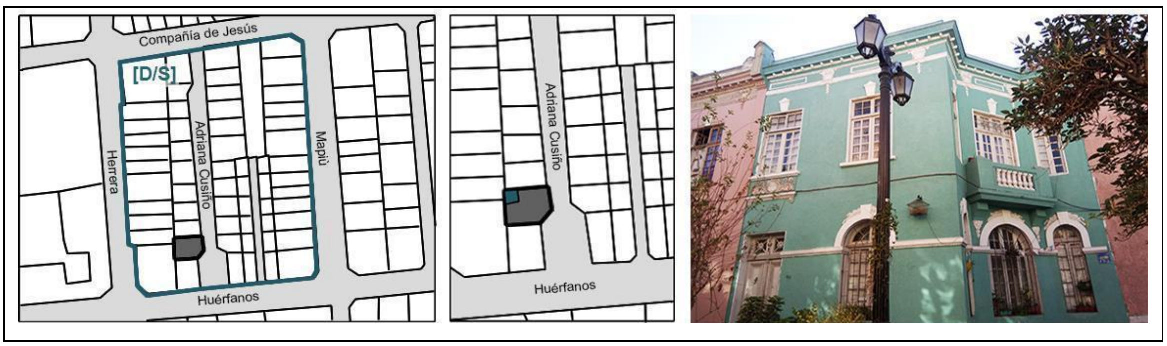

Figure 4: Example of classicist style: Adriana Cousiño cité 320, in a divided block (n° 22) with small lots

While in the case of 2-storey CL&Va_T1 buildings, the absence of compartment walls and shared partitions between adjacent SUs favour fire spreading; for the 2-storey CL&Va_T2 structures, the masonry partition walls help contain the spread of fire and allow people to reach other areas of the building with better chances to exit. In CD buildings, the modifications, remodelling, enlargement, and addition have direct implications on the fire vulnerabilities, thus increasing the risk of spread and propagation. Recent fires in this neighborhood have shown the high vulnerability of CL&Va_T1 buildings. In fact, the 11.09.2021, 17.10.2020, and 07.10.2020 fires generated in a single residential unit, quickly expander over 5-8 adjacent properties affecting between 40 to 113 people including children. Although the rapid development of fires is extremely dangerous for rescue actions, the prompt evacuation and combat observed during the last fires has been effective, recording less than 1% (0.6%) fatalities in the last 21 fires (4 people).

Between 2016 and 2021, 21 Yungay's structural fires in historical buildings (Figure 5) caused losses of 17.4% of its building heritage. About 77 historical properties were irreparably damaged by fires, more than 580 people lost their homes or suffered physical damage, and as said before, 4 people died. The inherent fire exposure and risk of historical buildings due to their morphology, construction systems, and materials, are dramatically increased by socio-demographic vulnerabilities that negatively impact resilience.

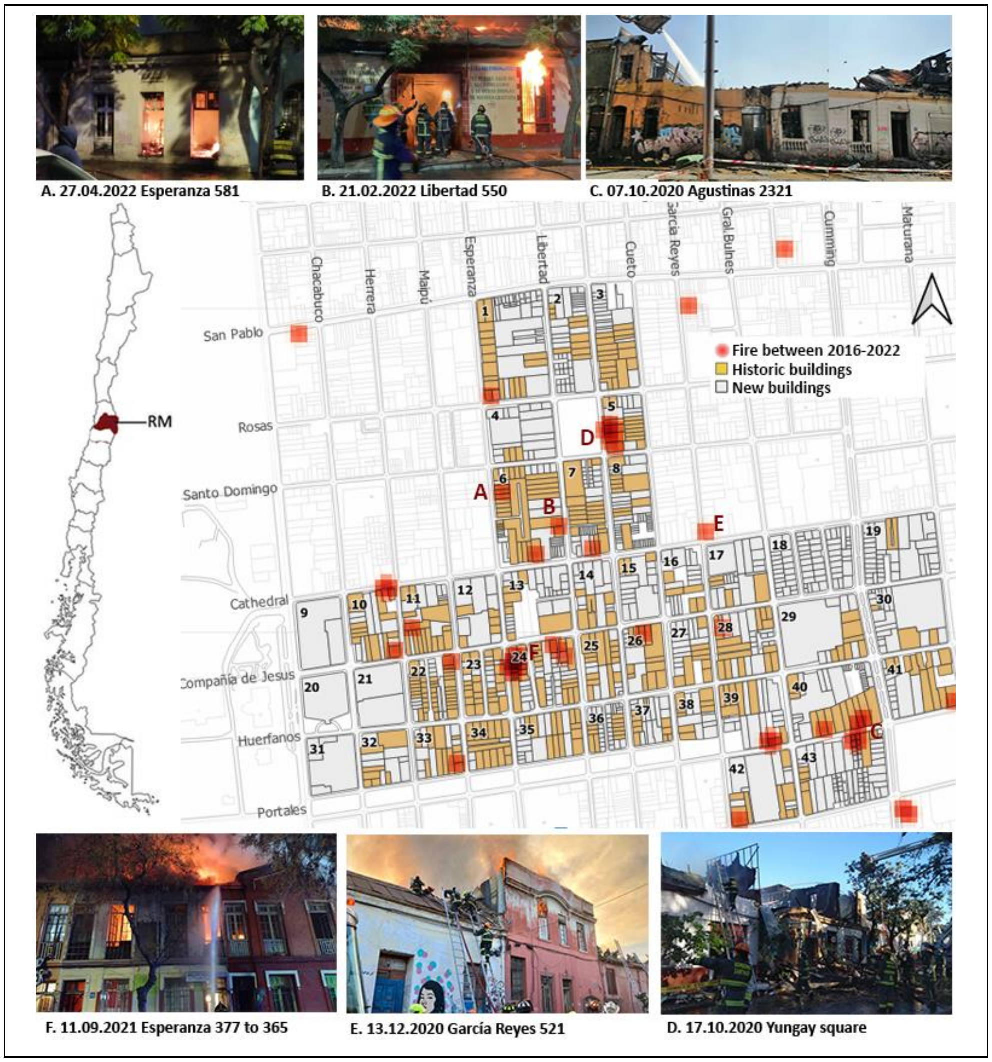

Figure 5: Fires of historical buildings of Yungay's quarter in Santiago, Chile (Metropolitan region, RM), between 2017 and 2022. (A) 26.04.2022 fire in Esperanza 581; (B) 21.02.2022 fire of Libertad 550; (C) 07.10.2020 fire of Agustinas 2321; (D) 17.10.2020 fire of Yungay's square; (E) 13.12.2020 fire of Garcia Reyes 521; and (F) 11.09.2021 fire of Esperanza 377-365 (SBI, 2021).

3. Fire risk assessment of Yungay Quarter

3.1 Inspection Procedure and Database Construction

In order to develop a complete database to assess the fire risk vulnerability, a stock of 443 SUs corresponding to aggregate unreinforced masonry buildings of the Typical Zone were identified and directly inspected between April 2020 and November 2021. During this period, two instances of community participation were carried out by *Vecinos del Barrio Yungay* (neighbors of the Yungay's quarter), with the aim of presenting the research and requesting to complete a questionnaire to collect some data necessary for risk analyses. A total of 384 questionnaires were obtained and processed such as the state of conservation of the electricity system, the number of inhabitants, the number of extension cords and households used, and the type of heating system. This information was supplemented with the database of constructive, architectural, and urbanistic parameters of the Yungay´s Sus. The database was processed in a GIS software, using the Q-Geographic Information

System open-source suite (QGIS), which allows combination of geo-referenced graphical data (vectorized information and orthophoto maps) with building parameters. Each polygon corresponding to a building, was linked with surveyed features allowing for visualization, selection, searching, layering and editing of building information. All data processed with the GIS tool could be updated at any time and will be openly available.

3.2 Proposed Methodology for Fire Vulnerability Assessment of Historic Aggregate Buildings

In this research, a modified version of the FRI method was selected to assess fire vulnerability of historic aggregate buildings. The FRI method was adapted to specific typological, constructive, and structural characteristics of the Chilean historic buildings, which are representative of several other South American historic urban centers. Following the conceptual basis of the ARICA method, the FRI method is composed of two global factors: a global risk factor (*FGR*) and a global efficiency factor (*FGE*), which together form the Fire Risk Index (FR_I). As shown in Table 1, the *FGR* is composed of three additional factors related to fire ignition (SF_I), fire propagation (SF_P) and evacuation (SF_E), whereas FGE is related to the fire combat factor (SF_C). The FRI is obtained by taking the quotient between the weighted average of the four factors already mentioned and a Reference Risk Factor (FR_R) that considers the type of building use, i.e.

$$FR_I = \frac{(1.20 \ \cdot SF_I + 1.10 \cdot SF_P + SF_E + SF_C)/4}{FR_R} \quad (1)$$

Table 1:Fire Risk Index method: Global factors and partial factors identified in Ferreira et al., 2016 *modified or integrated in this research. Score values are according to Ferreira et al., 2016.*

	Sub-factors	Partial factors	
Global risk factor (FGR)	Fire ignition (SF_I)	Building conservation state (PF_{I1})	
		General electric installations (PF_{I2})	**(Modified partial factor)**
		Gas installations (PF_{I3})	
		Fire load nature (PF_{I4})	
		Type of heating system (PF_{I5})	**(New partial factor)**
	Fire propagation (SF_P)	Gap between aligned openings (PF_{P1})	
		Safety and security teams (PF_{P2})	
		Fire detection, alert and alarm (PF_{P3})	
		Fixed fire loads (PF_{P4})	**(New partial factor)**
		Fire compartmentalization (PF_{P5})	
		Movable fire loads (PF_{P6})	**(New partial factor)**
	Evacuation (SF_E)	Evacuation and escape routes (PF_{E1})	
		Building properties (PF_{E2})	
		Evacuation correction factor (PF_{E3})	
Global efficiency factor (FGE)	Fire combat (SF_C)	Building external fire combat factors (PF_{C1})	
		Building internal fire combat factors (PF_{C2})	
		Security teams (PF_{C3})	

Table 2: Reference Risk Factor, FR_R, for Different Types of Building Use. Source: (Ferreira et al., 2016)

Reference risk factor	**Residential**	**Service or industrial spaces, libraries and archives**
FR_R	0.19 + 0.25 × *Fc**	0.10 + 0:25 × *Fc**
Fc is a correction factor that can assume the values of 1.10, 1.20 or 1.30, for a building of<3, <7, and 7 + floors, respectively.*		

Factors SF_I and SF_P are preceded by two scalar values, 1.20 and 1.10, respectively, which have been previously proposed and account for the more significant role of ignition and propagation in the overall fire risk process (Ferreira et al., 2018). According to Ferreira et al. (2018), the FR_R is the reference risk factor, which is determined from the type of building use (Table 2). The modified and new FRI-factors proposed in this work include the partial ignition risk factors C_{ee}—the condition of the extension cords and the possibility of overloading the basic installation— the partial propagation risk-factors, PF_{P4}—fixed fire load categorization according to structural typologies (CD or CL&Va styles) and PF_{P5}, which accounts for the categorization of movable fire loads according to the building use. A more detailed definition of each of these partial factors is presented next.

