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Towards Urban Resilience: A Multi-Criteria Analysis of Seismic Vulnerability in Iasi City (Romania)

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Abstract: When relating to hazards such as earthquakes, a primary task of a resilience approach is to evaluate vulnerability in an integrative manner by taking into account the most relevant indicators. Focused on Iasi, one of the major Romanian cities which are exposed to the earthquakes originating in Vrancea area, this study aims to assess seismic vulnerability using a multi-criteria analysis of buildings infrastructure and social vulnerability. Several indicators are taken into account, such as physical (related to the characteristics of buildings and terrain) and social indicators (related to population and economic income), as well as the accessibility from/to emergency services/hospitals. The indicators were processed by standardization (Z score), processed and correlated using the principal components analysis (PCA) and integrated within an Analytical Hierarchy Process (AHP). By summing the weighted values of the standardized indicators, a (integrated) seismic vulnerability index was obtained. It is a pre-assessment of the seismic vulnerability in Iasi City and also a prerequisite for the identification of the necessary prevention measures to be taken in compliance with the identified spatial patterns of vulnerability as a part of a resilient approach.

Keywords: seismic vulnerability assessment; multi-criteria analysis; Iasi City

1. Introduction

Earthquakes are natural hazards occurring as ground shakings or displacements that are a big threat for human society due to damage or even collapse of built structures. The risk incurred by seismic activity is given by the sudden, unexpected nature of their outburst but also by the value of the potential material losses, injuries and deaths and disruption of social life [1].

The seismic risk is generally considered to be the probability of exceeding a given level of consequences in case of an earthquake at a particular site and during a certain period of time. The purpose of assessing it is to predict and map the damages expected at a particular territorial scale [2,3]. A simple framework for evaluating the seismic risk should calculate the seismic hazard for the site of interest and convolve this hazard with the vulnerability of buildings, infrastructure [4] and exposed population and assets.

The seismic hazard—the first component in the equation of seismic risk—is given by the scale of ground motion as a result of the intensity of an earthquake in a certain place and within a certain period of exposure [5]. The second component—exposure—can be defined by the number of people and value of goods and resources present in an area that could be affected by the hazardous event [6]. It is a precondition for risk and disaster, giving the ultimate measure of the degree of damages or injuries. Regarding the third component—vulnerability—increasingly numerous studies gives it the lead role in the risk equation. As well as resilience, vulnerability is an emergent concept as one can notice a shift from seeing disaster as an event caused by an external agent to a more sociologically oriented interpretation of catastrophes as a complex, socially, politically, environmentally and economically constructed process i.e., from reducing the probability of hazards towards diminishing vulnerability and increasing communities' resilience [7]. Post-disaster mitigation and adaptation also become important in order to minimize the impact of such events by assuring/providing shelter and sanitation or by planning reconstruction [8].

In a common approach, vulnerability is considered to be the degree to which a system or part of a system may react adversely and suffer losses during or after the occurrence of a hazardous event [2]. These losses vary geographically, over time and among different social groups inducing variations of vulnerability in time and space [9].

One can identify multiple dimensions of vulnerability reflecting various susceptibilities and sensitivities of different systems: (1) physical vulnerability related to the impact of events on assets based on geological features and constructed environment (buildings, and infrastructure); (2) social vulnerability that includes barriers to resilience related to the poor coping capacity of people; (3) economic vulnerability that encompasses sensitive economic assets and business interruptions; (4) environmental vulnerability that takes into account the possible impact of hazards on valuable and sensitive natural systems; and (5) systemic vulnerability comprising the accessibility to trauma and other support services [10].

When referring to seismic vulnerability, the main purpose is to evaluate the predisposition or probability of physical damage related to the geological features and built environment considering a certain earthquake scenario. In order to assess the physical seismic vulnerability of structures of an urban area, different tools can be used such as qualitative descriptors or variables, physical vulnerability indices, and capacity curves [5].

From a holistic perspective, a comprehensive seismic vulnerability assessment requires a multi-disciplinary approach that takes into account not only the direct impact (i.e., the expected physical damage, the number and type of casualties or economic losses), but also the difficulties in accessing trauma and other support services [11], as well as the indirect impact (i.e., the conditions related to social fragility and lack of resilience conditions, which sometimes favor the second-order effects when a high magnitude earthquake strikes an urban center [12–14]). Urban seismic vulnerability actually describes the degree to which physical assets and social-economic systems are susceptible or resilient to the impact of earthquakes [3,15].

Various integrated approaches should be taken into account as vulnerability is a fuzzy concept and an ill-structured problem that cannot be solved out through a unique optimal solution. In this sense, vulnerability is more a problem of spatial decision under the conditions of uncertainty [3].

A holistic approach of vulnerability as an early phase of urban resilience assessment constitutes an obvious need [16]. An opportunity in this sense is given by the multi-criteria analysis which links physical vulnerability, to social and systemic vulnerability or studies it in itself [10,11,17–19].

For Romania, the seismic hazard constitutes a serious threat not because of the occurrence of crustal earthquakes in different parts of its territory, inducing shallow and limited-area effects, but mainly because of sub-crustal earthquakes with hypocenters usually located at 100–130 km depth, originating in Vrancea zone at the Carpathians arch bend. Magnitudes may reach 7.5 on the Richter scale and the preferential directions of propagation of the seismic energy flow are NE and SW [20], affecting extended territories in the southern and eastern parts of Romania, which represent about one third of the country and support more than half the population. In this way, the capital city, Bucharest, and other large- and medium-sized cities such as Ploiesti, Galati, Focsani, Bacau and Iasi are vulnerable to seismic activity [21].

Over the past two decades, Romania has continuously updated its regulatory framework and building structure design codes in the seismic evaluation field, in direct connection to the European framework (EUROCODE 8). Maps of seismic hazard have been elaborated in terms of macro seismic intensity [22], peak ground acceleration [23] and spectral displacement at the fundamental elastic period of vibration. There have also been assessments made of physical seismic vulnerability specific to the conditions of Romania [24], particularly seismic surveys of the existing buildings stock in urban areas. More detailed studies have been focused on the seismic vulnerability of Bucharest [25–27]. Similar or more comprehensive earthquakes vulnerability assessments are needed for the settlements from southern and eastern parts of the country, outside the Carpathian arch.

For the interest area of this study—Iasi City—one should note several studies on seismic hazard [28,29] or residential buildings seismic risk assessments by correlation to the risk classes established after 1995 [30,31] and by application of GIS and statistical methods [32,33]. Most of these studies only refer to certain buildings within the city and are focused mainly on their structural vulnerability, while a comprehensive holistic vulnerability assessment at city level is still missing.

