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Spatial Vulnerability Assessment of Critical Infrastructure Based on Fire Risk through GIS Systems—Case Study: Historic City Center of Guimarães, Portugal

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Featured Application: The application of this study is to provide a comprehensive understanding of the vulnerability and risk of fire to critical infrastructure within the historic city center of Guimarães. These insights highlight the need for robust emergency plans that prioritize high-risk zones and address the specific challenges posed by the city center's medieval layout. By addressing the identified areas of concern and working collaboratively, stakeholders and authorities can enhance the resilience of the city center and ensure the safety of its residents and assets during extreme events.

Abstract: One of the most important factors when assessing the resilience of critical infrastructure is its vulnerability to extreme events. This study focuses on developing correlation maps that define the vulnerability to fire risk of critical infrastructure and its zone of influence. Using an index approach, a vulnerability assessment is challenging due to the fact that observing and measuring certain vulnerability aspects is not too easy. Furthermore, analyzing the unique vulnerabilities of individual elements becomes intricate, given their interdependencies and correlations. Leveraging GIS mapping techniques, we investigate the impacts of infrastructure disruption on neighboring elements and the urban fabric. The methodology enables multiple levels of assessment, facilitating the identification of vulnerable elements and optimizing decision-making processes before and after extreme events. Our findings highlight the significance of prioritizing emergency planning, enhancing accessibility, implementing preventive measures, and adopting a proactive emergency response approach. In conclusion, these measures contribute to mitigating vulnerability and safeguarding critical infrastructure and surrounding communities from extreme events.

Keywords: vulnerability assessment; critical infrastructure; correlation maps; historic city center; GIS mapping; spatial assessment

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1. Introduction

According to the World Bank, more than 50% of the global population currently resides in urban areas, and this number is expected to increase by 1.5 times by 2045 [1]. The concentration of population, assets, and economic activities in urban areas significantly amplifies the risks associated with extreme events [2]. Critical infrastructure, defined as assets or systems that, if destroyed or disrupted, greatly affect societal well-being and effective governance [3,4], is primarily located in urban city centers. For instance, a significant earthquake can often disrupt essential services, including electricity, water, and road availability. The impact on this critical infrastructure can lead to widespread consequences for communities and emergency response efforts [5,6].

These disruptions in critical infrastructure can occur due to technical issues such as design flaws, operational failures, and mechanical breakdowns, as well as man-made or natural hazards [7,8]. Therefore, it is crucial to understand population trends and the characteristics of this critical infrastructure, as well as its interconnections, to minimize potential socio-economic damages [9].

While there are numerous codes, standards, and rules in place for the construction of new critical infrastructure, historical city centers often struggle to comply with current guidelines. However, the consequences of failure in these historic centers can be more significant in terms of human and cultural losses [10]. One natural hazard that particularly affects historical city centers is urban fires. Infrastructures within old historic centers often consist of traditional materials with morphological characteristics that do not meet current comfort and safety standards. This infrastructure possesses significant fire loads, such as wooden ceilings and floors, textiles, and paintings. Additionally, installing common fire protection devices is often not feasible [11,12]. Moreover, the lack of proper maintenance practices in these centers, combined with their frequent use for services and the presence of vulnerable groups (e.g., elderly people without financial support), exacerbates the problem.

In this context, it is important to assess the vulnerability of historical city centers. This involves examining the system network and understanding the failure modes based on a predefined set of events. Vulnerability assessment is an extensively researched area, primarily within the context of risk analysis and natural hazard assessments [7,13,14]. In general, vulnerability is quantified using appropriate vulnerability indices that measure the negative consequences of extreme events such as floods, earthquakes, and fires [8]. For instance, some studies employ fragility curves to quantify vulnerability in various contexts, such as quantifying the seismic vulnerability of bridges [6]. Other vulnerability assessment frameworks view critical infrastructure as complex social-technological systems that are interdependent, meaning the condition of one part of the infrastructure influences others, and vice versa [7]. These assessments aim to characterize the process by which vulnerability is shaped within specific domains of the analyzed network. Numerous studies have examined vulnerabilities in different regions of Europe, considering aspects related to the expected severity of impacts, level of adaptation, and capacity for recovery [14]. These studies often incorporate features related to hazard, exposure, sensitivity, and capacity within the vulnerability assessment. However, most of these works focus on modern urban cities and specific climate hazards (e.g., heat stress or coastal and pluvial flooding), with limited research specifically addressing vulnerabilities in old historic cities [8].

To address this gap, this study introduces a correlation mapping approach aiming to facilitate the assessment of extreme events. Correlation maps [15] are employed to assess the vulnerability of infrastructure and identify the zone of influence of extreme events on this infrastructure. Vulnerability is assessed using an index-based approach, acknowledging that certain aspects of vulnerability may be difficult to directly observe or measure. Moreover, the complex task of assessing cumulative vulnerabilities resulting from mutual dependencies and correlations among different elements is particularly challenging. To address this, GIS mapping has been developed to estimate the effects of non-functioning infrastructures on neighboring infrastructures, as well as on the urban and social scale.

2. Methodology

2.1. Conceptual Framework on Vulnerability

Vulnerability analysis of a given territory involves assessing the transmission of vulnerabilities that characterize areas and elements essential for the functioning of the territory in a normal period (pre-event) and a critical period (during the event). This analysis relies on the integration of three types of information [16]: (i) spatial vulnerability of urban centers, (ii) essential and strategic infrastructures for the areas to be managed, and (iii) vulnerability of the essential infrastructures for operational and crisis management purposes. Vulnerability is also defined in terms of the asset's exposure (i.e., presence of valuable assets before the fire occurs), sensitivity (i.e., susceptibility to damage during or after the fire), and adaptative capacity (i.e., ability to cope with damage and recover after the fire) [17,18].

The Fire Risk Index (FR_I) is calculated using the simplified Arica methodology [10,19–21]. This methodology is based on empirical data and comprises four main sub-factors: fire inception or ignition (SF_I), fire propagation (SF_P), evacuation (SF_E), and fire combat (SF_C). Each sub-factor is evaluated based on a range of partial factors that contribute to its overall quantification. These factors, subfactors, and partial factors are presented in Table 1.

Table 1. Global and partial factors of the simplified ARICA methodology, based on [10,19,21].

Global Factors		**Partial Factors**
Global Risk Factors	Beginning of the Fire (SF_I)	State of conservation of the construction–(PF_{A1})
		Electrical installations–(PF_{A2})
		Gas installations–(PF_{A3})
		Nature of Fire Loads–(PF_{A4})
	Development and Propagation of Fire in the Building (SF_P)	Fire Loads–(PF_{B1})
		Fire compartmentation–(PF_{B2})
		Fire detection, alarm, and alert–(PF_{B3})
		Security equipment-(PF_{B4})
		Distance between overlapping spans (PF_{B5})
	Building evacuation (SF_E)	Factors inherent to evacuation paths–(PF_{C1})
		Building inherent factors–(PF_{C2})
		Correction factors–(PF_{C3})
Efficiency	Firefighting (SF_C)	Internal and external firefighting factors in the building (PF_{D1})
		Safety teams (PF_{D2})

The FRI quantification with the simplified ARICA method is regarded as a deterministic-based approach and is computed using Equation (1), representing the quotient between the weighted average of the four subfactors and the reference risk factor (FR_R).