- **Fire ignition risk (SF_I)** of aggregate historical buildings requires values of four partial factors. Based on the peculiarities of Chilean dwellings shown by the results of a previous statistical study on Chilean fires between 2010 and 2020 undertaken by WTW-Chile (2020), some new ignition risk parameters related to the general condition of electrical installations (PF_{I2}), and a partial factor associated with the type of heating system (PF_{I5}) were proposed. Thus, fire ignition risk $SF_I = \sum_{i=1}^{5} \widehat{PF_{I,i}}$ is computed considering five partial factors as shown in the Appendix (Table A 1). The conservation state of the SU ($PF_{I,1}$) is based on the condition of the façade, lateral walls, and roof structure, and analysed according to Ferreira et al., 2016. The presence of a degraded, or fractured material, may expose other materials with higher combustibility and reduce fire compartmentalization (Salazar et al., 2021). Based on the state of conservation of these three structural elements, the value of $PF_{I,1}$ for the SU is "good" when none of the three elements show pathologies that affect their monolithicity (e.g., deep cracks, disconnection between structural elements, disconnections at the edges). On the contrary, when one of the structural elements presents a pathology that impedes to consider it as monolithic, $PF_{I,1}$ is "intermediate", while if the pathology involves more than one structural element, $PF_{I,1}$ is evaluated as "bad".

  The general condition of electrical installations ($PF_{I,2}$) is characterized by the basic electrical system (C_{be}) and electrical extension cords (C_{ee}). Because fire typically originates in conductors (49%), electronic devices and household appliances (19%) located in bedrooms (21%) and kitchens (15%) (WTW-Chile, 2020) typically overload power circuits heating bars and electrical extension cords, which creates an additional vulnerability parameter in the original FRI method. All electrical systems installed prior and not being replaced after the existence of this standard, are classified as "not-normal". Systems that are partially, or fully replaced after the application of this standard by a professional certified by the Chilean Superintendence of Electricity and Fuels (SEC), are classified as "partially normal" or "normal", respectively. Heating bars are classified as follows: if certified electrical extension cords (with SEC seal) are used without the possibility of overloading the electrical circuit, this parameter equals 1.00. On the contrary, if non-certified heating bars (without the SEC seal), and/or various household appliances that may lead to overloading the electrical circuit are detected, the value equals 1.5.

The gas system partial factor ($PF_{I,3}$) depends on the type of gas supply, which could be pipeline gas, outdoor or indoor cylinder installations in a ventilated or unventilated location. The partial factor related to fire-load nature ($PF_{I,4}$) is defined by the product of the combustibility coefficient (Ci) and the activation coefficient (Rai) of materials stored in greater quantity and with considerable risk (Vicente et al., 2010). Finally, the type of heating (fuel) system ($PF_{I,5}$) such as paraffin (kerosene), liquid gas, wood or pellets, was added to the original method, since it represents an important characteristic which affects the vulnerability factor according to the report of structural fire services (SBI, 2021).

- **Fire propagation risk (*SF_P*)** results from the average of five factors $SF_P = \sum_{i=1}^{5} \widehat{PF_{P,i}}$ as shown in the Appendix (Table A 2). Regarding $PF_{p,1}$, defined as the "number of gaps between aligned openings", Chilean regulations (Decree No. 47, 1992) do not include the distance between vertically aligned openings, so in this case a minimum distance of 1.10 m is used, as established in the A.R.I.C.A method (Coelho, 2010). The second partial factor, $PF_{p,2}$, refers to the existence of a safety and security team, defined as a group of individuals who are responsible for communicating fire ignition. While other international codes require the existence of these groups, the Chilean fire safety standard does not establish a criterion. However, some residents of the neighbourhood have independently organized security teams (e.g., neighbours of the *Maipú* street). This team was instrumental in the efficient combat of the latest fires, as they quickly informed the fire brigade, enabling response times to be reduced. The fire detection alert and alarm factor, $PF_{p,3}$, considers the use of active protection systems, such as installations connected to sensors or automatic detection devices. According to the "Detection and Alarm System" specified in the Chilean General Urban Planning and Construction Ordinance (Art. 4.3.8 and 4.3.22), fire detection alert and alarm systems are only mandatory in 5-story or higher structures with an occupational load greater than 200 people and in 3-story, or higher buildings destined for people's stay, such as non-ambulatory areas in hospitals and medical residences, or places aimed to detention or confinement. Moreover, the regulation indicates that an automatic fire detection system is required for Fire Prevention and Protection in Workplaces—Art. 52 (Decree No. 594, 2000)—which store or handle hazardous substances (NCh2120/4.Of98, 1998).

Herein, fire-load is defined as *the heat energy that could be released per square meter of a floor area of a compartment of a storey by the complete combustion of the contents of the building and any combustible parts of the building itself* (Suresh, 2015). Two types of partial factors related to fire-load are considered here, the $PF_{p,4}$ that related to fixed components, and the $PF_{p,5}$ related to movable fire loads. The $PF_{p,4}$ considers combustible materials of the structural and non-structural elements of the building. According to the Chilean standard for *Fire prevention in buildings* (NCh1916.Of99), the fire load densities of the SUs of Yungay were calculated (Table A 2**Error! Reference source not found.**) to identify SU typologies that could increase the risk of fire propagation.

Given that other historical centers may have different SU typologies, and hence different fixed fire-loads, it is proposed to replace the partial factor $PF_{p,4}$ with a simplified version $PF_{p,4s}$ evaluates the existence of passive components that protect certain areas of a building and the structure from the effects of fire for a time window, allowing evacuation of occupants. Because estimating the fire resistance of each structural element is a complex task, the FRI method proposes a simplified assessment considering only four building components: structural walls, interior walls, floors, and openings. The consideration of walls was incorporated herein since it is one of the main factors that delays the spreading of fire to adjacent buildings.

According to the Chilean Detection and Alarm System Ordinance (Art.4.3.3), fire protection must be designed depending on building types and construction elements. Most buildings in Yungay are constructed of adobe and brick masonry, and therefore comply with the required fire resistance, with the exception of a firewall present only in some buildings. Buildings with firewalls on both sides imply a partial factor 1.0. For other buildings, we verify the assumptions for the calculation of the partial factor base on the other construction elements (see Table A 2).

Like many historic urban centers, most buildings in Yungay have wood floors, ceilings and openings (Ferreira et al., 2016; Granda & Ferreira, 2019a; Vicente et al., 2010). Wood is the most fire sensitive material, with all other materials having higher fire resistance. Although adobe and brick masonry walls have a good fire performance, their preservation state may affect resistance. As shown in Table A 2, factors that increase the risk of propagation are verified for each element with an upper limit value of 2.00.

The factor $PF_{p,5}$ evaluates the movable fire load (q_{mf}) depending on the material with the largest quantity present in a building. According to **(Claret & Andrade, 2007; Suresh, 2015; and Su at al, 2019**) to normalize movable fire load value, the q_{mf} (MJ/m^2) is divided by 1000 (obtaining a lower limit of 0.10 and an upper limit of 5.00).

- **Fire evacuation risk** (*SF_E*) is evaluated through three partial factors presented in the Appendix (Table A 3) based on this expression $SF_E = \sum_{i=1}^{3} \widehat{PF_{E,i}}$. The first factor $PF_{E,1}$, evaluates the features of horizontal and vertical evacuation routes, number of exits, and the presence of emergency signs. Since no requirements for escape routes are present in the Chilean regulations, herein the FRI method prescriptions are adopted (Table A 3). The partial factor $PF_{E,2}$, related to building properties, integrates some partial factors previously assessed as security teams ($PF_{P,2}$) and fire detection, alert and alarm ($PF_{P,3}$), and a new partial factor corresponding to the performance of security drills ($PF_{e,2}$). Based on the FRI method, an evacuation correction factor ($PF_{E,3}$) is applied if any of the building properties assessed in the partial factors of $PF_{E,1}$ and $PF_{E,2}$, does not comply with the regulation requirements. For 3-stories or less, 7-stories or less, or higher than 7-stories, $PF_{E,3}$ assumes the values 1.10, 1.20 and 1.30, respectively (Vicente et al., 2010) (Granda & Ferreira, 2019a). When the conditions of $PF_{E,1}$ and $PF_{E,2}$ are not verified, $PF_{E,3}$ increases the values of these terms.

- Last, **fire combat conditions (SF_C)** are evaluated with three partial factors presented in the Appendix (Table A 4) and given by the expression $SF_C = \sum_{i=1}^{3} \widehat{PF_{C,i}}$.

  The first partial factor $PF_{C,1}$ is related to the external fire combat conditions (PF_{C1}) depending on the following criteria:

  - Accessibility of the building ($C_{1,1}$): This criterion considers the physical characteristics of the street used to access the building (width, clear height and slope).
  - Hydrant maximum distance ($C_{1,2}$): In Chile, the hydrants are regulated by different legal and regulatory provisions, with regard to installation, technical and operating requirements—Regulation of the General Law of Sanitary Services (Decree No. 1199, 2004) and the General Ordinance of Urbanism and Construction (Decree No. 47, 1992). The factor considers the distance between the nearest fire hydrant and the building and whether the building has a fire reel. The regulation on fire hydrants (NCh1646.Of98) recommends a distance between hydrant and the farthest building (maximum distance) as measured through streets and passages depending on building typologies. For isolated or attached buildings (with less than 2 SUs), the maximum distance is 150 m; for attached buildings of 3 to 50 SUs (houses, offices, commercial premises, etc.) the maximum distance is 100m; while for continuous buildings with more than 50 SUs the maximum distance is 50m. In FRI analysis, the value of the External Fire Hydrant parameter is equal to 1.00 if the standard requirements are satisfied, while equal to 1.5 when it does not.
  - Reliability of the existing hydraulic network ($C_{1,3}$): In addition to the maximum hydrant distance, the main requirements considered for hydrant effectiveness are fire volume and static pressure, which are computed as follows:

    (i) Fire volume. The minimum value of water volume supply for hydrant operation (Vp_{min}), regulated by Chilean standards (NCh1646.Of98; NCh691.Of98) is:

    $$Vp_{min} = max\,\{Vre + Vf;\ Vre + Vri\}$$

    where Vre is the regulation volume, equal to a minimum of 5% of the maximum daily volume; Vf is the fire volume, determined by the water flow rate of the hydrants in use times the duration of the incident and a minimum 2 hour incident should be considered (with a flow of 16 L/s for each 100mm diameter hydrant, equal to 259 GPM minute, a unit of measurement used by Chilean firefighters; and the number of hydrants in simultaneous use indicated in the Table 3); and Vri is the reserve volume (equal to 2 hours of the daily flow of maximum consumption foreseen for towns with up to 200,000 inhabitants supplied, and 4 hours for more than 200,000 inhabitants).