The purpose of this study is to evaluate seismic vulnerability in Iasi City in an integrative manner, using a multi-criteria analysis, taking into consideration certain indicators reflecting the physical vulnerability of the exposed buildings, but also the social and economic sensitivity of their inhabitants and the systemic accessibility for post-event context. It is not an engineering assessment, but a pre-assessment that gives a general picture of the most susceptible areas, this being an important stage/step for an effective resilient seismic risk management.

2. Study Area

Located in the Moldavian Plateau, at 170 km northeast form Vrancea zone, Iasi City is one of the largest urban areas in Romania, with a population of about 350,000 inhabitants [34] (Figure 1). The city lies in the floodplains and terraces of Bahlui River and of some of its tributaries and on their interfluves. The general geological framework is given by Sarmatian alternating sedimentary deposits consisting of clay, marl, sandstone, gravel and sand and surface alluvial, colluvial and delluvial deposits [35,36]. Geological and hydrogeological characteristics favor the occurrence of landslides on some important sectors of slopes.

The city's population is concentrated in the Bahlui floodplain, where large residential neighborhoods were built during the communist period [37], on a fragile substrate, facing serious problems related to groundwater movement, which can enhance vulnerability to seismic events. A potential risk is faced by those constructions which are located on hillsides, especially when associated to bypassing restrictions and defying building codes in the context of an urban inconsistent legislation.

The structure of constructions is rather complex and diverse: from historical monuments to high-rise collective buildings more than 40 years old, to critical facilities and one-story houses over 100 years old [38].

From the seismic point of view, Iasi City is subject to earthquakes, originating in Vrancea zone, which were historically recorded in 1471, 1516, 1620 and 1783. For the nineteenth and twentieth centuries five earthquakes with magnitude over 7 (1802, 1829, 1940, 1977, and 1986) resulting in material losses are mentioned [39]. Some spatial differentiations of earthquakes intensity and manner of manifestation were recorded within the city territory, which can be placed both on account of the surface geological heterogeneity and built environment behavior. The seismic waves are amplified across sediments areas, which are also subject to liquefaction by phreatic water level or by sand deposits under pressure.

Recent maps of seismic hazard highlight significant values for Iasi City: according to the map of macroseismic intensity, the city falls into the zone with values of 7.5; according to "Seismic design code—Part I—Provisions for buildings design" (P100-1/2013) for earthquakes with 100-year average recurrence interval, Iasi is situated within the zone with a peak ground acceleration ag = 0.25 g (Figure 1); on the map elaborated in terms of spectral displacement at Tc, Iasi City is attributed to the value of 0.7 s.

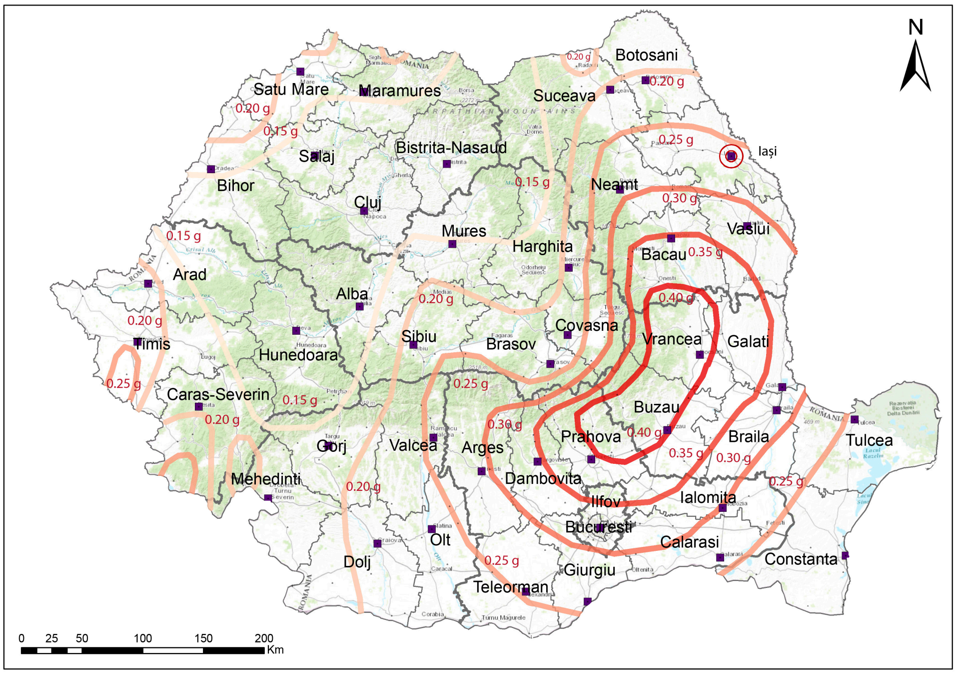


Figure 1. Location of Iasi City on the Romanian zoning map in terms of peak ground acceleration for earthquakes with a 100-year return period (Data source: [39]).

3. Materials and Methods

The multi-faced concept of vulnerability and the (lack of) resilience in case of seismic hazards can only be described by electing an appropriate set of proxy variables (dependent variables). In this case three categories of indicators were taken into consideration. The first is related to the physical features of buildings and terrain, the second includes social characteristics (population indicators and economic values), while the third takes into consideration measures of accessibility from/to emergency services/hospitals. Using specific statistical methods, an integrated seismic vulnerability index was obtained.

The first step of the methodological approach was to integrate data in order to construct a comprehensive GIS database (see Table 1) by using official available data and field studies, comprising data on buildings in the city and their inhabitants as well as terrain landslides susceptibility—having in view that the latter puts seismic vulnerability in relation not only to ground stability, but also to the phreatic level which affects the foundations of buildings and, therefore, increases seismic risk.

Information was obtained mainly from field research, but also from different official institutions such as Iasi City Hall and Chamber of Civil Law Notaries & Real estate evaluations (prices of apartments), or other public documents and databases which are detailed in Table 1.

One of the most important indicators of the present assessment is represented by the seismic risk classes. The technical audit of seismic risk is required by the Ministry of Regional Development and Public Administration (within the Seismic Risk Mitigation Programmes, see http://www.mdrap.ro/) and ordered, in the case of Iasi municipality, by the local authorities (City Hall) in many stages between 1992 and 2015. The authorized experts evaluate the state of the buildings using a comprehensive form. After 1996, the seismic classes provided by national authorities are the following:

- High risk (R1)—Risk of collapsing in case of an earthquake with a magnitude higher than 7;
- Average risk (R2)—No major risk of collapsing in case of earthquake, but risk of structural damages;
- Low risk (R3)—Small damages in walls or decorations that can endanger the safety of the inhabitants; and

- No risk (R4)—No major risk in case of earthquake. Buildings with no risk were not taken into consideration in the present study.