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

The values employed in the quantification process of the partial factors have diverse origins, originating from expressions developed for specific effects in some cases, while others are obtained from tabulated data. To quantify the value of the subfactors from the partial factors, Equation (2) is utilized, which essentially calculates the mean of all the partial factors corresponding to the subfactor. In Equation (2), $PF_{j,i}$ represents the partial factor corresponding to the subfactor SF_j, and n_{PF} represents the total number of partial factors considered within the subfactor.

$$SF_j = \frac{\sum PF_{j,i} + PF_{j,i+1} + PF_{j,i+2}}{n_{PF}} \quad (2)$$

For a comprehensive understanding of the full quantification process and the individual partial factors involved in the simplified ARICA method, refer to the works of [10,19,21].

2.1.1. Essential Components and Strategic Spaces

The vulnerability assessment conducted in this study begins by evaluating essential components crucial to the normal functioning of a city. These components are categorized into three study groups for analysis. The first group pertains to the city's population and its intrinsic needs. Recognizing that cities are composed of citizens, it is crucial to consider their fundamental requirements for well-being, such as access to healthcare and education. The second group to examine is the economic aspects and city governance. This encompasses the city's ability to manage, generate wealth, and administer resources, supported by a range of actors including the private sector, public sector, and civil society. Finally, the last study group is related to networks and infrastructures, mainly known as critical infrastructure. This group primarily comprises transportation infrastructure, telecommunication systems, water supply networks, energy supply systems, fuel distribution networks, and food distribution systems.

The quantification of vulnerability involves zoning the area to assess the presence of critical infrastructure within each designated zone. To achieve this, a simple equal interval classification is applied. This method utilizes the highest and lowest count of critical infrastructure within each zone and selects three classes to determine the level of vulnerability: low, medium, and high. Equation (3) is employed to calculate the threshold values that define the vulnerability ranges, determining whether a zone exhibits high, low, or medium vulnerability based on the classification process. These threshold values play a crucial role in assigning the vulnerability levels to each zone, providing valuable insights into the overall vulnerability assessment.

$$\text{Vulnerability threshold values} = \frac{(\text{Highest value} - \text{Lowest value})}{\text{Number of classes}} \tag{3}$$

Two criticality rankings were established. The first ranking, known as the driving power ranking, assessed the criticality of a piece of infrastructure based on the number of other pieces of infrastructure dependent on it. This ranking drew upon a study conducted by [22], which employed expert knowledge to classify critical infrastructure sectors. The second ranking, called the hierarchy of needs, followed guidelines provided by [23] to determine infrastructure criticality based on the support they offer for essential human needs. The values assigned to each infrastructure sector in the case study area were derived from these studies, with a special classification applied to health infrastructure based on the services it provides. The values are compiled in Table 2.

Table 2. Driving power and hierarchy of needs ranks for the critical infrastructure in the historic city center of Guimarães.

Critical Infrastructure Sector	Driving Power Rank	Hierarchy of Needs Rank
Religion/Worship	1	3
Transport	5	4
Social Service	2	3
Sanitation	2	5
Health: Pharmacy	5	5
Health: Dental Clinic	4	4
Education	2	3
Culture and Monuments	3	3
Commerce (Basic Products)	2	2
Administrative	4	5
Accommodation	5	5

2.1.2. Spatial Vulnerability

Spatial vulnerability refers to the characterization of the spatial context, considering various parameters that influence the functioning of the urban fabric before and during an event [16] in the periods before and during a disruptive event. In the case of urban centers at risk of fire, the focus is on analyzing the map combined with criteria that refer to accessibility and exposure to that event. The accessibility of spaces is fundamental since it plays an important role in the period before the event, and a potential deficiency during an event can amplify the effects of a catastrophe. The accessibility of the study area is determined by analyzing the main transportation infrastructure network and the orographic and hydrographic obstacles. Exposure mapping is based on existing cadastral data regarding fire risk. The map of spatial vulnerability is a result of the combination of accessibility conditions and exposure to threats, allowing evidence of the fragility of the areas.

2.1.3. Sociodemographic Vulnerability

To assess the fire risk within the study area, the values obtained from the fire risk analysis conducted by [4,20] are compared with sociodemographic data gathered from the 2021 Census of Guimarães. This comparative analysis facilitates the identification of zones characterized by higher fire risk and helped determine the population potentially exposed to such risks.

By integrating the fire risk analysis data and socio-demographic information, this study gains valuable insights into the correlation between fire risk and population density. The results would enable the identification of areas where fire risk is particularly pronounced and where potential impacts on the local population might be more significant. The combination of fire risk analysis with sociodemographic data is vital for comprehensive emergency planning and preparedness efforts, with a focus on safeguarding the well-being of its residents and assets in the face of potential fire incidents.

2.1.4. Crisis Management Vulnerability

In the context of crisis management, several crucial indicators are mapped and analyzed to enhance emergency response preparedness. These indicators include the distance to the nearest hospital, the presence of fire brigades in the vicinity, and the proximity to intervention brigades. By correlating these indicators with the evaluation of different zones and infrastructures in terms of the Fire Inception Index (representing the likelihood of a fire ignition), a comprehensive assessment of the potential vulnerabilities and risks within the study area can be achieved.

Moreover, the incorporation of the Fire Inception Index of each building into the analysis allows for more detailed and nuanced visualization of the results. This data-driven approach enables emergency planners and authorities to identify areas and infrastructures with higher probabilities of fire ignition, thereby prioritizing resources and interventions accordingly.

By combining these indicators with vulnerability mapping and fire risk analysis, decision-makers gain valuable insights into the spatial distribution of risks and critical points. This information is crucial in formulating effective emergency plans and strategies to minimize potential damage and ensure the safety of residents and the preservation of the city’s invaluable cultural heritage in the event of extreme fire events.

2.1.5. Territorial Vulnerability

By cross-referencing spatial vulnerability with the location of essential infrastructure, we can identify the most strategically vulnerable areas in the study area. This allows for an initial analysis of the vulnerability of key infrastructures, such as electricity, water supply networks, businesses, and residential buildings.

Each part of the critical infrastructure will undergo a vulnerability assessment based on six stages: (i) its intrinsic vulnerability, (ii) the level of risk exposure, (iii) its dependence on other pieces of infrastructure, (iv) the capacity to control and intervene in case of failures, (v) available operating alternatives, and (vi) the level of preparation for crises.

This comprehensive evaluation process will produce vulnerability maps, highlighting the particularly vulnerable infrastructure. These maps can play a crucial role in guiding emergency planners and decision-makers to prioritize resources, implement targeted interventions, and formulate effective crisis management strategies to safeguard critical infrastructure and protect the well-being of residents during extreme events.