Table 3: Number of fire taps in simultaneous use. Source: (NCh691.Of98, 1998)

Population in thousands of inhab.	N° hydrants in simultaneous use	Fire volume m^3
until 6	1	115
> 6 - 25	2	230
> 25 - 60	3	346
> 60 - 150	5	576
> 150	6	690

*(ii) Pressure***.** The minimum hydrant pressure at ground level, calculated with dynamic pressure conditions, must be equal or greater than 49.03 kPa. Static pressure of the hydrant is equal to a minimum of 0.15MPa. In a place with more than 10.000 habitants, or in the city centre, two taps used simultaneously must have a minimum pressure of 0.05 MPa with a minimum flow of 16L/s. In fire risk index analyses (Ferreira et al., 2016; Granda & Ferreira, 2019b, 2019a), the water supply parameter (depending on fire volume and static pressure) is usually assumed to be equal to 1.00. In the specific case of Yungay, the history of fires show that we require a water fire volume greater than 259 GPM per minute as imposed by the regulation (NCh1646.Of98). In fact, a fire load of 400 Mcal/m^2 in historical buildings need about 1,080 GPM to be extinguished. Because all the hydrants were designed according to the same standard of water supply, and with an underestimated pressure and volume, this parameter is assumed here equal to 2.00.

- Internal fire combat conditions ($PF_{C,2}$) is related to the firefighting means present in buildings, such as manual fire extinguishers, fire networks, dry or wet columns, automatic extinguishing systems, and reliability of the water network. The Chilean Standard only requires the presence of manual extinguishers in the workplace if a risk of fire exists, due to the nature of construction materials or the nature of work. If a high potential fire risk exists, given the nature of the materials present, it may require the installation of an automatic fire extinguishing system -Art. 52 - (Decree No. 594, 2000). The standard also establishes the number of extinguishers and their distribution according to the surface area to be covered, indicated in Table 4. In residential buildings with at least one fire extinguisher, the FRI method proposes a value of 0.9, or 1.0 otherwise. In the workplace, the number of fire extinguishers should match the requirements of the Chilean Standard. The existence of additional fire protection systems, such as wet fire sprinkler systems, dry pipe systems and pre-action systems can be also considered by the adoption of subtraction coefficients equal to -0.25and up to -0.75 (Vicente et al., 2010, Granda & Ferreira, 2019a, 2019b).

Table 4: The minimum extinction potential per coverage surface and safety distance. Source: (Decree No. 594, 2000)

Covering surface maximum per extinguisher (m2)	Minimum extinction potential	Maximum distance from transfer of the extinguisher (m)
150	4 A	9
225	6 A	11
375	10 A	13
420	20 A	15

As for evacuation risk assessment and combat risk, the existence of a “Safety and security teams” is associated with the partial factors $PF_{C,3}$ and $PF_{P,2}$, respectively. Indeed, $PF_{C,3}$ should assume the same value as considered for partial factor $PF_{P,2}$ (Table A 2).

4. Application and discussion of results

The Fire Risk Index results are mapped in Figures 6, 7, 8, 9, 10 and 11, and the values summarized in Table 5 and Table 6. It shows the overall level of fire risk associated with each historical SU of the study area, and identifies unsafe and more critical buildings, considering four levels of risk as defined earlier by Granda & Ferreira (2019a, 2019b) according to the work of Renfroe & Smith (2016):

- Low risk level, or acceptable risk, implies $0.60 \leq \text{FRI} \leq 1.00$. The implications are to incorporate measures to further reduce or mitigate fire hazard by implementing security and mitigation upgrades in the structure (green color);
- Moderate risk level, or acceptable risk over the short term, implies $1.00 < \text{FRI} \leq 1.30$. In that case, one has to reduce and mitigate fire hazards by including actions in future plans and budgets (orange color);
- High risk level, or unacceptable risk, implies $1.30 < \text{FRI} \leq 1.65$, which requires the implementation of measures to reduce and mitigate fire hazard as soon as possible (red color); and
- Extreme risk level, or totally unacceptable risk, implies $1.65 < \text{FRI} \leq 2.0$. The implication is to enforce immediate measures to reduce and mitigate fire hazards (purple color).

As discussed in detail below, buildings classified as being classified into high or extreme risk present one or more than the following characteristics: (i) obsolete and overloaded electrical installations; (ii) significant fire loads and adjoint roof and *tabique* structures; (iii) absence of firewalls and compartmentalisations; (iv) lack of alert and alarm systems; (v) inefficient hydrant systems in terms of volume, pressure and maximum distance; and (vi) restricted or even inaccessible evacuation routes.

The analysis of results shows that 39% of the building stock (173 buildings) presents moderate fire risk, while about 61% (270 buildings) has high levels of risk. No buildings resulted on a lower level of risk. In summary, there are no buildings that comply with the requirements of the Chilean fire safety regulations currently in force, which means that the study area is currently in an ‘‘unsafe’’ situation.

A statistical summary of the partial factors (PF_I, PF_P, PF_E, PF_C) and the value of the Fire Risk Index (*FRI*), including their associations can be found in Table 5 and Figure 6. These variables exhibit low variability, generally centered around intermediate and high risk, which PF_I (ignition risk) being the only variable spanning low risk levels. Regarding correlations, all variables are positively correlated, meaning that the greater the value of a variable, the greater the value of other correlated variables. The correlations among the partial factors, however, are not large (<0.54), which show that they probably capture different phenomena. With regards to the Fire Risk Index (*FRI*), the correlations it has with the other variables are not surprising, because its functional dependency is practically a linear combination of them.

Table 5: (a) *Statistical summary of the partial factors (PF_I, PF_P, PF_E, PF_C) and Fire Risk Index (FRI) obtained for the units considered in this study (average, standard deviation σ, Min, Median and Max of data set).;* and (b) *correlations among the Fire Risk Index (FRI) and the partial factors (PF_I, PF_P, PF_E, PF_C).*

	Average	σ	Min	Median	Max
PF_I: Ignition Risk	1.46	0.15	1.06	1.47	1.83
PF_P: Propagation Risk	1.71	0.13	1.25	1.72	2.12
PF_E: Evacuation	1.33	0.13	1.24	1.24	1.93
PF_C: Fire Combat	1.48	0.17	1.38	1.38	2.00
FRI: Fire Risk Index	1.31	0.08	1.06	1.30	1.60

	FR_I	PF_I	PF_P	PF_E	PF_C
FR_I	1.00				
PF_I	0.44	1.00			
PF_P	0.36	0.20	1.00		
PF_E	0.46	0.18	0.53	1.00	
PF_C	0.36	0.38	0.54	0.44	1.00

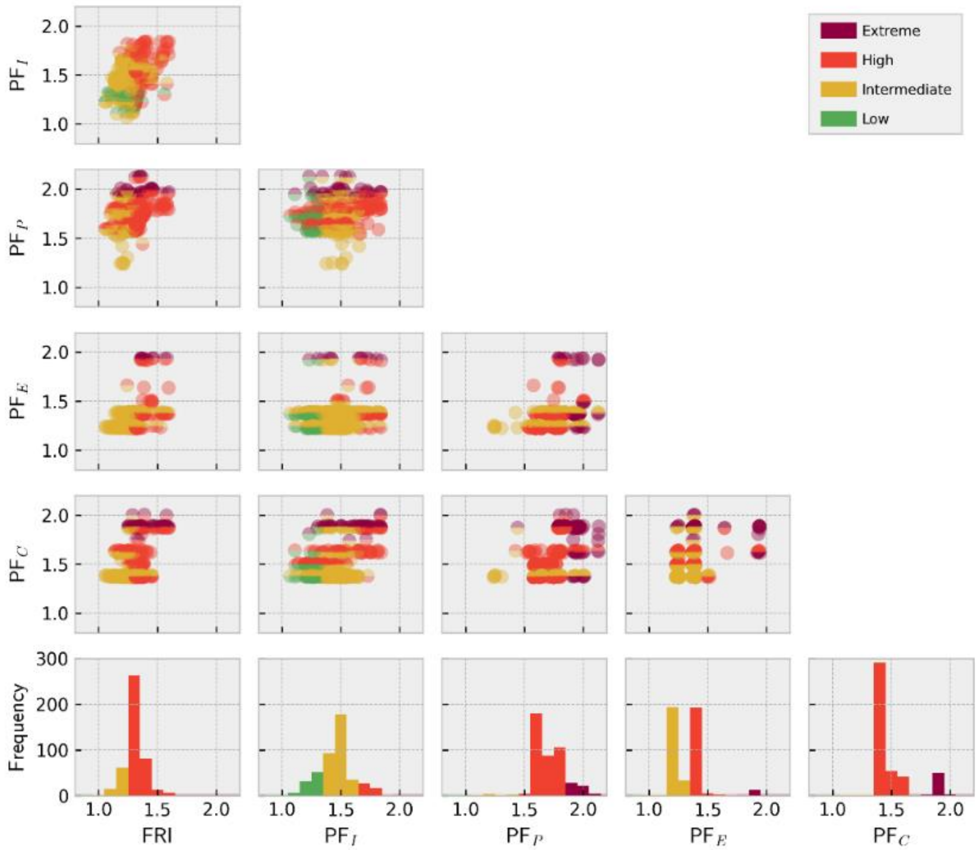

Figure 6: *Scatter plots and histograms depicting the distribution and cooccurrence of the Fire Risk Index (FRI) and partial factors (PF_I, PF_P, PF_E, PF_C) in the units considered in this study. Colors depict the levels of risk (low, intermediate, high and extreme), whose thresholds are defined differently for each variable*

As shown in Table 6 *Cités*, CL&Va, 2-storey and commercial lots have the highest fire risk level relative to other historic buildings with an index FRI = 1.4 (i.e., unacceptable risk), with high propagation and evacuation risk levels (SF_P=1.7-1.8 and 1.4, respectively). *Cités* and commercial lots also present high levels of combat risk SF_C = 1.5 and 1.6, respectively. Only commercial buildings, both legal or informal, exhibit high ignition and combat risk levels, SF_I =1.66. Finally, crowded and empty lots have a high propagation risk level (SF_P=1.8), and crowded buildings also have high levels of evacuation risk.