In Iasi Municipality, 385 buildings were catalogued in classes with seismic risk (R1, R2, and R3) and they were also taken into account in present study. The rest of the buildings record no seismic risk or have not been evaluated by the experts. Most of the buildings with seismic risk fall into the third category (low risk—218), followed by high seismic risk (92), while the average seismic risk affects the other 75 buildings. In addition, in order to complete the missing data from the official technical reports, questionnaires were filled within a field research and Google Street View visualization was used for each building, both activities being carried out in November 2015.

Based on all these data, the vulnerability indicators were configured and grouped into three categories according to the physical, social and systemic dimensions already commented above. They are explained in Tables 1–3:

Table 1. Categories of vulnerability indicators—Physical vulnerability.

Indicator/ACRONIM	Description	Data Source	References
Seismic risk categories/RISK	Established by the official experts' reports made until 2015 by taking into account physical characteristics and state of buildings	Iasi City hall—public information	[30]
Age of buildings/AGE	It also helps determine the type of construction and materials in a certain area	City hall site, GIS database that included information from other scientific papers, older maps	[10,40–42]
Number of floors/FLOORS	It distinguishes the percent of buildings with one or two floors from those that have 3 or more floors	Field research, Google Street	[10,42]
Structural types of buildings/MATERIAL	The materials have different stiffness, strength and ductility capacity to inertial forces that exert stresses. Two main categories were taken into account: (a) unreinforced masonry buildings; and (b) reinforced concrete buildings	Existing databases, field research	[40,42]
Total area of exterior walls/WALLS	The walls provide the primary lateral resistance/stability to earthquake loads. Determined by calculations considering the perimeter and the height of buildings, also taking into account the average percentage of openings which could be an evidence of soft-story mechanisms	GIS database, own calculations	[17]
Thermic rehabilitation/THERMO	Improving thermo-isolation should succeed or be a part of the consolidation process of buildings. Otherwise it represents a drawback for a future structural rehabilitation	Google street, field research	[22,28,43]
The state of building structure/REHABIL	Obtained from numerical simulation or field survey to assess damage of a structure	Former studies, field research	[31,41]
Terrain landslide susceptibility/SLIDE	Gives an insight on the increasing damages caused by associating earthquakes to geology, slope and land use	Published work data	[44]

In the case of physical vulnerability, the first indicator (seismic risk categories) was decisive in establishing/calibrating the weights of the variables (although the collinearity effect had to be removed, given the fact that it includes some of the other indicators, therefore it is redundant to a certain degree).

Table 2. Categories of vulnerability indicators—Social Vulnerability.

Indicator/ACRONIM	Description	Data Source	Reference
Population density/INHAB_DENS	A high concentration of population within a relatively small area can increase damages in case of a strong seismic event	Census data 2011, field research, estimation	[14]
The percent of elder population/ELD_POP	Elder population is more sensitive to injures and life losses, especially when there are old people living alone (>70 years old)	Census data 2011, field research, estimation	[11]
Total number of inhabitants/TOT_POP	Gives an indication on total human losses or injures that could take place in case of a disastrous earthquake	Census data 2011, field research, estimation	[40]
Empirical economic losses/ECON_VALUE	Based on the estimated value of each building, it takes into account specific indicators of building values distribution and presumes, in addition, that, generally, the more expensive the residence the higher the value of the assets that could be subject to destruction in case of earthquake	GIS database, own calculations, real estate market and minimum prices established	[42]

Table 3. Categories of vulnerability indicators—Systemic Vulnerability.

Indicator/ACRONIM	Description	Data Source	Reference
The density of buildings/BUILT_DENS	Density and height of buildings, at district scale, could facilitate the occurrence of barriers in case of collapse	GIS Database, Google Street views	[27]
Distance to hospitals/HOSP_DIST	Distance from hospitals and trauma centers gives a certain level of population vulnerability to adverse health outcomes just after a major earthquake	GIS Database, Google Street views	[11]
Distance to emergency services/EMERG_DIST	Time for emergency services (ambulance, SMURD, firemen) is highly important in order to get to damaged building and contribute to saving lives	GIS Database, Google Street views	[3,11]

The social vulnerability comprises not only the total number and the percentage of sensitive population, but is also a reference to the value of assets that are subject to losses in case of calamity. They were calculated by taking into account the minimum market value of apartments as stated by Chamber of Civil Law Notaries and Real Estate evaluations.

Regarding the systemic vulnerability, spatial arrangement and quality of transport infrastructure are considered essential for proper road access to hospitals and emergency management stations [45]. A distance based network analysis and the calculation of densities were able to provide a simple but suggestive image on the system capacity to face a seismic disaster [11].

Furthermore, statistical data processing was done by using a multivariate analysis in order to reduce the number of variables and to extract the underlying dimension of vulnerability. It is stated that a challenge in decision-making processes involving multiple criteria is how to measure the relative importance of each criterion amongst a group of criteria which transposes to different levels of significance for the decision-makers [40,46]. The indicators were processed by standardization (Z score) and by factor analysis (PCA). Further they were integrated by using the Analytical Hierarchy Process (AHP). The reason to initially use PCA was to obtain a first objective assessment of the relevance of each indicator and of the whole set of indicators to confirm the selection of the variables and to derive a set of components that explains the social vulnerability characteristics, while analyzing the correlations between all indicators [47]. This was used in the second part of the methodological approach in order to calibrate weights for all indicators and categories by pair-wise comparison within AHP.

AHP method, developed by Saaty [48], was used in order to find weights for the indicators. The method is considered a multi-criteria decision making tool useful to find suitable alternatives also for seismic vulnerability [49]. It offers a matrix model of integrating indicators, based on the systemic interpretation by pair-wise comparison of a list of factors, options or alternatives. Basically, each factor is rated against every other factor by means of predefined scores (from 1 to 9) indicating their relative importance (Table 4). In order to ensure that the weighting of the criteria pairwise is not random, AHP incorporates the calculus of consistency ratio (CR).

Table 4. Scale of preference between two parameters in AHP [48].

Scales	Degree of Preferences	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one activity over another
5	Strongly	Experience and judgment strongly or essentially favor one activity over another
7	Very strongly	An activity is strongly favored over another and its dominance is shown in practice
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9
Reciprocals	Opposites	Used for inverse comparison

Finally, an (integrated) seismic vulnerability index was constructed by using a simple additive weighting method, i.e., the linear sum of weighted indicators. The software used for statistical purpose was XLStat 2016 trial version. Meanwhile, data analysis for AHP was done using AHP priority calculator (open source) developed by Klaus D. Goepel http://bpmsg.com. Maps were made using ArcGIS software, version 10.2.2 produced by Environmental Systems Research Institute (ESRI, Redlands, CA, USA, 2014).