3. Case Study Application

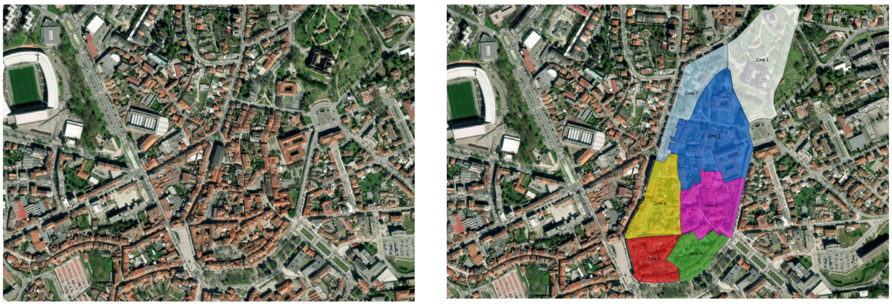
3.1. Historic City Center of Guimarães

The historic city of Guimarães, located in the district of Braga in northern Portugal, holds a special significance as the birthplace of Portugal. Its historic center, renowned for its remarkable preservation, was officially included on the UNESCO World Heritage List on 13 December 2001 [4]. The city's historical significance lies in its well-preserved architecture, showcasing the evolution of various building styles from medieval settlements to the present, particularly between the 15th and 19th centuries. The authenticity of Guimarães is a testament to the diligent protection strategies implemented by local authorities. Urban conservation policies in Guimarães have primarily focused on promoting the rehabilitation and revitalization of public spaces, preserving the resident population, and safeguarding existing historic structures constructed using traditional techniques [21].

The origins of Guimarães' Historic Center date back to the 10th century when it consisted of two distinct elements: a monastery situated in the valley and a fort perched on the mountain. These two focal points gradually expanded and eventually merged, forming a walled town in the 13th century. As the region continued to grow, the village extended beyond the protective walls. However, these fortifications remained largely unchanged until 1853 when Guimarães was officially granted city status, prompting the removal of the surrounding wall. Subsequently, the city underwent a period of extensive urban development, including improvements to the city's extramural areas and various interventions within the historic center [10,24].

Analysis of cadastral data on fire incidents in Guimarães reveals that most fires occur within the historic area. Although the number of human casualties resulting from these fires is relatively low, the city has suffered significant material, historical, and cultural losses. In response to this situation, the Guimarães city council developed a pilot Fire Fighting and Security Plan in 2004, which has been implemented and integrated with the Guimarães Municipal Civil Protection Emergency Plan [25]. It is important to highlight that the project and study area primarily focuses on the UNESCO-designated World Heritage area. In the event of a large-scale urban fire within this designated zone, the consequences for the municipality would undoubtedly be severe.

For this study, the designated study area was divided into vulnerability assessment and criticality zones as depicted in Figure 1. These zones were established based on fire risk models developed in previous works [4,10,20,21]. To ensure the validity of these models, it was crucial to compile a comprehensive database. Various data sources were used including an existing database within the research group of the University of Minho team [11], open data obtained from the Guimarães City Council [26], data provided by the Guimarães City Council as part of the National R&I Project known as InfraCrit (reference PO-CI-01-0247-FEDER-03955), which also contributed to this study as an outcome of the research conducted within the project, data derived from Copernicus services for climate change scenarios [27], and existing data from the official administrative chart of Portugal CAOP 2020 [16].



(**a**) (**b**)

Figure 1. Historic city center of Guimarães: (**a**) Study area; (**b**) Criticality zones of study (Zone 1—White area; Zone 2—Blue area; Zone 3—Pink area; Zone 4—Green area; Zone 5—Red area; Zone 6—Yellow area; Zone 7—Light Blue area.

3.2. Data and Characteristics Used within the Vulneravility Conceptural Framework

The analysis conducted in this study used the QGIS software, chosen due to its free and open-source nature as a geographic information system program. QGIS serves as a Geographic Information System (GIS) software, providing users with the capability to analyze and manipulate spatial data, while also enabling the creation and export of graphical maps. It seamlessly integrates with other open-source GIS packages, such as GRASS GIS and MapServer, facilitating collaborative and comprehensive geospatial analyses.

Multiple layers were created and incorporated into the project. For the case study in Guimarães historical center, relevant information was sourced from the municipality's online services [28] and an open-source project provided by Lisbon's university [29]. Additionally, data from previous studies, including the Fire Risk Index (FRI) obtained through the simplified Arica methodology, were considered [19,20]. Further layers were obtained using the QuickOSM plugin, enabling easy querying of various information specific to Guimarães. Finally, the project incorporated Quick Map services from Bing, offering satellite and map views.

3.2.1. Essential Components and Strategic Spaces

The components were thoroughly analyzed in the context of Guimarães' historic city center, and the collected data were integrated into a comprehensive database. Vulnerability factors were visualized and assessed using QGIS.

The initial map generated for this analysis provided a comprehensive representation of all the acquired layers within the case study. These layers included assessed buildings, infrastructure, hydrants, water networks, and the defined study area. Subsequently, a vulnerability zones map was created by dividing the area into seven distinct zones based on its urban development [19,30]. Delimiting these zones was crucial to quantify the concentration of infrastructures. For this purpose, the "Count Points in Polygon" analysis tool was utilized, resulting in a new layer with an additional column indicating the number of infrastructures within each zone. The vulnerability levels of these zones were then represented using a color gradient, ranging from green to red, based on the number of infrastructures present.

By applying Equation (3), as outlined in Section 2.1.1, the vulnerability levels were derived. The maximum number of critical infrastructure parts within a zone was found to be 22, while the minimum was 5. Considering that this analysis utilizes only three classes (low, medium, and high), a threshold value of 5.6 was obtained. This threshold categorizes zones with a number of critical infrastructure (CI) from 5 to 11 as low vulnerability, zones with 11 to 16 CI as medium vulnerability, and zones with 16 to 22 CI as high vulnerability.

To illustrate the intrinsic vulnerability of CI, a map was generated by overlaying the infrastructure layers with the pre-categorized building layers, using their corresponding Fire Risk Index (FRI). The infrastructure layers were merged into a single layer using the "Merge Vector Layers" tool, and each infrastructure was assigned a specific type in an explicit column, facilitating the subsequent clustering process based on infrastructure type.

The "Inf&Buildings" layer, containing information about both buildings and the infrastructure, was created by unifying the layer with all buildings in the study area and the layer containing all infrastructures. To address conflicts within the buildings layer, the "Check Validity" tool was employed to identify and resolve polygon errors hindering the unification process. After resolving these conflicts, the unification was successfully performed, resulting in the "Inf & Buildings" layer.

For the categorization of buildings based on their criticality, additional columns were added to the "Inf&Buildings" layer, allowing for their classification according to their criticality. The criticality rankings specified in Table 2 were used for this purpose. To enhance the output, a 2.5D symbology tool was employed to provide a three-dimensional perspective for buildings containing infrastructure in the two-dimensional representation. Furthermore, a classification was assigned based on the criticality of each infrastructure's building, prioritizing the most critical ranking for buildings offering multiple services (e.g., pharmacy and accommodation). Two maps were then created, one for each criticality ranking (Driving Power and Hierarchy of Needs), which also displayed the type of infrastructure. To improve readability, the WMS (Web Map Service) from Bing Satellite was replaced with the WMS from Bing Map, providing a clearer and more user-friendly appearance for the maps.