Table 6: FRI analysis results of Yungay historical buildings classified according to Fire risk sub-factors, urban block types, architectural style and typologies (mode, standard deviation σ, Min and Max of data set).

		Fire Risk Sub-factors and FRI index				
		SF_I	SF_P	SF_E	SF_C	**FRI**
Urban block types	Cités	1.53 σ=0.2 Min=1.13 Max=1.83	**1.7** σ=0.12 Min=1.6 Max=2.0	1.4 σ=0.05 Min=1.2 Max=1.4	**1.5** σ=0.21 Min=1.4 Max=2.0	**1.4** σ=0.08 Min=1.2 Max=1.6
	Penetrated	1.47 σ=0.132 Min=1.12 Max=1.83	1.6 σ=0.122 Min=1.4 Max=2.0	1.4 σ=0.062 Min=1.2 Max=1.4	1.3 σ=0.17 Min=1.4 Max=2.0	1.3 σ=0.086 Min=1.1 Max=1.6
	Divided	1.53 σ=0.15	1.6 σ=0.14	1.4 σ=0.11	1.4 σ=0.19	1.3 σ=0.08

		Min=1.06 Max=1.83	Min=1.6 Max=2.0	Min=1.2 Max=1.9	Min=1.4 Max=1.9	Min=1.1 Max=1.6
	Closed	1.53 $\sigma=0.139$ Min=1.10 Max=1.83	**1.8** $\sigma=0.14$ Min=1.2 Max=2.1	1.2 $\sigma=0.16$ Min=1.2 Max=1.9	1.4 $\sigma=0.17$ Min=1.4 Max=2.0	1.3 $\sigma=0.08$ Min=1.1 Max=1.6
Architectural styles and typologies	CL&Va lots	1.53 $\sigma=0.14$ Min=1.12 Max=1.83	**1.8** $\sigma=0.13$ Min=1.2 Max=2.0	**1.4** $\sigma=0.14$ Min=1.2 Max=1.9	1.4 $\sigma=0.17$ Min=1.4 Max=2.0	**1.4** $\sigma=0.08$ Min=1.1 Max=1.6
	CD lots	1.53 $\sigma=0.156$ Min=1.06 Max=1.83	1.6 $\sigma=0.112$ Min=1.6 Max=2.1	1.2 $\sigma=0.078$ Min=1.2 Max=1.9	1.4 $\sigma=0.167$ Min=1.4 Max=2.0	1.3 $\sigma=0.062$ Min=1.1 Max=1.6
	1-storey	1.53 $\sigma=0.137$ Min=1.12 Max=1.83	1.6 $\sigma=0.116$ Min=1.3 Max=2.0	1.2 $\sigma=0.140$ Min=1.2 Max=1.9	1.4 $\sigma=0.181$ Min=0.5 Max=2.0	1.3 $\sigma=0.081$ Min=1.1 Max=1.6
	≥ 2storey	1.53 $\sigma=0.159$ Min=1.06 Max=1.83	**1.8** $\sigma=0.111$ Min=1.6 Max=2.1	**1.4** $\sigma=0.079$ Min=1.2 Max=1.9	1.4 $\sigma=0.172$ Min=1.4 Max=2.0	**1.4** $\sigma=0.068$ Min=1.1 Max=1.6
	Non-crowded	1.47 $\sigma=0.102$ Min=1.14 Max=1.83	1.6 $\sigma=0.130$ Min=1.3 Max=2.0	1.2 $\sigma=0.086$ Min=1.2 Max=1.7	1.4 $\sigma=0.164$ Min=1.4 Max=1.9	1.3 $\sigma=0.068$ Min=1.2 Max=1.6
	Crowded	1.53 $\sigma=0.153$ Min=1.06 Max=1.83	**1.8** $\sigma=0.131$ Min=1.3 Max=2.1	**1.4** $\sigma=0.141$ Min=1.2 Max=1.9	1.4 $\sigma=0.180$ Min=0.5 Max=2.0	1.3 $\sigma=0.080$ Min=1.1 Max=1.6
	Commercial	**1.66** $\sigma=0.153$ Min=1.25 Max=1.83	**1.8** $\sigma=0.128$ Min=1.4 Max=2.0	**1.4** $\sigma=0.167$ Min=1.2 Max=1.9	**1.6** $\sigma=0.181$ Min=1.4 Max=1.9	**1.4** $\sigma=0.090$ Min=1.1 Max=1.5
	Empty	1.40 $\sigma=0.072$ Min=1.22 Max=1.51	**1.8** $\sigma=0.086$ Min=1.5 Max=1.8	1.2 $\sigma=0.157$ Min=1.2 Max=1.9	1.4 $\sigma=0.169$ Min=1.4 Max=1.9	1.3 $\sigma=0.056$ Min=1.2 Max=1.6

Buildings with moderate, high, or extreme fire risk levels are represented in Figure 7. Also, in this Figure, historical events of fires between the year 2016 and 2020 are indicated in black dots. A total of 75% of the historical fires occurred in high fire risk structures, while 25% in moderate risk SUs. Thus, it is apparent that the FRI index can be considered a relevant indicator of higher risk and predictor for future fires.

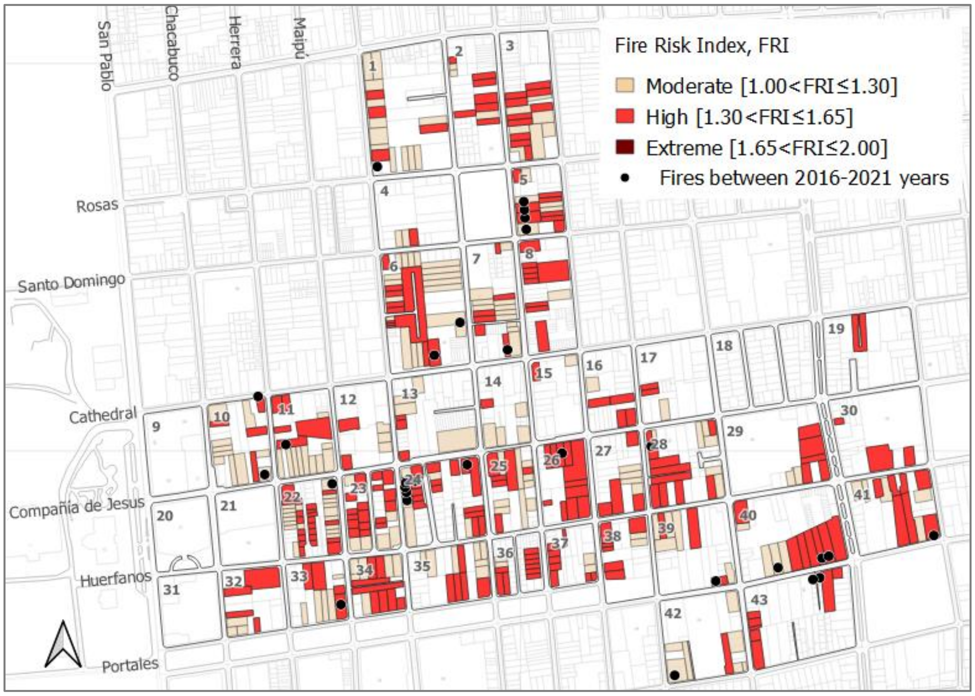

Figure 7: Past fire events vs FRI index in Yungay typical zone

3.1 Fire ignition risk [SF_I]

The results for the ignition risk factor presented in Figure 8a are alarming, because several vulnerabilities were identified as potential contributors for increasing fire ignition probability, such as: a poor conservation state of the buildings, existence of old and overloaded electrical installations with a lack of maintenance, use of non-certified power bars which could overload the electrical circuit, and of gas cylinders placed inside buildings in non-ventilated areas. Figure 8b shows the value of the SF_I factor for each SU. According to thresholds risk levels defined by Granda & Ferreira (2019a, 2019b) and Renfroe & Smith (2016), 10% (43) of the analysed structures present a high-risk level, unacceptable conditions that should be reduced or mitigated as soon as possible (red color), while 90% present low to moderate risk.

A total of 22.8% of the analysed structures (101) were classified as having a good conservation state, due to restoration and consolidation interventions after the 2010 and 1985, Chile earthquakes, and regular maintenance of the facades. Another 50.8% of the building stock (225) was classified as having a reasonable conservation state with some damage that does not structurally compromise the safety of inhabitants, while 26.4% (117) present a bad state of conservation, not having being repaired, it is abandoned, or was converted into parking lots or reused in poor condition after previous seismic and fire events.

Also, the results regarding basic electrical installation conditions ($C_{e,1}$) are worrying: only 4.7% of the electrical systems in buildings (21) have been remodelled, and partially remodelled (15.8%, 70), while 79.5% (352) are old. Another important problem with the electrical system is the use of non-compliant devices (power bars and electrical extension cords) to which household appliances are connected, risking an overload of the basic electrical installation. In the analysed buildings 73.1% (324) use non-compliant power bars and electrical extension cords (without a SEC approval certificate), and 51.2% (277) have two or more household appliances connected. The evaluation of the gas system shows that the 10.4% (46) of SUs have pipeline gas, 12.6% (56) outdoor cylinders, 22.8% (101) indoor cylinders in a ventilated location, and 82.2% (364) indoor cylinders in unventilated locations, and 18.3% (81) do not use any system. Finally, the lowest temperature of ignition of predominant materials–considering structure and warehouses—are >200°C in 75.6 % of the cases (335), < 200°C in 11.1% of the cases (49), and 100 ≤ Ci ≤ 200°C in 13.3% (59) of the cases. The ignition susceptibility-depending on the main use of the building—shows a low activation coefficient in 82.8% (311) of the cases, and a medium activation coefficient in 17.2% of the cases (96). According to the results of the application of the methodology it is recommended to pay special attention to the electrical installations, as in almost 80% of the buildings they have not been renovated. It is also recommended to inform the community about possible problems related to the use and recharging of non-compliant devices (power strips and extension cords.