4. Results

4.1. Physical Vulnerability

The integration of the physical vulnerability variables showed a lack of accuracy of data. Therefore, in order to obtain the indicator, the risk categories of buildings were used for calibration. It is stated that some of the variables are already integrated when including constructions in categories of at-risk structures. The conclusions of technical expertise conducted between 1992 and 1996 classified examined buildings into three emergency classes, while since 1996 the buildings have been classified into four classes of seismic risk I–IV (those in classes I and II are considered to require seismic retrofitting) [50].

Mapping data on the buildings which are officially classified as falling in one of the first three classes of seismic risk led to obtaining a first relevant image of the spatial distribution of physical seismic vulnerability in Iasi City (Figure 2).

Information regarding buildings inventories and technical expertise reports show that most of the buildings that were included in one of the three risk/emergency classes are mainly residential (>95%) and comprise a population of about 47,000 inhabitants (13% of the total city population). They are located especially in the central, southeastern (Podu Ros) and eastern parts (Ciurchi) of the city, but also on the hilly side of Pacurari district in the west.

There are numerous variables that can explain these results, but only some are available and accurate (age of buildings, construction materials, number of floors, and total area of exterior walls) while others, although used in literature, proved to be less feasible (thermic rehabilitation, the state of building structure, and terrain landslide susceptibility).

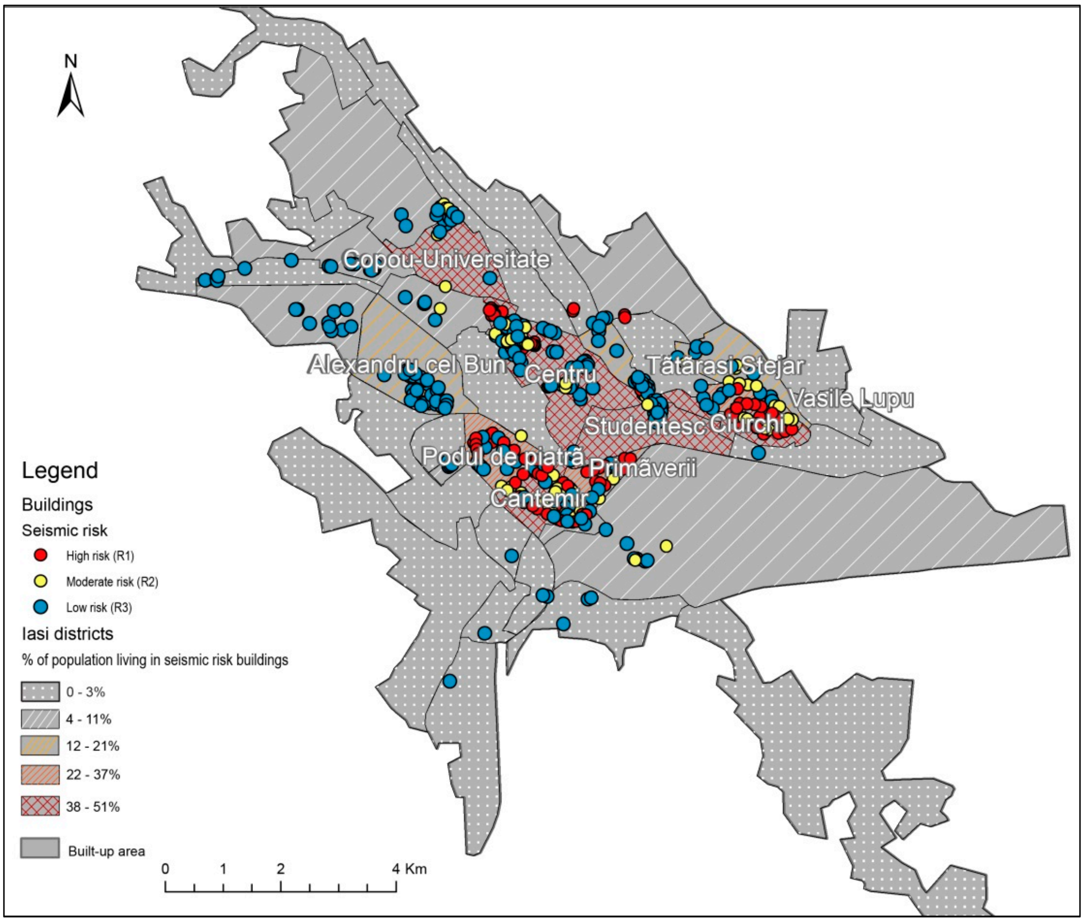


Figure 2. Spatial distribution of buildings by categories of seismic risk and the percent of population living in these buildings by districts in Iasi.

The type of construction material and the age of buildings seem to play the most important part and are the most relevant predictors in this case. The correlation between seismic risk and the age of buildings is strong but it sometimes leads to false conclusions. Many of the old buildings (1920–1945) in the central area or Copou district are included in the 1st or 2nd category of seismic risk. The same risk defines many constructions located in the east of the city (Tatarasi district, Vasile Lupu, and Ciurchi) or in the central-south area (Podu Ros–Primaverii, and Cantemir) constructed before the 1977 earthquake. Meanwhile, there are also buildings constructed in the same period in the western part of the city (Alexandru cel Bun and Dacia districts) that have lower seismic risk [33]. On the other hand, in the neighborhoods with old buildings brick and stone represent the prevailing constructions material, while many of the later communist districts have masonry and concrete blocks of flats [36]. Depending on construction the methods and materials, brick, in particularly, becomes, in time, more susceptible to seismic damage than reinforced concrete structures [33]. Shear wall buildings are included in the most vulnerable category of four-level blocks constructed after 1965 [38].

The number of floors and the exterior surface of walls are two correlating indicators that give a clue on the possible effects of a strong earthquake. Although high rise-condominium blocks of flats with more than five floors expose many people and a higher value of assets, in Iasi, the risk to collapse is lower (because of the construction methods and materials), most of the buildings exposed to a collapse risk have 1–2 floors (in the central area) or five stories (the majority, in residential neighborhoods).

4.2. Social-Economic Vulnerability

The total population that is exposed to an earthquake represents the most important variable that has to be taken into account when analyzing vulnerability. The typical high-rise condominium buildings, with a high number of inhabitants should be given very much attention especially when they are included in 1st or 2nd risk class. Most of these are located in the central area, Tatarasi district and Cantemir neighborhoods. Meanwhile, in the central and industrial area, there are many buildings that have very few inhabitants or are completely deserted.

When analyzing the number of senior population (aged over 70 years old) living in the analyzed buildings and the age dependency ratio (the percent of senior population in the total adult population), one can notice that the highest values are concentrated in the central area and in those neighborhoods with a high standard of living (Copou district) (Figure 3). Higher contingencies of young population (including many children, which also represent a sensitive population category) are located in Cantemir–Podu Ros and Tatarasi districts, but especially in the neighborhoods dating back to the later communist period (Alexandru cel Bun and Dacia districts), being planned for a large number of inhabitants and high densities [36].