3.2.2. Spatial Vulnerability

The map generated presents the accessibility classification and Fire Risk Index (FRI) for each building within the study area. To create this map, the road layer was initially clipped using the "Cut" tool in QGIS, based on the boundaries of the case study area. The resulting layer was then renamed as "road_classification" and symbolized using color coding to represent different road types.

Moreover, the buildings were clustered based on their FRI values, employing a yellow-to-red color scheme to visualize the varying levels of fire risk. The map also includes visual representations of the case study zone, pedestrian zones, and buildings that were not evaluated for their Fire Risk Index.

By presenting the accessibility classification and Fire Risk Index in this map, valuable insights into the potential impact of fire events in different areas of the study zone are provided. The color-coded representation of road types and the FRI clustering enhance the understanding of fire risk distribution and accessibility patterns within the historic city center of Guimarães. Additionally, the inclusion of pedestrian zones and buildings not evaluated helps to delineate areas of interest and highlights potential areas of vulnerability.

3.2.3. Sociodemographic Vulnerability

For this mapping, data were collected from the database of the National Statistics Institute of Portugal [31]. The data included information on the age of buildings within the Oliveira do Castelo district (in which Guimarães is located) and demographic data for the case study area in Guimarães. Since the data were not geolocated and represented general statistics for the district, an interpolation was performed based on the number of existing buildings in the case study area. For the map depicting the Fire Risk Index (FRI) and buildings' age, the new data were randomly assigned to the buildings using the "Select Randomly" tool, and values were allocated accordingly. It is important to note that the results of this map do not perfectly reflect reality due to the randomization of data. However, given the limitations of obtaining real-time data, this approach was deemed the most optimal, utilizing the 2021 national database. Furthermore, an extensive manual grouping of the buildings was conducted based on the year of construction and the assigned Fire Risk Index. In the second map, the focus was on portraying the FRI, the number of inhabitants within each building, and whether the buildings with inhabitants accommodated individuals with disabilities. This analysis was based on categorizing the buildings as residential, as established in previous studies [4,10,19–21], and incorporating the newly interpolated data obtained from the 2021 census. Similar to the previous map, a comprehensive manual grouping of the buildings was carried out based on the number of inhabitants, the number of people with a disability, and the assigned Fire Risk Index.

3.2.4. Crisis Management Vulnerability

To ensure emergency vehicle access, a 3.5 m buffer was created around the roads within the case study area, adhering to the normative guidelines of Decreto-Lei nº 409/98 de 23 December 1998 (Law nº 409/98 of 23 December 1998) [32]. This process led to the development of the "Accessible roads" layer, which was utilized in network analysis.

Using the shortest route tool in QGIS and incorporating the "Accessible roads" layer along with the previously mentioned infrastructure and building layers, a network analysis was performed. This analysis aimed to identify the shortest routes from the infrastructure points to each building in the study area. The result was a new layer containing distance measurements from each of the five infrastructures to all the buildings.

To visually represent the accessibility routes for pertinent authorities, the result layer was categorized and color-coded accordingly. Furthermore, to enhance the visualization of the assessment results, the fire inception index of each building was integrated into the analysis. The fire inception index was categorized into low, moderate, and high-risk levels.

This approach yielded four informative maps, showcasing the shortest routes, in meters, from each piece of infrastructure to every building in the case study area. The maps also displayed the Fire Inception Index categorization for each building, providing a comprehensive and visually intuitive overview of the fire risk vulnerability assessment. These maps will prove instrumental in supporting decision-making and emergency planning efforts to enhance the resilience and safety of the historic city center of Guimarães.

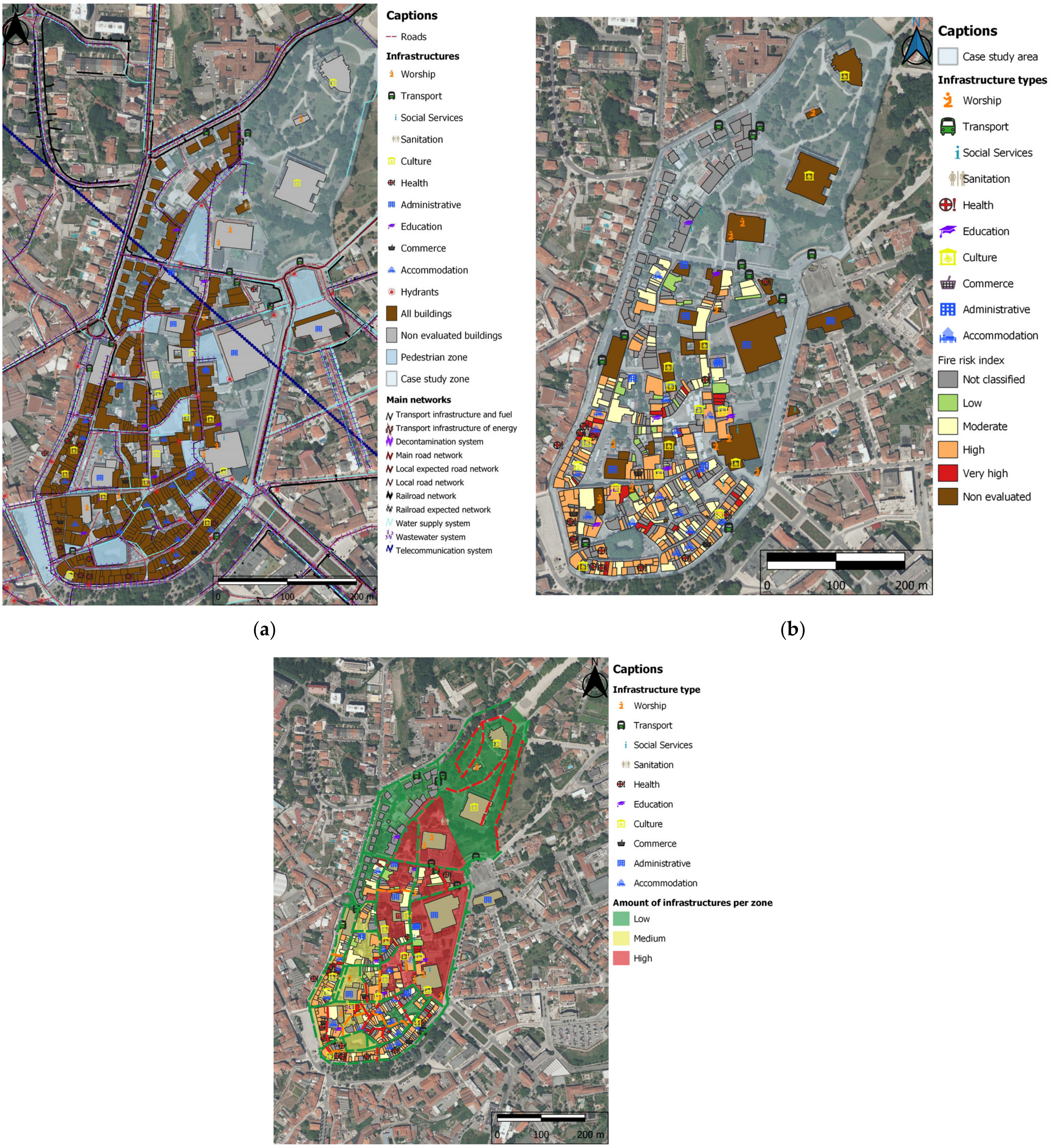
4. Results and Discussion

In this section, the results for the different vulnerability indicators in the study area are presented.