(a) (b)

Figure 8: (a) Mapping and (b) results of fire ignition analysis of Yungay typical zone

3.2 Fire propagation condition [SF_P]

The propagation speed is one of the main causes of high fire risk in this neighbourhood, and is responsible for most of the past losses. It is apparent in Figure 9(a) and (b) that only 1.6% (7) of the building stock presents a moderate propagation risk. A total of 89.6% (388) and 11.1% (214) of SUs have high and extreme risk levels, which is a high and unacceptable risk condition (Granda & Ferreira, 2019a, 2019b; Renfroe & Smith 2016), which should be immediately corrected. The SF_P factor results (Table 6) show that CL&Va structures are more susceptible to fire propagation ($SF_P = 1.77$ corresponding to high risk level) than CD buildings ($SF_P = 1.67$). This is mainly due to (i) the lack of compartmentalisations and partition firewalls (CL&Va_T1) in dwellings characterized by a first floor built in adobe or brick masonry, and 2nd story in mixed techniques; (ii) the presence of sharing wood roof and *tabique* walls with moderate to high fire load densities; and (iii) the absence of detection and alarm systems.

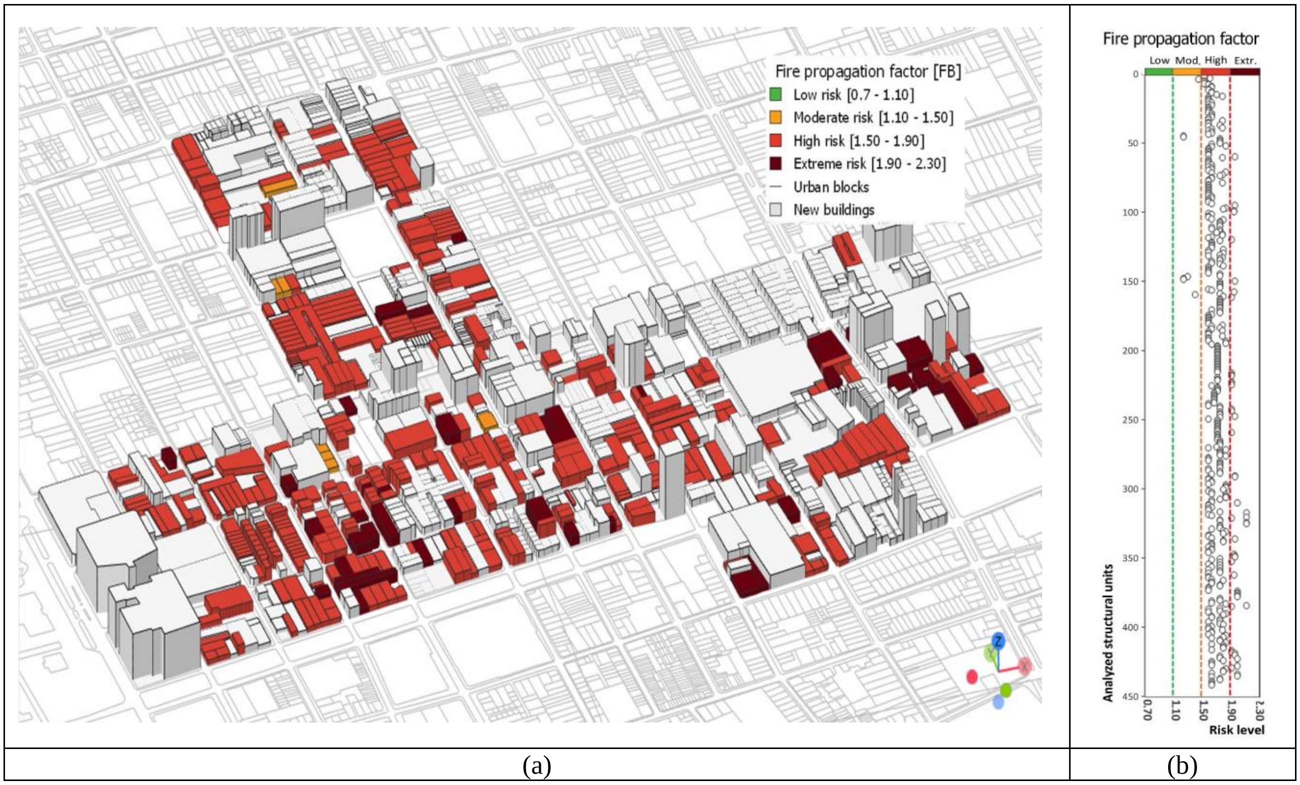

Figure 9: (a) Mapping and (b) results of fire propagation analysis of Yungay typical zone

In particular, regarding the gap between aligned openings ($PF_{P,1}$), only 1.1% (5) satisfies the FRI requirements, while 34.5% (153) and 64.3% (285) have one or more openings with a vertical gap of less than 1.10m. Even the *Cités* of P and D urban blocks present a risk level ($SF_P = 1.76$), which is higher than the buildings on closed and less densified blocks ($SF_P = 1.71$). Generally, high or moderate levels of propagation risk are related to use (non-residential-buildings with lack of fire detection and alarm systems). The destination of the SU is a determining factor in fire propagation (e.g., commercial lots $SF_P = 1.75$), as there are construction techniques and partitioning systems.

According to the Chilean GUPCL, safety-security teams and active protection systems are not mandatory for residential buildings characterized by 1 or 2-storey facades as it is the case of Yungay. Thus, 81.3% of the analysed buildings (360) do not have pre-arranged groups of individuals in charge of communicating fire ignitions. Consequently, the formation of safety and security groups for urban blocks is considered a useful strategy to reduce fire propagation risks.

3.3 Fire evacuation conditions [SF_E]

The characteristics and conditions of internal escape routes determine transit flow capacity and evacuation efficiency during a fire. The results obtained for the building evacuation factor have a rather homogeneous distribution as shown in Figure 10 (a) and (b). A total of 99.5% (421) of the people in this neighbourhood live in buildings with moderate risk relative to evacuation ($SF_E = 1.24 - 1.30$), and 0.5% (22) with high to extreme risk, which should be immediately mitigated. It is shown that CL&Va, Cités and 2 or more-storey building values—in terms of fire risk evacuation—are the most unfavourable (Table 6).

(a) (b)

Figure 10: (a) Mapping and (b) results of fire evacuation analysis of Yungay typical zone

The typical architectural layout of CL&Va and 2 or more-storey structures make the evacuation difficult due to steep wooden stairs, often in a precarious state of conservation, and with a high degree of overcrowding. These features increase the evacuation time of buildings, especially for people with reduced mobility (Figure 10), leading to evacuation factors equal to $SF_E = 1.38$ and 1.39 (moderate risk levels), respectively. Also, in the case of *Cités* in penetrated urban blocks, the vulnerability with respect to evacuation capacity and times during a fire is greater than that of the other historic buildings in the quarter. In this case $SF_E = 1.36$, which corresponds to a moderate risk level. This group of aggregate dwellings, composed of several social housing units—with high land occupation levels (70-90%)—and organized around a narrow central or lateral alley, present deficient evacuation escape routes and a lack of detection and alarms systems. Since the risk factors associated with the evacuation phase are limited to certain types of urban lots and urban block types, specific interventions can be pointed out for increasing evacuation time. As it is difficult to change the width of doors or the inclination of openings, special consideration should be given to improving fire detection and fire alarm installations or through the implementation of fire drills with the community.

3.4 Fire combat efficiency [SF_C]

As shown in Figure 11 (a) and (b), the 67.4% (291), 22.2% (96), and 12.9% (56) of the SUs have a conditioned, limited, or extremely limited fire combat capacity, respectively, which is unacceptable and totally unacceptable risk according to thresholds risk levels defined elsewhere (Granda & Ferreira (2019a, 2019b), and Renfroe &

Smith (2016)). This result is related to the inefficiency of hydrants, the accessibility of streets, and the hydrant location. The requirements of the Chilean Code relative to hydrant efficiency in terms of *fire volume* and *static pressure* are inadequate if the nature of fire loads of historical structures is considered. In fact, a fire in a 400 square meter historical building requires approximately 1,080 GPM to be extinguished, respectively. The flow of Chilean hydrants is only 259 GPM per minute (NCh1646.Of98, 1998), therefore it is not guaranteeing an efficient fire combat. Furthermore, if two or more fire hydrants of the same flow rate are used simultaneously, a *water static pressure* drop is given, which further reduces the water volume per second. Thus, to assess the building's external fire combat efficiency, all hydrants are considered unavailable.

(a) (b)

Figure 11: Fire combat results: (a) Mapping and (b) classification of buildings

Finally, the *street accessibility conditions*, based on building height, street width and slope, together with the *hydrant maximum distance*, were evaluated. The dimensions of central and lateral alley in the *Cités* of penetrated urban blocks, and of secondary streets in divided urban blocks (numbers 6, 22, 23, 24, 37, 38, 42), present free widths lower than the minimum threshold of 2m. Consequently, 13.1% (58) of the analysed buildings present a potential risk due to the impossibility of access of emergency vehicles close to the buildings, and to help and rescue the victims during the fire.

Considering the location of hydrants, it is 87% (385) of buildings with 3 to 50 SUs that have at least one hydrant located closer than 100m from their main exits, according to NCh691.Of98 (1998). On the other hand, 13% (58) do not comply with Chilean fire safety regulation, presenting a potential risk due to the impossibility of efficient fire combat due to the absence of active fire protection. This problem affects 100% of penetrated urban blocks (numbers 1, 6, 13, 19, 22, 24, 28, 34, 42, and 43) and 50% of divided urban blocks (numbers 7, 22, 24, and 36) (Figure 11).

3.5 FRI versus sociodemographic data

It is interesting to correlate FRI value with a characterization of the social vulnerability of the population potentially exposed to fire risk. For that purpose, specific social and demographic indicators were collected using the SoVI variables selected from those proposed initially for United States (Cutter et al., 2003), and then modified and integrated for central Chile by (Martínez et al., 2020), which are summarized in Table 7. The vulnerability characteristics presented in Table 7—obtained from the last census (INE, 2018) and National Socioeconomic Characterization Survey, CASEN, (MIDESO, 2015)—are common factors considered in the literature as strong influencers of the social vulnerability. For the former, the analysis unit is the urban block, and for the later (CASEN) are districts.