The social-economic vulnerability is also correlated to the prices of the apartments on the real estate market. The apartments in blocks built in the 1960s and 1970s have relatively lower values even though they are in attractive urban areas (Cantemir, Primaverii, Tatarasi–Ciurchi, Vasile Lupu, and Tudor Vladimirescu–Studentesc) compared to others, from more less desirable neighborhoods which are newer, more comfortable and have a lower seismic vulnerability (Frumoasa, Industrial District CUG II) [35].

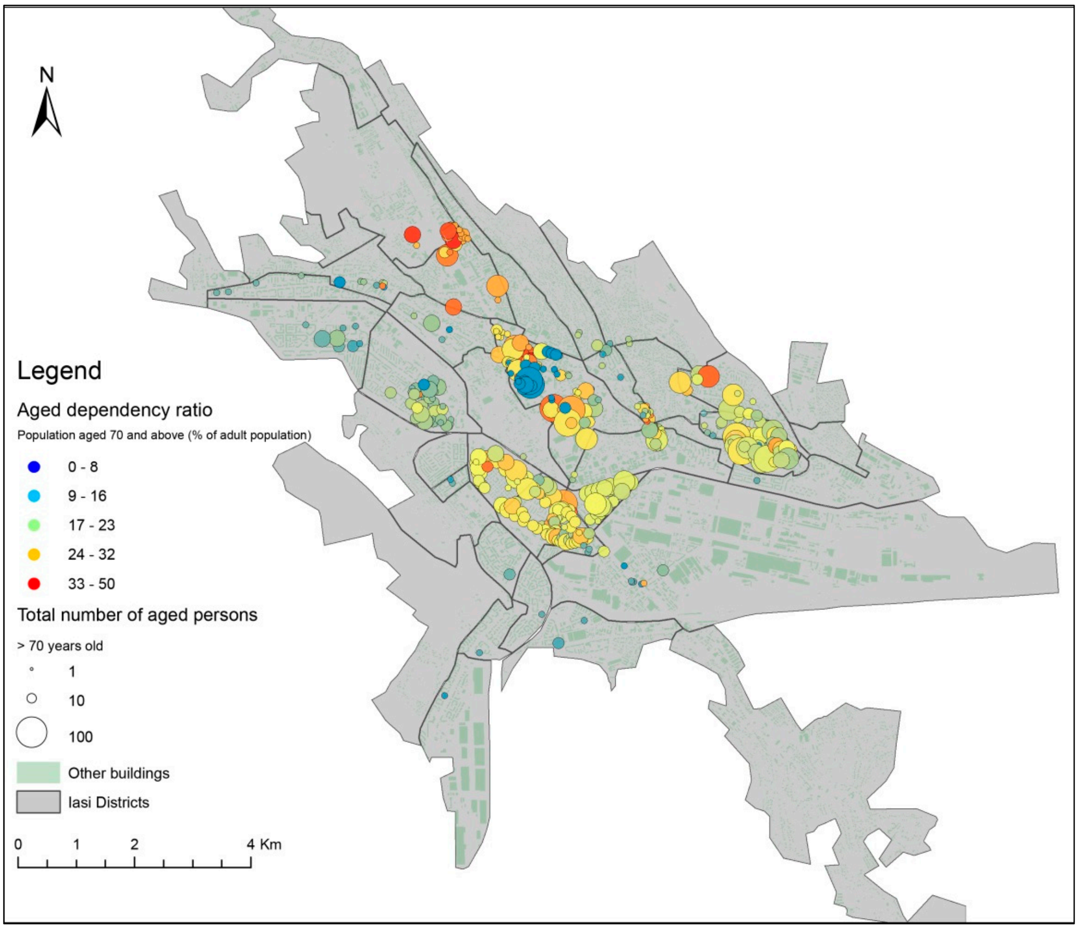


Figure 3. Elder population in buildings presenting seismic risk in Iasi City.

4.3. Systemic Vulnerability

It is known that travel distance from emergency services and to trauma centers is significantly negatively correlated to the chances of survival for the injured. In Iasi City, the access of emergency service vehicles depends on location, in relation to the two-main ambulance/SMURD stations in Copou and Primaverii districts.

Northern and southern neighborhoods are advantaged, while the eastern and western areas face longer delays (Figure 4), especially if taking into account the low fluency of traffic at certain hours [37].

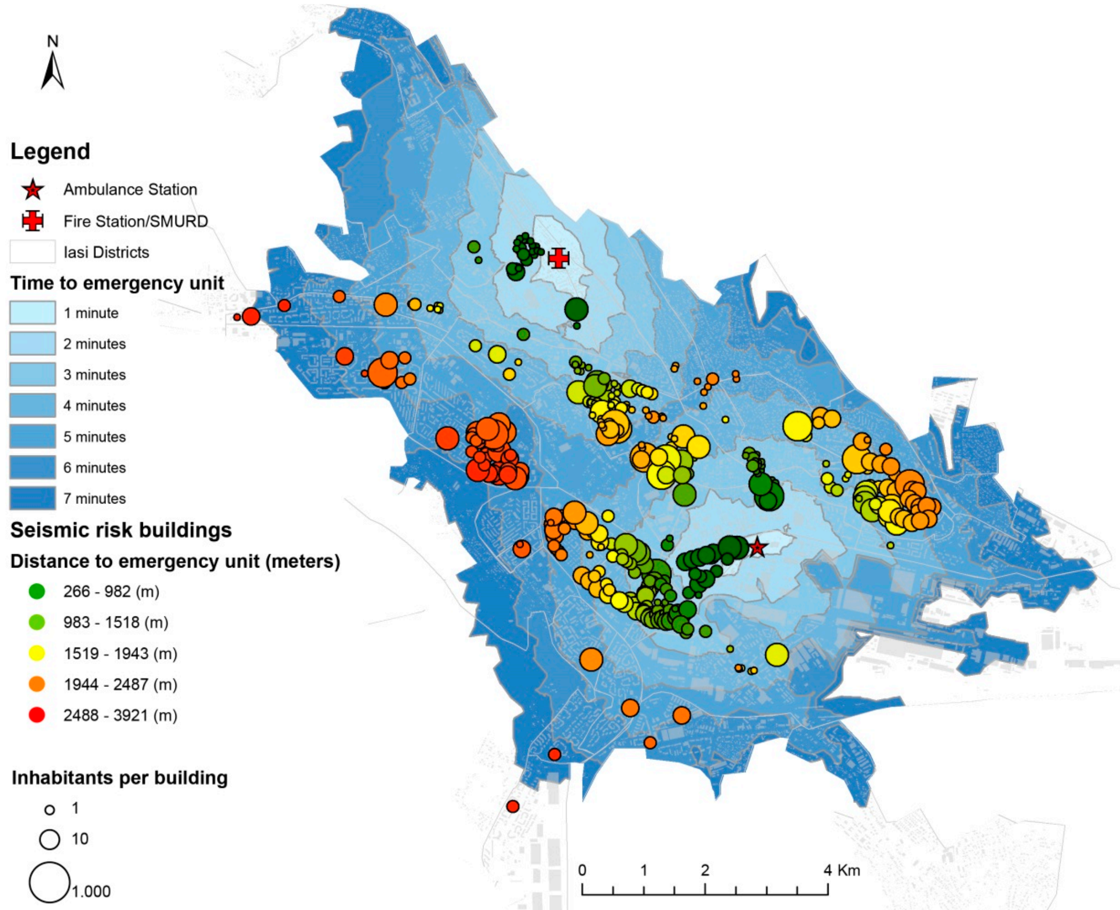


Figure 4. Distance and time-distance to emergency services in Iasi City.