4.1. Essential Components and Strategic Spaces

The analysis of the essential components and strategic spaces began by mapping the critical infrastructure in the historic city center of Guimarães. In addition, an evaluation of several buildings within this area was conducted, indicated by the brown color on the map (Figure 2a). As mentioned in the methodology section, previous studies on fire risk in this area have already been conducted and documented in [4,10,20,21]. This assessment is made based on the ARICA Simplified Method and takes into consideration some building characteristics: type of use, number of floors, state of conservation, number of people that live on the building with and without disability, and building materials, among others. The Fire Risk Index obtained from these studies is derived from four main phases: (i) the ignition or inception phase, (ii) the development and propagation phase, (iii) the building evacuation phase, and (iv) the firefighting phase. These phases are crucial to assessing and understanding the overall fire risk in the area [4,10,20,21]. Considering that vulnerability is closely linked to fire risk, the level of fire risk for each evaluated building/infrastructure was also mapped (Figure 2b). The historic center contains numerous critical infrastructure, including those related to commerce, culture, education, health, sanitation, social services, transport and telecommunications networks, water, and worship. The remaining mapped buildings are primarily used for residential or service purposes. It is worth noting that the majority of this infrastructure and these buildings have a high Fire Risk Index, highlighting the vulnerability of the city center. Furthermore, the vulnerability of each studied zone was analyzed, considering the number of existing critical infrastructure (Figure 2c). Zone 2 and Zone 3 (as defined in Figure 1b) present high vulnerability, while Zone 5 and Zone 6 (as defined in Figure 1b) exhibit medium vulnerability. In the case of extreme events, these areas are the most susceptible, emphasizing the need for emergency plans to prioritize attention to these areas.

Additionally, a detailed analysis was conducted to assess the intrinsic vulnerability of each piece of critical infrastructure by evaluating its criticality (Figure 3). The results indicate that the majority of critical infrastructure with very high levels of criticality is situated in Zones 2 and 3, which aligns with the areas exhibiting the highest vulnerability due to the concentration of critical infrastructure. On the other hand, the remaining critical infrastructure exhibits either a very low or low level of criticality. Therefore, even if they have a moderate Fire Risk Index, they do not demonstrate important intrinsic vulnerability.



(**a**) (**b**) (**c**)

Figure 2. Mapping of the (**a**) critical infrastructure present in the study zone and the buildings that were evaluated in terms of fire risk; (**b**) Fire Risk Index for each building and critical infrastructure and (**c**) vulnerability of each zone considering the amount of critical infrastructure present in each zone.

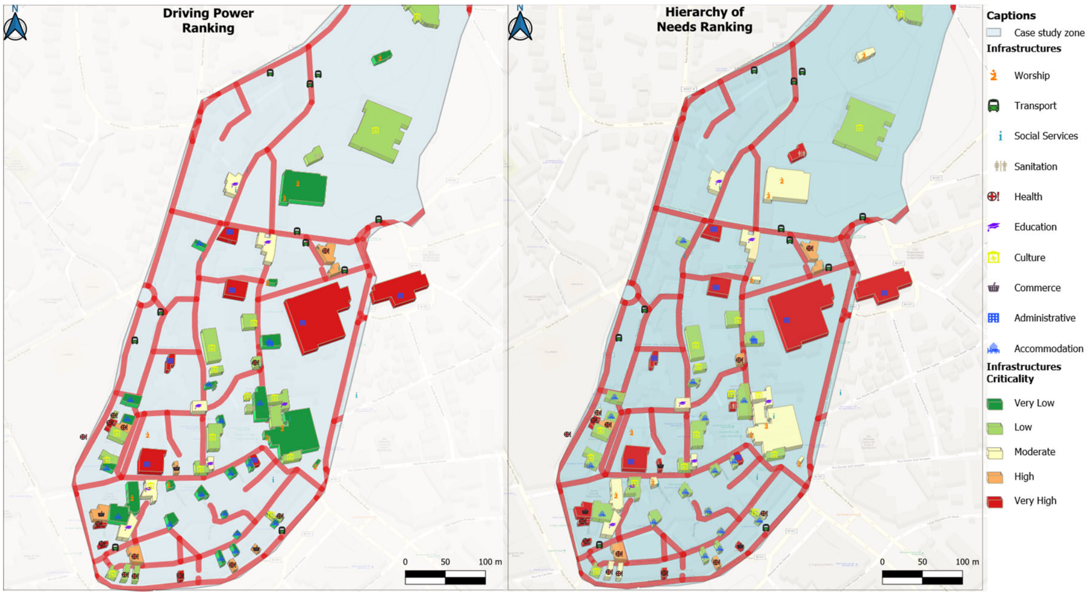


Figure 3. Mapping of the criticality of each part of the critical infrastructure.

4.2. Spatial Vulnerability

In Figure 4, it is presented a map that integrates the accessibility of emergency services with the fire risk assessment conducted for each analyzed building. The unique feature of this city center is that it is surrounded by large roads, allowing emergency services to access most buildings. However, due to its medieval nature, the buildings in this city center were constructed very near the protective wall of the castle.