FRI results were correlated visually with sociodemographic data. For that sake, risk levels of the SUs were overlapped with the total population for each urban block (Figure 12). Although the most populated urban blocks are those made up of new multi-storey buildings (4, 12, 15, 16, 17 and 19 urban blocks with 3026 people, and about 29.8% of the total population), some historic blocks also have very high population densities. This is the case of blocks 6 [P], 10 [P-D], 24 [C] and 43 [P] with a total of 1583 persons (about 9.1% of total population of the zone) and moderate to high fire risk levels ($1.00 < FRI \leq 1.65$).

Table 7: Factors that characterize fire and socio-economical vulnerability in the neighborhood.

ID	Variable	Calculation	Description	Reference
$\mathbf{N_l}$	Ratio of low incomes	$N_l=N_{tl}/N_{tp}$	L_{tp} = low incomes	(Cutter et al., 2003)
$\mathbf{N_{di}}$	Ratio of disability	N_{tds}/N_{tp}	N_{tds} = population with disabilities	(Cutter et al., 2003)
$\mathbf{N_{hf}}$	Ratio of heads of household	$N_{hf}=N_{thf}/N_{tp}$	N_{thf} = Female heads of household	(García & Naranjo, 2017)
$\mathbf{N_{im}}$	Ratio immigrant population	$N_{im} = N_{tim}/N_{tp}$	N_{tim} = immigrants	(Pulido, 2000)
$\mathbf{N_d}$	Ratio of dependent people in total population	N_{td}/N_{tp}	N_{td} = population with moderate or severe dependence	(Cutter et al., 2003)
$\mathbf{N_{in}}$	Ratio indigenous population	$N_{in}= N_{tin}/N_{tp}$	N_{tin} = indigenous population	(Pulido, 2000)
$\mathbf{N_{ibs}}$	Ratio people living in crowded conditions	$N_{lbs}=N_{tlbc}/N_{tp}$	N_{tlbc} = Population living in crowded conditions	(Martínez et al., 2020)

N_{tp} = total number of persons

Qualitatively speaking, the combination of high FRI values and high population density constitutes an unfavourable situation in terms of fire ignition and the fire evacuation during the event. Alternatively, southern urban blocks between streets *Compañia de Jesús* and *Agustinas*, have between 74 to 291 residents per block, a population density lower than the other historical urban blocks, but with moderate to extreme FRI levels ($1.00 < FRI \leq 1.99$).

In general, moderate to high levels of fire risk in these urban areas are closely related to use: (i) non-residential-buildings with low population density; (ii) storage of highly combustible materials; and (iii) absence of a minimum number of extinguishers.

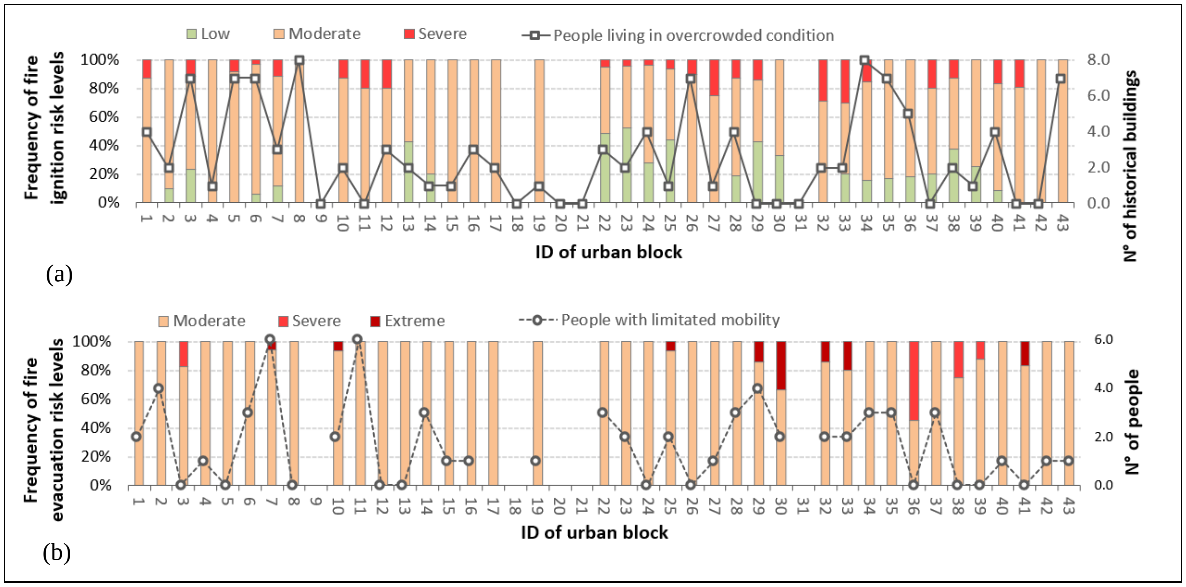

Figure 12: FRI results: (a) % of fire risk ignition levels for each urban block vs. number of historical buildings with people living in overcrowded condition; and (b) % of fire risk evacuation levels for each urban block vs. number of people with imitated mobility

Concerning low-income population, defined as the group of people without sufficient income to acquire basic personal needs including food, health, education and access to services (Cutter et al., 2003), we estimated that the Yungay's population has N_I = 29.6% (3649) of residents living in the condition of poverty. The most critical levels are communities in blocks 6, 10, 11, 12, 13, 22, 23, 24, 32, 33, 34, and 35, with 40.5% (1606) of their residents living in minimum conditions. A percentage of 1.1% (142 people) have limitations on movement (N_{di}); 18.3% (2252) are women taking care of their homes and domestic tasks (N_{hf}), and are more susceptible to hazardous impacts because they tend to first act on behalf of those who depend on them (older adults and children); 29.3% (3609) are immigrants (N_{im}) with greater vulnerability as less social capital in the territory. Indeed, sometimes they are not aware of territorial characteristics, they may not speak Spanish, and are not familiar with emergency plans and procedures to obtain aid and recover faster; 0.4% (52) have moderate to severe dependence (N_d); and 10.1% (1249) are identified as indigenous population (N_{in}), which face some cultural barriers that delay timely information in case of a disaster, and as a consequence have a reduced capacity to respond and recover financially. Finally, the percentage of people living in crowded conditions (N_{ibs}) was evaluated. According to (Martínez et al., 2020), all these factors limit the response capacity, absorption and recovery processes, i.e. the resilience of the community. All these social variables dramatically decrease the ability of the population to cope with and recover from a fire event.

The combination between the frequency of fire risk ignition levels and people living in an overcrowded condition for each urban block (Figure 12a), could be used to identify in which blocks there is higher risk of fire ignition due to a greater probability of overloading electrical systems, and therefore detect in which blocks prioritize actions. On the other hand, the comparison between frequency of fire evacuation risk levels and percentages of people with limited mobility (Figure 12b), could be used to identify in which blocks there is higher risk due to a limited response capacity of those people affected by a potential fire.

5. Conclusions

This work generated a comprehensive building database to study the fire vulnerability of Chilean historic buildings and offers a complete overview of the architectural, structural, and constructive features of 443 SUs in AppendixTable A 5. This material by itself has important archival value and may be used an input for several other risk assessment models. The information gathered includes architectural and structural aspects, such as the type of roof, floor type, vertical and horizontal structural components at the façade and interior, non-structural elements, state of conservation, building use, and several other characteristics of this varied cultural heritage.

This study applies a modified version of the FRI method (Ferreira et al., 2016) for empirical and qualitative fire risk assessment of historical aggregate-buildings belonging to the Yungay neighborhood in Santiago, Chile. The method was adapted to the constructive features of Latin American aggregate heritage buildings, and was validated using an available catalog of historic fire events between 2016 and 2020. A total of 75% of historical fires are identified as high-risk structures by the modified-FRI method, while 25% as moderate risk level. Data collection was based on detailed in-situ inspections aimed to understanding the fire vulnerability of these 443 units. It was our interest to obtain data to characterize the different stages of fire growth (ignition, propagation, evacuation, and combat).

One modification of the FRI methodology includes the original $PF_{I,2}$ partial-factor, aimed to consider the condition of household electrical installations, which was extended to account for the condition of electrical extension cords ($C_{e,2}$). Surveys carried out in the field showed that the condition of electrical extension cords is relevant, since: 73.1% (324) of households use non-compliant power strips and extension cords (no SEC approvals), and the 51.2% (277) overload the electrical system by using two or more high-consumption appliances simultaneously. Also, new partial-factors $PF_{I,5}$, $PF_{P,4}$ and $PF_{P,5}$ were introduced into this index to account for the type of heating system, the fixed fire loads based on the structural typologies, and movable fire loads classified according to the building use, respectively (Table 1).

One of the constraints in the use of index-based risk assessment methodologies applied on a large urban scale is the large amount of data involved. Collecting information, analysing it and obtaining results for a large number of buildings can be a major challenge. To simplify the data interpretation, the FRI method assigns values to the identified phenomena related to the ignition, propagation, evacuation, and combat phase. The values obtained are related to risk levels (low, medium, high, extreme) and processed through the GIS tool. This process allows for a simplified identification of the areas with the highest risk that require more attention from the authorities. However, the methodology also allows for detailed identification of each of the parameters that make up the sub-factors, e.g., identifying buildings that could be eligible for state support for electrical installation upgrades.

It is first concluded that the fire risk index results are well correlated with the data of historical fires (from 2016 to 2021), and hence, the index has the ability to predict potential cases of larger fire risk. The risk level for each fire development stage is linked with urban and architectural configurations in order to identify the most vulnerable cases in the neighborhood. The distribution of FRI values show that the levels of fire risk are well beyond what is acceptable: 39% of the building stock (173) presents a moderate fire risk, while the rest 61% (270) has high levels of risk. In conclusion, there are no buildings that comply with the requirements of the Chilean fire safety regulations, which implies that the study area is currently ‘‘unsafe’’ and needs to be intervened.

It is also the case that *Cités* with CL&Va architectural style, 2-storey and commercial lots, have the highest fire risk index (FRI = 1.4, which is unacceptable) with a high-level of propagation and evacuation risk ($SF_P = 1.8$ and 1.4 for the two-story and commercial lots, respectively). *Cités* also present high levels of risk in fire combat risk $SF_C = 1.4$. Only commercial buildings exhibit simultaneously high-ignition and combat risk levels, $SF_I = 1.66$ and $SF_C = 1.6$, respectively. Crowded and empty lots have a high propagation risk level ($SF_P = 1.8$), and crowded buildings also have higher levels of evacuation risk.