Hospitals are more homogenously located, but there are two main clusters (Figure 5). The most important is in the northern and northeastern parts of Iasi, with many hospitals situated close to the central area, but also on Copou and Ticau Hills. The second is in the south and southwest with fewer, private or narrowly specialized hospitals that serve a rather numerous population. Meanwhile, higher time-distance values are specific to peripheral districts, some hosting a numerous population (Pacurari) or being areas of recent urban expansion (Pacurele–Valea Lupului).

Other issues have also to be taken into account: in Iasi, 21 hospitals were classified as seriously damaged, requiring immediate technical assessment, 17 being subject to a technical report, 2 being approved for retrofitting and 5 being already retrofitted [51].

High densities of constructions (especially when dealing with high buildings) were also taken into account since they could create barriers in case of seismic damage. For example, in the central area, the frontline of old highly vulnerable buildings on both sides of Cuza Voda street, which is crossed by heavy public transport (tramways, essential for urban connectivity), presents a major risk in case of building collapse, which could block the access within the area. High densities of buildings are also typical of Mircea cel Batran, Cantemir, Podu Ros-Tudor Vladimirescu districts, especially in areas with smaller apartments, while Copou district and the peripheral areas have a higher percent of open spaces and lower densities of houses, which reduces structural vulnerability.

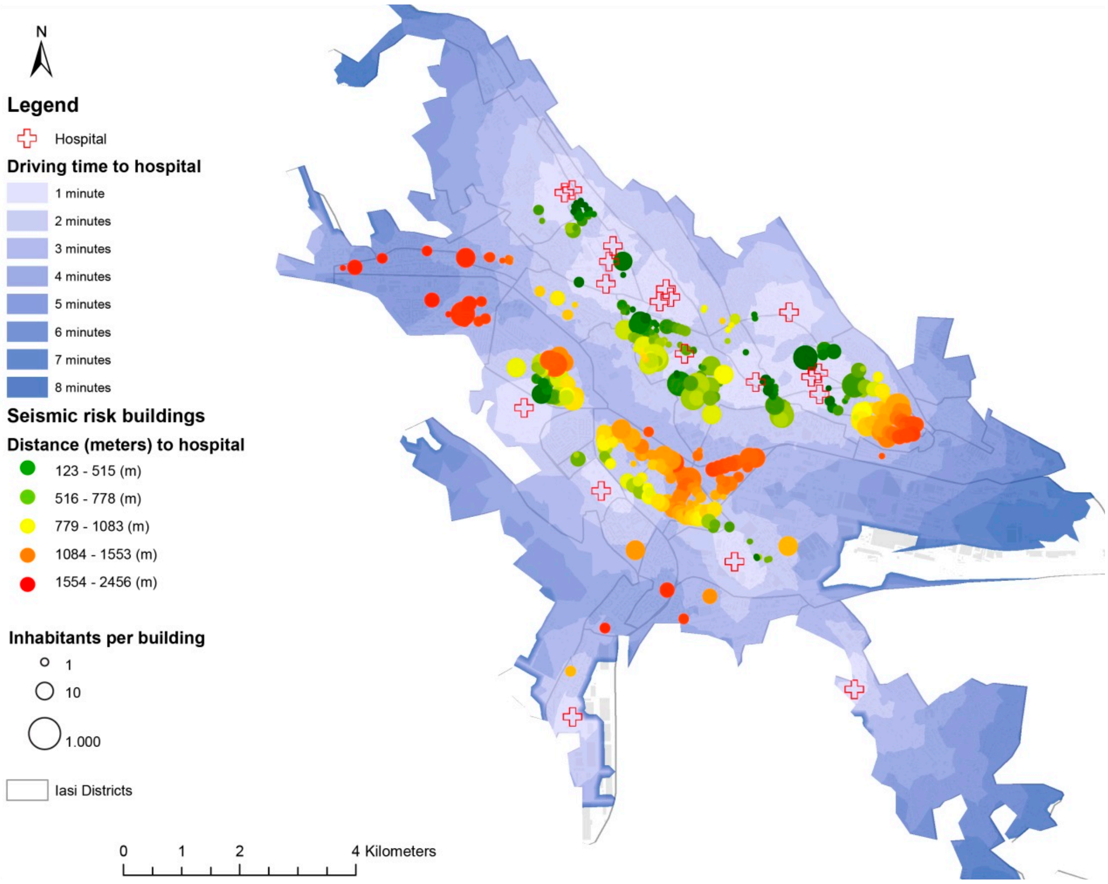


Figure 5. Distance and time-distance to healthcare units/hospitals in Iasi City.

4.4. Integrated Assessment of Vulnerability

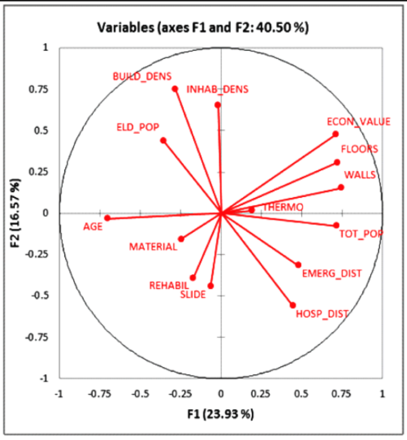
The results of processing indicators by using standardization (Z score) and the principal components analysis (PCA) are presented in Figure 6, revealing the Spearman correlation matrix, variables factor map (correlation circle) and the graphic which shows the relation between seismic risk classes and the other indicators taken into account. The indicators weights, obtained by applying the AHP method, are displayed in Table 5. The table shows the weights of indicators within the category to which they belong (obtained by normalizing the values assigned in the pair-wise comparison) and the consistency ratio (CR) which is required to assess the reliability of the obtained weights. It also shows the weight of each category of indicators and the corresponding CR. In the AHP, the resulting CR must be less than 0.1 in order to accept the computed weights [48]. The CR values of the present analysis demonstrate a trustworthy judgment of our approach.