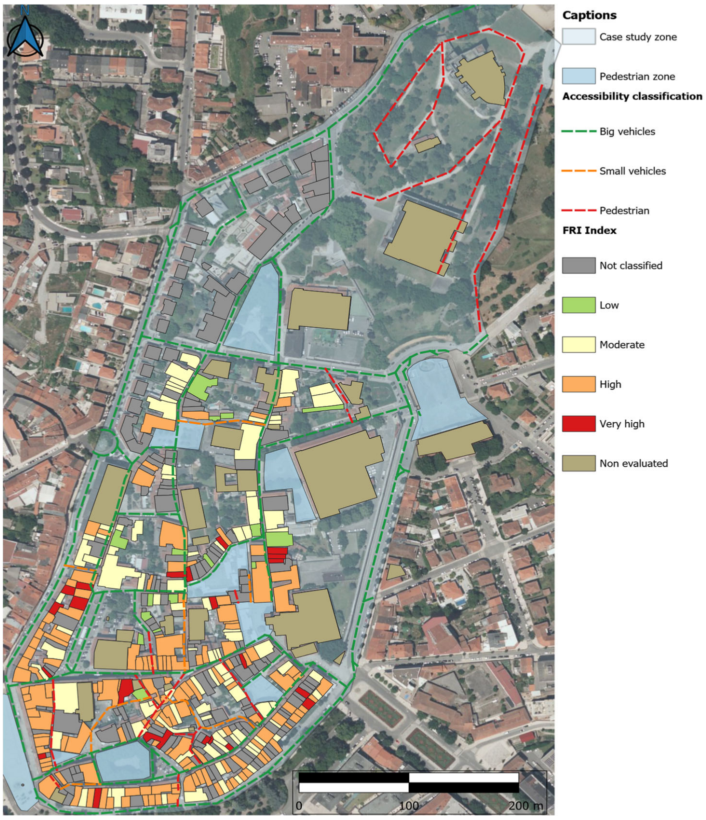
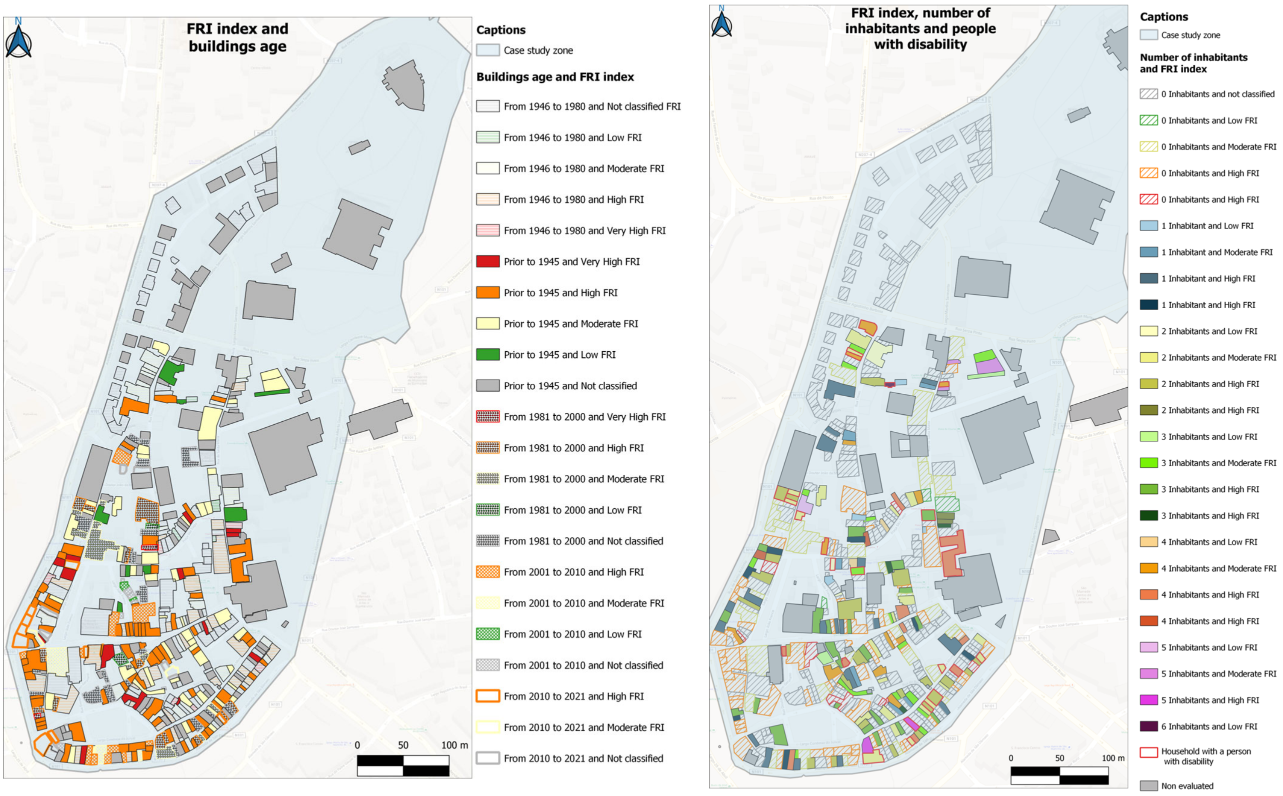


Figure 4. Spatial vulnerability map.

As a result, some parts of the city, even today, can only be accessed by pedestrians or by directly entering the buildings (such as Zones 4 and 5). These areas are particularly vulnerable during extreme events, as a fire originating in one of these zones could easily spread throughout the entire historic city center. This vulnerability is further exacerbated by the high Fire Risk Index observed in most buildings in this area.

4.3. Building Technique and Population Vulnerability

Figure 5 presents a comparative analysis of the identified characterized zones in terms of fire risk evaluation and the population potentially exposed to the risk. The analysis reveals that most buildings were constructed before 1945 and have a high or very high Fire Risk Index (Figure 5a). This high risk can be attributed to the traditional construction techniques employed in the city center. The dominant construction techniques, known as “taipa de rodízio” and “taipa de fasquio”, involve using plaster as the final coating within a timber matrix, followed by the application of handmade paints. These techniques, rooted in medieval practices, have persisted over time due to their ease of implementation. The “taipa de rodízio” technique is primarily used for exterior and interior walls above the ground floor, while the ground floor is always constructed using granite masonry. On the other hand, the “taipa de fasquio” technique is also employed for exterior and interior walls above the ground floor. These walls consist of wooden planks placed vertically and nailed to a second panel of diagonally arranged planks secured with a lath known as “fasquio”, giving the technique its name.



(**a**) (**b**)

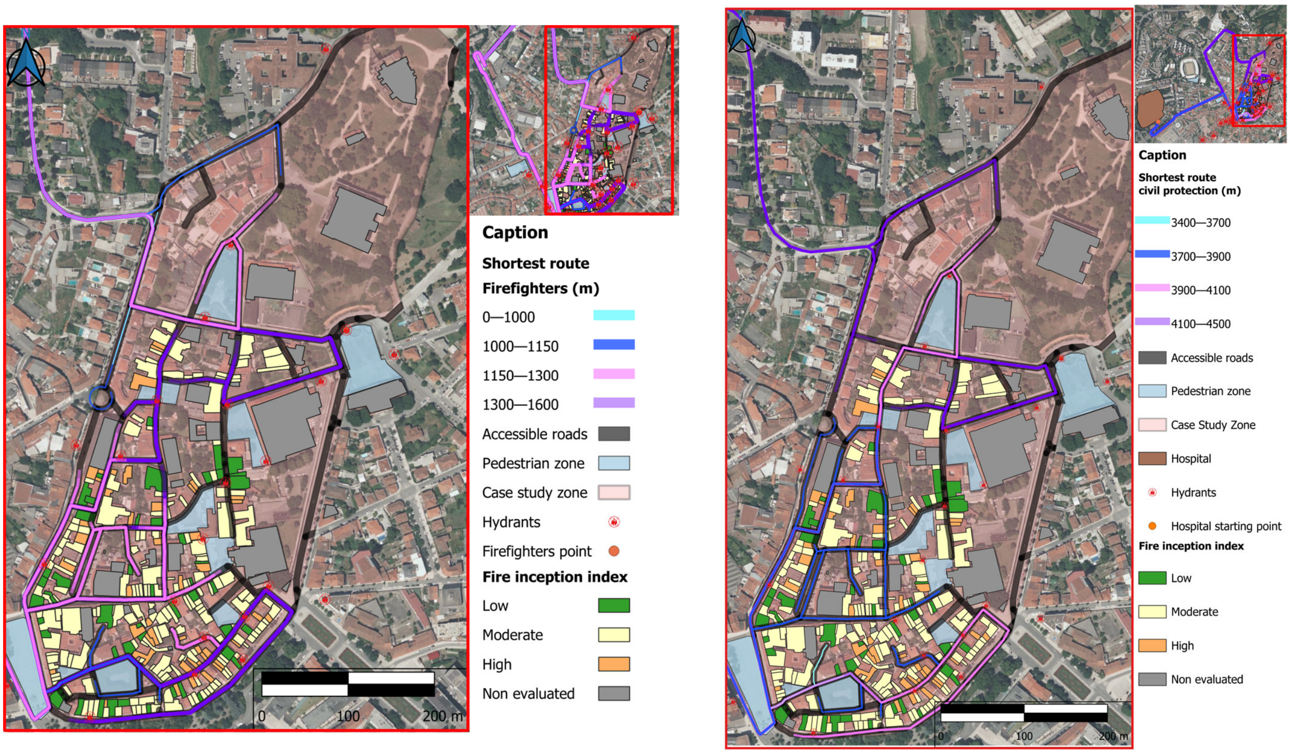
Figure 5. Mapping of the sociodemographic vulnerability. Legend (**a**) The age of the buildings and fire risk assessment and (**b**) the number of people living in each building, number of people with a disability, and fire risk assessment.