A 10% of the analysed structures present high-ignition risk, which is unacceptable and should be reduced or mitigated as soon as possible, while 90% have low to moderate risk levels. Several vulnerabilities were identified as contributors for increasing fire ignition probability, such as the poor conservation state of the buildings, the existence of old and overloaded electrical installations with poor maintenance, use of non-certified power bars with potential of overloading the electrical circuit, and gas cylinders placed inside buildings in non-ventilated areas.

Furthermore, 89.6% (388) and 11.1% (214) of the portfolio of structures have high and extreme risk levels of propagation, corresponding to unacceptable and totally unacceptable conditions, which should be immediately reduced or mitigated. Also, in terms of evacuation conditions, we conclude that 99.5% (421) of the people live in buildings with moderate risk ($SF_E = 1.24 - 1.30$), and 0.5% (22) with high to extreme risk. Moreover, high levels of propagation risk are closely related to building use, especially in non-residential-buildings that lack a fire detection and alarm systems. In addition to use, construction techniques and partitioning systems are a determining factor in fire propagation (e.g., commercial lots $SF_P = 1.8$).

Finally, 67.4%, 22.2%, and 12.9% of the SUs have a conditioned, limited, or extremely limited fire combat capacity, respectively. This result is correlated with the inefficiency of hydrants, their location, and the accessibility of streets. It is concluded that the requirements of the Chilean Code relative to hydrant efficiency in terms of *fire volume* and *static pressure* are insufficient for the typical fire loads of historical structures.

Fire Risk Index (*FRI*) and the partial factors (PF_I, PF_P, PF_E, PF_C) exhibit low variability, generally centered around intermediate and high risk, which PF_I (ignition risk) being the only variable spanning low risk levels. Regarding correlations, all variables are positively correlated, meaning that the greater the value of a variable, the greater the value of other correlated variables. The correlations among the partial factors, however, are not large (<0.54), which show that they probably capture different phenomena. With regards to the Fire Risk Index (*FRI*), the correlations it has with the other variables are not surprising, because its functional dependency is practically a linear combination of them.

It is apparent that the proposed method could be extended to other historical urban areas in Chile, and possibly to other historical neighborhoods in Latin America, if they share some common origin. However, to apply the modified FRI method in other countries, modifications need to be introduced at least in certain factors appropriate to the country's fire safety standard. Since the FRI method has limitations, further statistical and analytical investigations are still necessary for a systematic fire standard review and method calibration in different contexts. Although it goes beyond the scope of this study, the impact of different mitigation measures could also be incorporated rather straight-forward by modifying the fire risk subfactors. Fire risk evaluation of the urban blocks and structures with and without mitigation measures would enable a fair comparison of the technical effectiveness of each measure. Finally, the FRI analysis enable us to include other urban and socio-economic variables in the analyses that could be correlated to formulate more integrated risk assessments and better public policies. Due to the historical condition of the Yungay neighbourhood, there are many actors involved who could influence decision-making to prioritise risk mitigation measures (neighbours, the municipality, Council of National Monuments, firefighters, among the most relevant). There must be coordination of the different actors in order to achieve effective risk management, using the great organizational capacity of the community and preserving the environmental characteristics of the heritage site.

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7. Referencies

Abatzoglou, J. T., Rupp, D. E., O'Neill, L. W., & Sadegh, M. (2021). Compound Extremes Drive the Western Oregon Wildfires of September 2020. *Geophysical Research Letters*, *48*(8). https://doi.org/10.1029/2021GL092520

Arborea, A., Mossa, G., & Cucurachi, G. (2014). Preventive fire risk assessment of Italian architectural heritage: An index based approach. *Key Engineering Materials*, *628*, 27–33. https://doi.org/10.4028/www.scientific.net/KEM.628.27

Baquedano Juliá, P., & Ferreira, T. M. (2021). From single- to multi-hazard vulnerability and risk in Historic Urban Areas: a literature review. In *Natural Hazards* (Issue 0123456789). Springer Netherlands. https://doi.org/10.1007/s11069-021-04734-5

Bramerini, F., & Castenetto, S. (2014). *Manuale per l'analisi della Condizione Limite per l'Emergenza (CLE) dell'insediamento urbano. Commissione tecnica per la microzonazione sismica.* (BetMultime).

Coelho, A. L. (2010). *Incêndios em edifícios* (E. Orion (ed.); Primerira).

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards. *Social Science Quarterly*, *84*(2), 242–261. https://doi.org/10.1111/1540-6237.8402002

Decree No. 1199. (2004). *Aprueba el reglamento de las concesiones sanitarias de produccion y distribucion de agua potable y de recoleccion y disposicion de aguas servidas y de las normas sobre calidad de atencion a los usuarios de estos servicios. Ministerio de Obras Públicas*.

Decree No. 43. (2009). *Declárese Monumento Nacional en la Categoría de Zona Típica o Pintoresca el Sector que indica de los Barrios Yungay y Brasil de Santiago Poniente, de la Cuidad de Santiago, Comuna y Provincia de Santiago, Región Metropolitana. Consejo de Monumentos Nacion*.

Decree No. 47. (1992). *del Ministerio de Vivienda y Urbanismo, que fija nuevo texto de la Ordenanza General de la Ley General de Urbanismo y Construcciones.*

Decree No. 594. (2000). *Reglamento sobre Condiciones Sanitarias y Ambientales Básicas en los Lugares de Trabajo. Ministerio de Salud*.

Faria, M. A., Rodrigues, J. P., & Coelho, A. L. (2012). *Aplicação dos métodos de arica e de gretener na avaliação do risco de incêndio no cua de setúbal*. *January*.

Ferreira, T. ., Vicente, R., Mendes da Silva, J. A. R., Varum, H., Costa, A., & Maio, R. (2016). Urban fire risk: Evaluation and emergency planning. *Journal of Cultural Heritage*, *20*(426), 1–7. https://doi.org/10.1016/j.culher.2016.01.011

Florentin, K. M., Onuki, M., Esteban, M., Valenzuela, V. P., Paterno, M. C., Akpedonu, E., Arcilla, J., & Garciano, L. (2022). Implementing a Pre-disaster Recovery Workshop in Intramuros, Manila, Philippines: lessons for disaster risk assessment, response, and recovery for cultural heritage. *Disasters*, *46*(3), 791–813. https://doi.org/10.1111/disa.12486

FRAME. (2008). *FRAME 2008. Theoretical basis and technical reference guide.*

García, M., & Naranjo, H. (2017). Factores influyentes en la vulnerabilidad ante desastres naturales en Bolivia 1980 – 2012. *Investigacion & Desarrollo*, *16*(2), 31–44. https://doi.org/10.23881/idupbo.016.2-3e

Granda, S., & Ferreira, T. M. (2019a). Assessing Vulnerability and Fire Risk in Old Urban Areas: Application to the Historical Centre of Guimarães. *Fire Technology*, *55*(1), 105–127. https://doi.org/10.1007/s10694-018-0778-z

Granda, S., & Ferreira, T. M. (2019b). Large-scale Vulnerability and Fire Risk Assessment of the Historic Centre of Quito, Ecuador. *International Journal of Architectural Heritage*, *September*. https://doi.org/10.1080/15583058.2019.1665142

INE. (2018). Síntesis Resultados Censo 2017. *Instituto Nacional de Estadísticas, Santiago.*

Jaiswal, K., & D'Ayala, D. (2011). Developing empirical collapse fragility functions for global building. *Earthq Apectra*, *27*(3), 2–6.

Kaiser, J. (1979). Experiences of the Gretener Method*. *Fire Safety Journal*, *2*, 213–222.

Martínez, C., Cienfuegos, R., Inzunza, S., Urrutia, A., & Guerrero, N. (2020). Worst-case tsunami scenario in

Cartagena Bay, central Chile: Challenges for coastal risk management. *Ocean and Coastal Management*, *185*(October 2019). https://doi.org/10.1016/j.ocecoaman.2019.105060

MIDESO. (2015). Encuesta de Caracterización Socioeconómica - CASEN 2015, Situación de la Pobreza en Chile. *Ministerio de Desarrollo Social. Subsecretaría de Evaluación Social*. http://observatorio.ministeriodesarrollosocial.gob.cl/casen-multidimensional/casen/casen_2015.php

NCh1646.Of98. (1998). Grifos de incendio – Tipo de columna 100 mm diámetro nominal – Requisitos generales. *Instituto Nacional De Normalización*.

NCh1916.Of99. (1999). Prevención de incendios en edificios - Determinación de cargas combustibles. *Instituto Nacional De Normalización*.

NCh2120/4.Of98. (1998). Sustancias peligrosas - Parte 4 : Clase 4 - Sólidos inflamables - Sustancias que presentan riesgos de combustión espontánea, sustancias que en contacto con el agua desprenden gases inflamables. *Instituto Nacional De Normalización*.

NCh691.Of98. (1998). Agua potable - Conducción, regulación y distribución. *Instituto Nacional De Normalización*.

Pais, P. A., & Santos, C. (2015). Fire risk assessment in historical centers - Castelo Branco case study. *Agroforum*, *n°34*.

Palazzi, N. C., Barrientos, M., Sandoval, C., & De, J. C. (2022). Seismic Vulnerability Assessment of the Yungay ’ s Historic Urban Center in Santiago , Chile Seismic Vulnerability Assessment of the Yungay ’ s Historic Urban. *Journal of Earthquake Engineering*, *00*(00), 1–28. https://doi.org/10.1080/13632469.2022.2087793

Pulido, L. (2000). Rethinking environmental racism: White privilege and urban development in southern California. *Annals of the Association of American Geographers*, *90*(1), 12–40. https://doi.org/10.1111/0004-5608.00182

Reszka, P., & Fuentes, A. (2015). The Great Valparaiso Fire and Fire Safety Management in Chile. *Fire Technology*, *51*(4), 753–758. https://doi.org/10.1007/s10694-014-0427-0

Rosas, J., & Parcerisa, J. (2017). *El canon republicano y la distancia cinco mil (The republic canon at a distance of five thousand): Santiago 1910 (Spanish Edition)* (Ediciones UC (ed.)).

Saavedra, M., & Starkman, N. (2000). *Santiago Poniente: desarrollo urbano y patrimonio* (Dirección).

Salazar, L. G. F., Romão, X., & Paupério, E. (2021). Review of vulnerability indicators for fire risk assessment in cultural heritage. *International Journal of Disaster Risk Reduction*, *60*(December 2020). https://doi.org/10.1016/j.ijdrr.2021.102286

Santana, M. L. A., Rodrigues, J. P., Leça Coelho, A., & Charreau, G. L. (2007). Fire risk assessment of historical areas: the case of Montemor-o-Velho. *The Art of Resisting Extreme Natural Forces*, *I*, 81–90. https://doi.org/10.2495/EN070091

SBI. (2021). *Sistema de Información Bomberil*. Sistema de Gestión de Actos de Servicio.