The PCA results demonstrate certain important correlations between the age of buildings and the older population, while older residences have usually a smaller number of stories and lower densities of people (and total population). This is characteristic to many constructions built before 1945, mainly those located in the central and Copou areas, some being part of the historical heritage and therefore not suitable to be inhabited, but still functioning as residences especially for the elder population.

Correlation matrix (Spearman):

	AGE	FLOORS	MATERIAL	WALLS	THERMO	REHABIL	SLIDE	INHAB_DENS	ELD_POP	TOT_POP	ECON_VALUE	HOSP_DIST	EMERG_DIST
FLOORS	**-0.519**												
MATERIAL	**0.176**	**-0.227**											
WALLS	**-0.311**	**0.463**	-0.099										
THERMO	**-0.140**	**0.127**	**-0.119**	0.056									
REHABIL	**0.161**	**-0.204**	**0.165**	-0.047	**-0.508**								
SLIDE	0.004	**-0.116**	**0.110**	-0.051	-0.086	**0.124**							
INHAB_DENS	**-0.110**	0.081	-0.059	0.093	-0.075	**-0.109**	**-0.117**						
ELD_POP	**0.351**	-0.046	**0.106**	**-0.141**	-0.021	-0.094	**-0.146**	**0.122**					
TOT_POP	**-0.351**	**0.494**	-0.034	**0.480**	0.027	-0.003	-0.084	**-0.357**	-0.031				
ECON_VALUE	**-0.365**	**0.518**	-0.077	**0.720**	-0.049	**-0.119**	**-0.168**	**0.368**	-0.036	**0.556**			
HOSP_DIST	**-0.257**	**0.157**	-0.025	**0.231**	0.065	**0.185**	**0.130**	**-0.234**	**-0.275**	**0.311**	0.059		
EMERG_DIST	**-0.369**	**0.158**	-0.088	**0.214**	0.046	-0.061	0.099	-0.036	**-0.426**	**0.171**	**0.146**	**0.197**	
BUILD_DENS	0.088	0.058	-0.019	**-0.152**	**-0.198**	**-0.128**	**-0.207**	**0.423**	**0.256**	**-0.229**	**0.151**	**-0.500**	**-0.316**

Values in bold are different from 0 with a significance level alpha=0.05



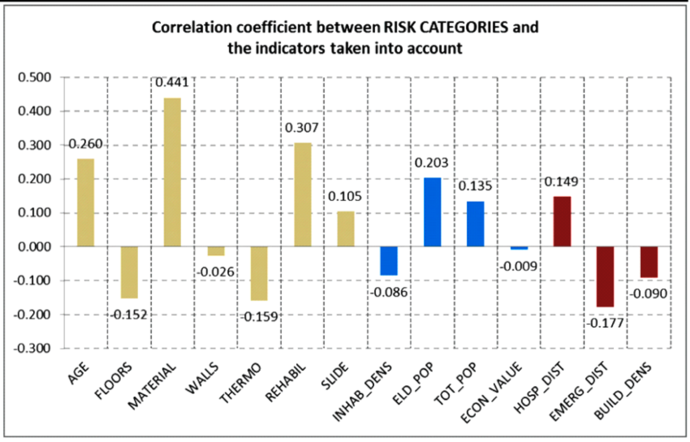


Figure 6. Principal Components Analysis (PCA) results.

Table 5. AHP resulted weights.

Indicator	Weight (Priority)	CR	Category	Weight (Priority)	CR	Final index
AGE	22.8%	0.042	Physical vulnerability	59.5%	0.006	Integrated seismic vulnerability index
MATERIAL	37.6%					
WALLS	13.7%					
FLOORS	8.7%					
SLIDE	8.8%					
REHABIL	5.7%					
THERMO	2.7%					
INHAB_DENS	29.6%	0.008	Social-economic vulnerability	27.6%		
ELD_POP	6.9%					
TOT_POP	51.5%					
ECON_VALUE	12.1%					
EMERG_DIST	60.0%	0.000	Systemic vulnerability	12.8%		
HOSP_DIST	30.0%					
BUILD_DENS	10.0%					

Nevertheless, both distances from emergency services and to hospitals are smaller for the old residential constructions with high seismic risk. The high buildings have usually a high total number of inhabitants and total economic value, but they have a lower accessibility to hospitals and emergency services.

When taking into account exclusively the relation between the risk categories and the others indicators, there is a significant positive correlation of coefficients with construction materials (0.441), structural rehabilitation (0.307) and age of buildings (0.260), while the number of floors (−0.152), thermal rehabilitation (−0.159) and distance to emergency centers (−0.177) are negatively correlated.

Therefore, seismic vulnerability shows that most of the areas at risk are rather resilient when it comes to post-earthquake intervention. Nevertheless, two peripheral areas are vulnerable both in terms of the distance from emergency services and to hospitals. The first is the western area—a dynamic district that juxtaposes, outside the city, an area of (peri-)urban expansion (Valea Lupului commune). The second, located in the southwestern part of the city is influenced by the presence of railways, including the railway station of the former industrial area that creates barriers and discontinuities within the urban body.

The integrated seismic vulnerability index gives a synthetic view on the analyzed matter (Figure 7). The most vulnerable neighborhoods are Cantemir—Podu Ros—Primaverii—a large area with numerous buildings at risk and sensitive population. The central area is less populated, but includes more the 50% of the analyzed buildings having significant risk to collapse in case of a high magnitude earthquake. A high percent of vulnerable buildings is also in the eastern part of Tatarasi district (Ciurchi).