The analysis also considers the potential population exposed to fire risk. (Figure 5b). It is worth noting that most of the buildings do not have regular occupants. However, among those with regular inhabitants, there is a moderate to high risk, including families with three members, as well as residential buildings accommodating individuals with disabilities. This analysis underscores the vulnerability of the city center of Guimarães in terms of fire risk and emphasizes the importance of considering sociodemographic data in understanding the potential impact of fires in the area of study.

4.4. Crisis Management Vulnerability

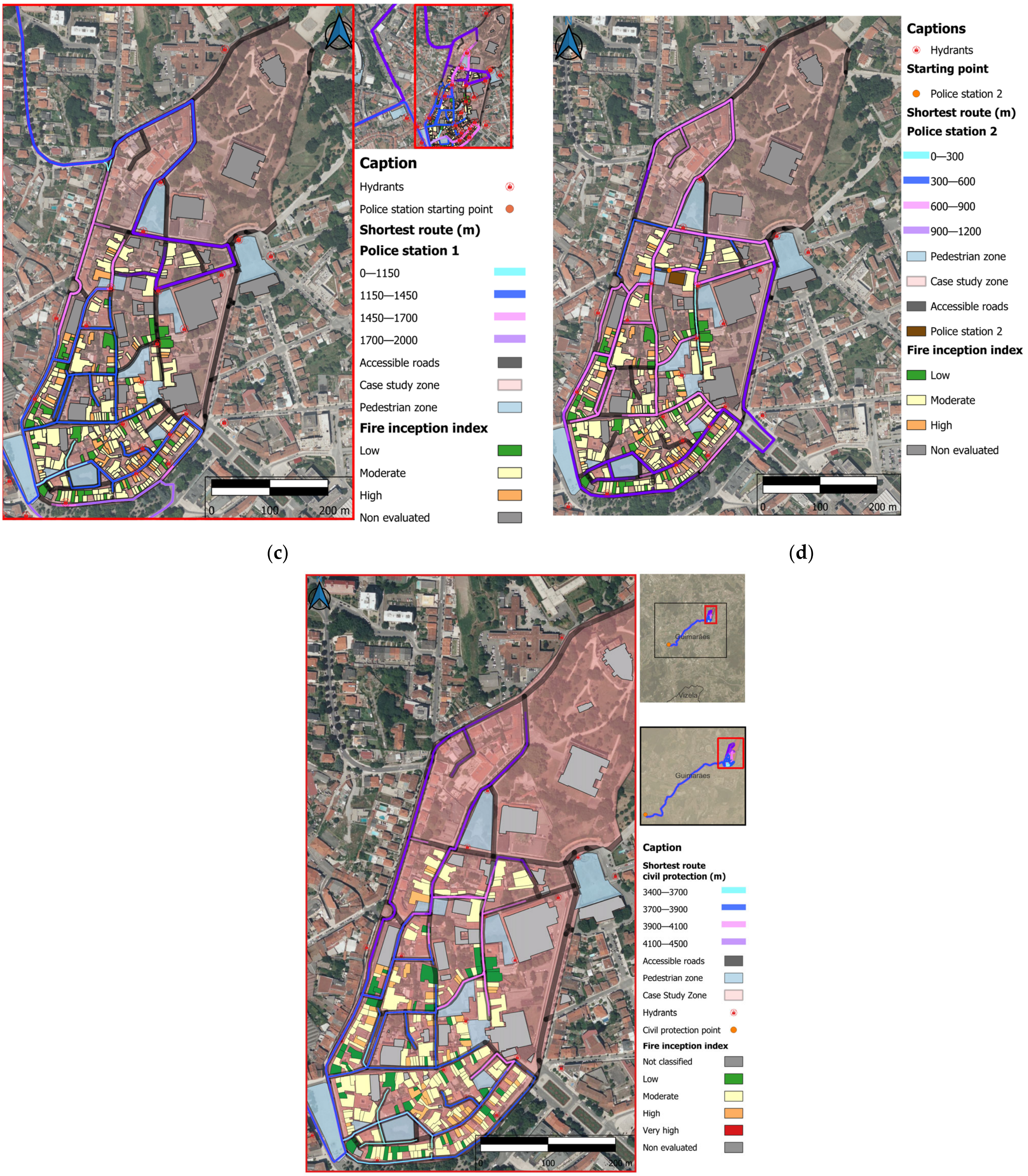
Upon examination, the obtained maps suggest that the majority of buildings within the study area pose a low to medium risk of ignition when considering all the factors combined, as mentioned in the preceding sentences. This finding indicates that firefighting operations can be conducted, provided that strategic plans are in place for emergency services, thereby minimizing potential impacts on the building stock and, most importantly, the population. It is important to highlight that no building presents a very high fire inception index; however, it is essential to implement improvement practices and measures, considering that a significant number of buildings possess a medium Fire Inception Index.

Furthermore, it is worth noting that the Civil Protection headquarters is located at a considerable distance from the city center, approximately 4 km (Figure 6e). Despite this distance, other emergency services are conveniently situated nearby or within the city center, offering various possible routes in case of a fire incident. These conditions signify that the historic city center has favorable circumstances for effective crisis management, facilitating the mitigation of significant fire-related impacts.



(**a**) (**b**)

Figure 6. *Cont.*



(**c**) (**d**)

(**e**)

Figure 6. Mapping of the crisis management vulnerability and the Fire Inception Index. Distance from the emergency services to the city center and possible accessibility routes (**a**) Firefighters, (**b**) Hospital, (**c**) Public Security Police, (**d**) Municipality Police, and (**e**) Civil Protection.

4.5. Territorial Vulnerability

By cross-referencing all the vulnerability mapping presented earlier, it is possible to identify the strategically vulnerable areas within the historic city center. Zones 2–5 emerge as particularly vulnerable based on different factors. Some of these zones have a high concentration of critical infrastructure, while others are deemed vulnerable due to the age of buildings, the population type and disabilities, and the inherent fire risk (Figure 7). It is crucial to acknowledge that these findings indicate a significant vulnerability across the majority of the historic city center. Therefore, when formulating emergency plans and strategies, extra attention and care must be dedicated to this specific part of the city. Safeguarding and mitigating risks in these vulnerable areas should be a priority to ensure the overall resilience and safety of the historic city center.