Suresh, N. (2015). Fire Loads in Heritage Buildings. *DHARANA - Bhavan’s International Journal of Business*, *9*(1), 17–21.

Vicente, R., Silva, J. A. R., Varum, H., Costa, A., Subtil, A., Santos, C., Santos, M., Ferreira, T., & Rodrigues, A. (2010). *Caderno de apoio à avaliação do risco sísmico e de incêndio nos núcleos urbanos antigos do seixal*.

WTW-Chile. (2020). Incendios en Chile : Estadísticas y Perspectiva desde la experiencia como Brokers de Seguros Tabla de Contenidos. *Consultoría de Riesgos (DCR) de Willis Towers Watson (WTW)*.

APPENDIX

Table A 1: Description of the partial-factors to assess the fire ignition risk (PF_I) of aggregate historical buildings. Score values are according to Ferreira et al., 2016.

FIRE IGNITION RISK: $PF_I = \sum_{i=1}^{5} \widehat{PF_{I,k}}$

Partial-factors	**Description**	**Score**
$PF_{I,1}$, Conservation state of SU	Good	1.00
	Intermediate	1.10
	Bad	1.20
$PF_{I,2}$, General condition of electrical system	**Condition of electrical system, C_{e1}**	
$PF_{I,2} = C_{e1} \times C_{e2}$	Normal	1.00
(Modified partial factor)	Partially normal	1.25
	Not-normal	1.50
	Condition of electrical extension cords, C_{e2}	
	Presence of certified extension cords – without possibility of overloading the electrical circuit	1.00
	Presence of certified extension cords - with possibility of overloading the electrical circuit	1.25
	Presence of Not-certified extension cords - without possibility of overloading the electrical circuit	1.25
	Presence of Not-certified extension cords - with possibility of overloading the electrical circuit	1.50
$PF_{I,3}$, Condition of gas system	Pipeline gas	1.00
	Outdoor cylinder installations	1.20
	Indoor cylinder installations in a ventilated location	1.50
	Indoor cylinder installations in an unventilated location	1.80
$PF_{I,4}$, Fire load nature,	**Combustibility coefficient, C_i**	
$PF_{I4} = (C_i \times R_{ai})$	Low risk: flash point C_i> 200 ° C	1.00
	Medium risk: flash point 100°C ≤ C_I ≤ 200° C	1.30
	High risk: flash point C_i<100 ° C	1.60
	Activation coefficient, R_{ai}	
	Low R_{ai}: e.i: electronic appliance stores; laundries;	1.00
	residential homes, pharmacies, bakeries; mechanical workshop	1.50
	Medium R_{ai}: e.i: carpentry; bar; printing; toy shop; sale of dried fruits and nuts; storage of pharmaceuticals; automotive accessories; footwear; textiles	2.00
	High R_{ai}: e.i: stationeries, archives, libraries	
$PF_{I,5}$, Type of heating system*	Liquefied gas	1.00
(* New partial factor)	Paraffin (kerosene)	1.20
	Electrical installation	1.50
	Wood or pellets	1.80

Table A 2: Description of partial-factors to assess fire propagation risk (SF_P) of aggregate historical buildings. Score values are according to Ferreira et al., 2016.

FIRE PROPAGATION RISK: $SF_P = \sum_{i=1}^{5} \widehat{PF_{Pi}}$

Partial-factors	**Description**	**Score**
$PF_{P,1}$, Number of gaps between aligned openings	0, Number of spans with gap between aligned openings less than 1.10m;	1.00 1.25 1.50

	1, Number of spans with gap between aligned openings less than 1.10m;	
	2, Number of spans with gap between aligned openings less than 1.10m	
$PF_{P,2}$, Safety and security teams	Not required but exist	0.50
	Not required and do not exist	1.00
	Required, exist	1.00
	Required, do not exist	2.00
$PF_{P,3}$, Detection alert and alarm systems	Not required, there is an automatic fire detection system;	0.50
	Not required, there is a manual fire alarm box;	0.90
	Not required, there is no fire detection system;	1.00
	Required, existing equipment in compliance with the	1.00
	regulation;	1.20
	Required, there is no manual fire alarm box;	
	Required, there is only a manual fire alarm box, when an	1.80
	automatic detection system is also required;	2.00
	Required, there is no fire detection system.	
$PF_{P,4}$, Fixed fire load* **(*New partial-factor,** only for building of CD and CL&Va typologies)	Small lot (6-9m wide and 8-25m long)	2.00
	Large lot (7-15m wide and 25-40-60m long)	3.70
	Square lot	3.80
	2 or more-storey building with tabique structure in upper floors	4.30
or simplified calculation with		
$PF_{P,4s}$, Simplified fixed fire load (Also called Compartmentalization sub-factor in FRI method, for all historic buildings that do not fall under the CD and CL&Va typologies)	*Compartmentalization factor*, C_f	
	With fire walls, no-shared roof structure (entire façade and transverse structural walls are masonry elements), and total surface of SU = 0 - 150m^2;	1.00
	With compartmentation walls, shared roof structure (entire façade and transverse structural walls are masonry elements), and total surface of SU >150m^2;	3.00
$PF_{P,4s}$ = Cf + $\sum_{i=1}^{4} F_{P4,si}$	With-out compartmentation walls (only the first floor of façade and transverse structural walls are masonry elements while the others are tabiques).	3.50
	Internal structures, $F_{B4,si}$	
	$F_{P4,s1}$, wooden openings;	+0.20
	$F_{P4,s2}$, wooden partition walls	+0.20
	$F_{P4,s3}$, wooden roof structures;	+0.20
	$F_{P4,s4}$, horizontal wooden elements.	+0.20
$PF_{P,5}$, Movable fire load* (*New partial-factor)	No relevant fire loads	0.50
	Footwear	1.20
	Pharmacy; construction materials; medicines	1.40
	Office supplies	1.65
	Records	1.85
	Libraries; fabrics in general	2.00
	Thinners	2.70
	Printers, wineries	4.00

Table A 3: Description of partial-factors to assess fire evacuation risk (SF_E) of aggregate historical buildings. Score values are according to Ferreira et al., 2016

FIRE EVACUATION RISK: $SF_E = \sum_i^1 \widehat{PF_{E,k}}$

Partial-factors	Description	Score

	Base value	1.00
$PF_{E,1}$, Evacuation and escape routes	Passage units and spans less than 90 cm	+0.25
	Number of exits below regulation	+0.25
	Vertical track inclination greater than 45	+.025
	Lack of emergency signalling and lighting, when required	+0.25
	PF_{P2}: Safety and security teams	
	PF_{P3}: Fire detection, alert and alarm	
	PF_{e2}: Safety drills:	
	Not required - At least 2 evacuation exercises were performed;	0.50
$PF_{E,2}$, Building properties E2 = (PF_{P2} + PF_{P3} + PF_{e2})/3		1.00
	Not required - Evacuation exercises were not performed;	1.00
	Required - Evacuation exercises were carried out with periodicity as required;	2.00
	Required - Evacuation exercises were not performed at intervals as required;	
	The building complies with all regulatory provisions for partial-factors PF_{P2}, PF_{P3} and PF_{e2}	1.00
$PF_{E,3}$, Correction factor	The building does not comply with all regulatory provisions for partial-factors PF_{P2}, PF_{P3} and $PF_{e.2}$	
	n° of storey ≤3;	1.10
	3 < n° of storey ≤ 7;	1.20
	n° of storey >7	1.30

Table A 4: Description of three partial-factors for the assessment of fire combat risk (SFC) of aggregate historical buildings. Score values are according to Ferreira et al., 2016.

FIRE COMBAT RISK: $\boldsymbol{PF_C} = \sum_i^1 \widehat{PF_{C,k}}$

Partial-factors	**Description**				**Score**
$PF_{C,1}$, External fire combat conditions $PF_{C,1} = \left[\frac{C_{1,1}\ C_{1,2}}{2}\right] C_{1,3}$			**$C_{1,1}$**		
	Building height (m)	Street width (m)	Street clearance height (m)	Slope of the street (%)	
	≤ 9.00	≥ 3.5	≥ 4.0	≤15.00	1.00
		≥ 3.5	≥ 4.0	>15.00	1.50
	> 9.00	≥ 6.0	≥ 5.0	≤10.00	1.00
		≥ 6.0	≥ 5.0	>10.00	1.50
			$C_{1,2}$		
	Hydrant distance		Fire reel existence		
	≤ 100 m		No		1.00
	> 100 m		Yes		1.50
			No		2.00
			$C_{1,3}$		
	Reliability of the existing hydraulic network				
	Yes				1.00
	No				2.00
$PF_{C,2}$, Internal fire combat conditions	Residential: at least 1 extinguisher;				0.90
	Residential: no extinguisher;				1.00
	Market, other number of fire extinguishers ≤ storey n°;				1.00
	Market: number of fire extinguishers below the number of floors;				1.75
	Market: there are no fire extinguishers.				2.00
$PF_{C,3}$, Security teams	Not required, but exists				0.50
	Not required and do not exist				1.00
	Required, exists				1.00
	Required, do not exist				2.00

Table A 5: Summary of the physical aspects, occupancy and main uses of the units studied.

Category	**Subcategory**	**Item**	**Frequency**
Physical aspects of the units	Architectural style	Colonial derivation	288
		Classist & Va	144
		Eclectic	10
		Other	1
	Belongs in a cité	In cité	49
		No	394
	Number of floors	0	1
		1	271
		2	152
		3	12
		4	6
	Construction materials	Adobe	154
		Brick	289
		Quincha	61
		Wood	10
	Number of materials per unit	1	372
		2	71
Unit occupancy and crowding	Typical occupancy per unit	0	43
		1-5	92
		6-10	98
		11-20	71
		21-40	34
		41-60	6
		Variable	87
	The unit is overcrowded	Yes	108
	Occupants with low mobility	Yes	38
		Maybe	19
Use or destination of each unit	Typical use	Residential	319
		Food and drink	28
		Mart	24
		Office	14
		Warehouse	9
		Workshop	8
		Stylist	6
		Lodging	5
		Education	4
		Mechanic	4
		Organization	4
		Health	3
		Music and dance	3
		Parking	3
		Other	6
	Number of uses per unit	0	41
		1	355
		2	33
		3	5
		4	1