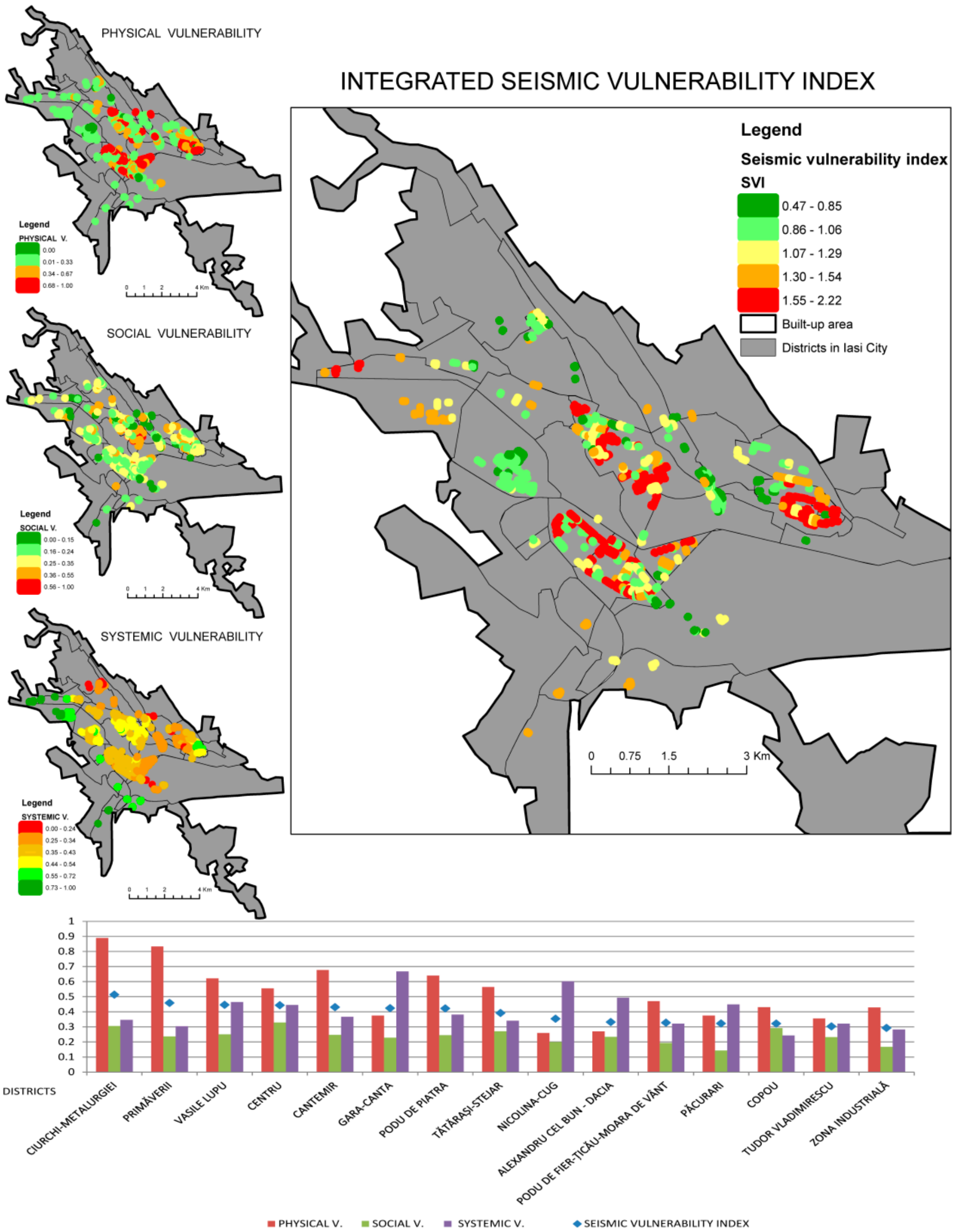


Figure 7. The Integrated Seismic Vulnerability Index (SVI).

By contrast, the least vulnerable areas in terms of the number of at-risk buildings are Copou (with low social and systemic susceptibility), Tudor Vladimirescu and the industrial area, with smaller social vulnerability. Average values are typical of neighborhoods that excel in only one type of vulnerability: Podu de Piatra and Tatarasi-Stejar with high physical vulnerability, and Canta-Gara Nicolina-CUG and Alexandru cel Bun-Dacia with high systemic vulnerability.

5. Discussion and Conclusions

Vulnerability to earthquakes is dependent on particular conditions that influence the physical environment and the capacity of the society to cope with disasters. It does not depend so much on the spatial distribution of hazards, but on the characteristics of urban fabric [3] and sometimes on the social-economic state of households [15] sustainable livability, which diminishes vulnerabilities.

The purpose of this study is to evaluate seismic vulnerability in Iasi City in an integrative manner, using a multi-criteria analysis, by taking into consideration certain indicators reflecting the physical vulnerability of the exposed buildings, but also the social and economic sensitivity of their inhabitants, and the accessibility to emergency services and hospitals in case of disaster.

It is work in progress, a pre-assessment of vulnerability in Iasi, offering a general picture of the areas which are most susceptible of physical destruction of buildings and assets, human losses and injuries, sustained by high densities and sensitive groups of population and the delays in response caused by the location of emergency services and hospitals or by barriers that can appear in densely constructed sectors.

The multivariate analysis of these indicators facilitated their integration by establishing certain weights in order to obtain a complex index of vulnerability, but it also permitted the observation of certain clusters of buildings (although sometimes spatially dispersed), with similar features and confronting similar issues. By combining two statistical methods that seem rather redundant, the purpose was to use the results of the first (PCA) in order to ground the (subjective) approach of the second (AHP). Finally, the integrated seismic vulnerability index is an outcome of a holistic approach of vulnerability in Iasi, one of the Romanian cities that are exposed to seismic activity capturing its spatial variation at neighborhood and building scale.

The proposed model has to be improved and reiterated. Study limitations and drawbacks are related to the lack of (access to) complete databases that induced a certain lack of accuracy and consistency in the case of certain indicators. Although there is a need for adding more indicators, while others should be refined, the removal of some values would also be useful. The number of buildings to be taken into account should be higher as some of the districts are, by far, underrepresented in the analysis. Meanwhile, in order to give weights to the indicators within AHP, existing literature (but referring to other case studies therefore not applicable as such) and the opinion/expert knowledge of the authors (therefore subjective) was also used within the model. Nevertheless, although the consistency ratio in the process was very good, the algorithm being therefore suitable in this case, it could be applied in other contexts only in an adapted form.

As a general outcome of the present work, one could assert that the efforts of planners and decision makers in adopting general mitigation measures and adaptive risk governance [52], should be oriented towards:

- Retrofitting vulnerable buildings in order to reduce the physical damage of the built environment;
- Making technical audits for more buildings that might be vulnerable in order to provide reports indicating the category of risk in case of an earthquake;
- Reducing spatial barriers and discontinuities in order to provide fluent transport and effective intervention in case of disaster;
- Planning places for gathering and relocating densely populated area after an earthquake, increasing potential for rescue and supplementing centers of intervention and health care (including the regional hospital in the western part of the city); and

- Informing and instructing the sensitive population in order to properly react in extreme situations caused by earthquakes [53].

In conclusion, vulnerability, as well as resilience, is an ill-structured problem, which means that there is no unique, identifiable, objectively optimal solution, but rather a multitude of approaches that could be taken into consideration. In this sense, vulnerability is more a problem of spatial decision under the conditions of uncertainty. Spatial patterns of seismic vulnerability of 385 buildings in Iasi City, identified as hot spots, could be important within the decision-making process in order to prioritize the above-mentioned measures of reducing actual vulnerability by diminishing weaknesses, by taking into account the characteristics of each individual building, but also by planning the preparedness, response and adaptation of urban structures and of the city as a whole in case of a major earthquake.

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