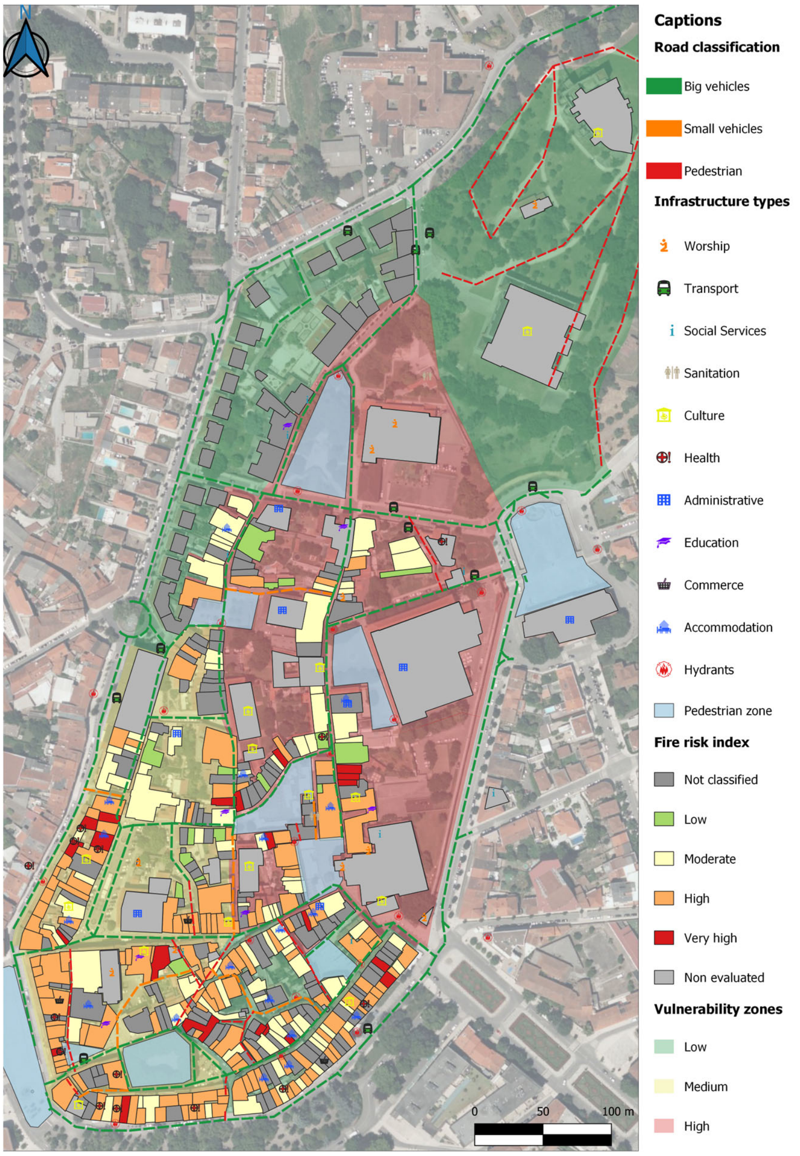


Figure 7. Mapping of the territorial vulnerability.

4.6. Discussion

The city center's close building proximity and limited access points create a vulnerability to fire outbreaks. Emergency services can access most buildings through surrounding roads, but certain areas are only reachable by pedestrians or direct building entry, potentially leading to rapid fire spread. The presence of numerous buildings with a high Fire Risk Index and medium Fire Inception Index further magnifies the vulnerability. To mitigate these risks, ensuring emergency service accessibility and implementing effective fire safety measures are crucial steps.

In line with [33], urban fire triggers in certain cases have been attributed to changes in illegal building usage. Regular inspections to enforce fire safety standards and ensure the proper condition of fire safety facilities are essential preventive measures. Additionally, [34,35] it is important to underscore the maintenance of technical installations, such as electrical and gas systems, in optimal conditions. The historical city center's specific limitations necessitate a focus on indoor installations. Similarly, ref. [21,35] emphasize vigilance over uninhabited buildings to prevent potential fire risks.

Local governments, as proposed by [33,34], must also take proactive measures to enhance fire safety consciousness among urban residents. Implementing fire prevention training programs, fire safety regulations, and building guidelines has proven effective in cities such as Hong Kong and Taipei [34]. Another important finding from our study suggests the need to establish efficient routes for emergency services, considering the distances to be covered and ensuring vehicles' capability to access each zone. Additionally, the analysis of fire hydrants per zone should be conducted, aiming to comply with Portuguese fire safety regulations.

Given the historic nature of most buildings in the area, it is essential to adhere to UNESCO guidelines and standards to preserve the unique architecture. As a result, advanced construction technologies do not apply to this case study. Moreover, improving vehicle access routes, as suggested by [10,34], may not be feasible due to the city center's constraints, where some areas are only accessible to small vehicles or pedestrians.

Overall, the combination of proactive measures and an understanding of the unique challenges faced in the historic city center of Guimarães will contribute to enhancing fire safety and resilience in this culturally significant area.

5. Conclusions

Overall, this study provides valuable insights into the critical infrastructure, fire risk, and vulnerability within the historic city center of Guimarães. The findings emphasize the need for robust emergency plans that prioritize the high-risk zones and consider the specific challenges posed by the medieval layout of the city center. By understanding the vulnerabilities and addressing areas of concern, stakeholders and authorities can enhance the resilience of the city center and ensure the safety of its residents and assets during extreme events, by providing adequate preparation and response to these events.

The unique characteristics of the city center, with its buildings situated close to each other and limited access points, present a particular vulnerability. While emergency services can access most buildings through the surrounding large roads, certain areas can only be reached by pedestrians or by directly entering the buildings. This poses challenges in the event of a fire outbreak, as it has the potential to rapidly spread throughout the entire historic city center.

The severity of this vulnerability is amplified by the high number of buildings in this area with a high Fire Risk Index. Furthermore, the examination of potential population exposure reveals that most buildings do not have regular occupants. However, among those with regular inhabitants, there is a moderate to high fire risk, including households with three members and buildings accommodating individuals with disabilities. This sociodemographic analysis highlights the vulnerability of Guimarães' city center to fire risk.

Based on these findings, it is imperative to prioritize emergency planning and preparedness efforts in the historic city center. Addressing fire risks in the historic city center of Guimarães requires a multifaceted approach, including regular inspections, maintenance of technical installations, proactive measures such as fire prevention training, and efficient emergency service routes. Adherence to preservation guidelines is crucial considering the area's limitations. Prioritizing emergency planning and preparedness, ensuring accessibility of emergency services, and implementing fire safety regulation, education, and awareness campaigns are vital to mitigating the high fire risk in the area. Proactively addressing vulnerabilities and adopting a coordinated approach to emergency response can enhance the resilience of Guimarães' historic city center, safeguarding residents' well-being and protecting its invaluable cultural heritage.

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