Methodology for provision assessment indexes based on Spatial Multi-Criteria Decision Making

Methodology for provision assessment indexes based on Spatial Multi-Criteria Decision Making for seismic-flood-meteo-tsunamis

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Summary

List of abbreviations and terms

PAI – Provision Assessment Index

GIS – Geographic Information System

MCA – Multi-Criteria Analysis

MCDM – Multi-Criteria Decision-Making

Abstract

This Deliverable presents methodology for provision assessment indexes based on Spatial Multi-Criteria Decision Making. A state-of-the-art is given in regard to risk analysis, especially to combined risk analysis of multi-hazard. Methods and approaches are analyzed and proposal of methodology for provision assessment index based on MCDM PROMETHEE method is given. The methodology is evaluated for multi-hazard on HR test site Kaštel Kambelovac.

1 Introduction

Enhancing safety and resilience for disasters due to natural hazards requires knowledge about individual territorial hazards, vulnerabilities and risks, appropriate multi-risk methodology to combined individual risks as well as an integration of existing data and knowledge with methodology for combining risks into an interactive and easily understanding map that will enable the visualization of individual and combined risks. Integration of this methodology in open GIS and ICT-based information systems will give important information to local and regional authorities for preventing, managing and overcoming multi-hazard natural disasters specific for Italian and Croatian nuts, such as river and sea floods, meteotsunamis (or extreme sea waves) and earthquakes which are the subject of analysis in the PMO-GATE project.

The exposure of the Italian and Croatian test areas to natural hazards differs. Namely, the Italian test area of Ferrara is exposed to river floods and earthquakes. The Croatian test area (Kastel Kambelovac) located along the eastern Adriatic coast is endangered by rising sea levels due to climate change, high sea waves caused by changes in atmospheric pressure, wind speed and direction and earthquakes. Some of these hazards are mutually independent while others affect each other and increase the vulnerability of the area. For example, river floods and earthquakes in the Italian test area can generally be analyzed as independent phenomena, however in the case of seismic damage of water lifting plants, which is focus of the investigation in the PMO-GATE project, the flood risk increase due to their out-of-service. In the Croatian test area, rising sea levels due to climate change in the long run increase the risk of flooding of low-lying old stone buildings in the historic area of Kastel Kambelovac, but also raise the level of oscillations of high sea waves caused by changes in atmospheric pressure and wind direction and speed. Therefore, this phenomenon can be observed dependent on one another or independently. The impact of the earthquake will be seen as an independent phenomenon.

Since completely different hazards are studied, it is necessary to have a robust multi-risk methodology that will provide information on the area's exposure to combined hazards, both with the aim of preventive action and increasing the area's resilience, and at the moment of the danger. Methodology based on Spatial Multi-Criteria Decision-Making offers an approach for combining individual hazards and/or vulnerabilities and/or risks for such different phenomena which are addressed in this project.

PMO-GATE project approach is based on the following key research issues:

- **Multi-hazard approach:** An innovative methodology for preventing, managing and overcoming multi-hazard natural disasters in the involved IT-HR NUTS, and increasing the level of protection and resilience against natural disasters specific of the IT-HR NUTS, such as river and sea floods, meteo-tsunamis (replaced with high sea waves) and earthquakes will be developed. The approach is based on definition of probabilistic scenarios with detailed analysis and identification of the hazard level for mentioned natural disasters in the respect of the community legislation governing the Strategic Environmental Assessment.
- **Vulnerability analysis:** Definition of individual building vulnerabilities is based on vulnerability index method for characteristic territorial hazards (sea floods, extreme sea waves and earthquakes)

- **Risk analysis based on multi-level GIS approach:** Data obtained by hazard and vulnerability analyses will be integrated in the multi-level GIS maps together with other important data which can influence to the overall risk. In order to develop the methodology for assessment of single and multi-hazard exposure in coastal and urban areas, an algorithmic approach has been made for evaluation of "*Provision assessment index*" (PAI) based on Spatial Multi-Criteria Decision-Making and presentation on the Web Map.
- **Risk assessment and risk plans**: Risk assessment is a basis for development of risk plans which will be integrated on a cross-border level with a bottom-up approach respectful of the real IT-HR territorial challenges, namely taking into account peculiar multi-hazards and multi-vulnerabilities at the urban, extra-urban and rural level. A plan of risk management aimed at overcoming the emergency conditions with the least possible social and economic impact will be developed.

2 Provision Assessment Indexes based on Spatial Multi-Criteria Decision-Making

In the PMO-GATE project, the Risk assessment has multi-criteria approach because its factors (criteria) cannot be mutually summed or multiplied, but instead some multi-criteria analysis or multi-criteria decision-analysis method must be used. The coping capacities are not in the project scope, but plan of risk management can definitely reduce the severity of the hazard impact.

2.1 Methodology for Provision Assessment Index

2.1.1 Factors in the Risk assessment

A common practice in the hazard risk assessment is to focus on the hazard frequency and intensity in combination with area vulnerability or severity of damage caused by the hazard (Kappes et al. 2012). Furthermore, the severity is not just result of hazard intensity and area vulnerability, but also by the coping capacity of the emergency units in the area (Greiving et al. 2006). Hazard occurs in some period of time with some intensity and causes damage (severity of the hazard) which is a function of area vulnerability and coping capacity.

A brief literature survey was made among scientific and professional papers to investigate what are the common factors used to calculate the risk of a natural hazards (Table 1).

Table 1. Literature survey on factors used to calculate the risk of a natural hazards

Approach	Factors				Output	Source
	Frequency	***Intensity***	***Vulnerability***	***Other***		
Single hazard	Yes	No	No	Damage	Risk	Di Mauro et al. 2006
Multi-hazard	Yes	Yes	Yes	Coping capacity	Risk	Fleischhauer et al. 2005
Multi-hazard	No	Yes	Yes	Coping capacity	Integrated risk	Greiving et al. 2006
Single hazard	Yes	Yes	No	No	Risk	Kunz et al. 2008
Multi-hazard	Yes	Yes	Yes	Consequence (loss)	Risk	Liu et al. 2017
Multi-hazard	Yes	No	No	Aggregated losses	Risk	Mignan et al. 2014
Single hazard	No	No	Yes	Hazard exposure, Exposed value	Risk index	Munich Reinsurance Company 2003
Single hazard	Yes	Yes	No	Area impact	Hazard score	Odeh Engineers, Inc. 2001

Multi-hazard	Yes	No	Yes	Social vulnerability	Place vulnerability	SCEMD 2002
Multi-hazard	Yes	Yes	Yes	Elements at risk, Temporal / Spatial probability	Risk	Van Westen 2017

From Table 1, it is clear that hazard frequency (or probability of occurrence) is the most common factor used in risk assessment in 80% of the papers. Some of the approaches are focused on hazard intensity and some on vulnerability in combination with damage or loss (severity or consequence of hazard). However, 50% of the papers dealing with multi-hazard approach are taking into account all three emphasized factors (frequency, intensity, vulnerability) and additional other factors.

So, in multi-hazard risk assessment many factors are used. Since each factor can represent one criterion, evaluation of these factors can be used as an input matrix for multi-criteria analysis, thus ushering the application of some multi-criteria analysis or multi-criteria decision-analysis method.

The reason of using of so many factors when calculating multi-hazard Risk assessment is in fact that, according to standard for risk assessment ISO IEC 31010:2009, the Risk assessment is the overall process of Risk identification, Risk analysis and Risk evaluation (EC 2010). According to this norm, multi-criteria analysis or multi-criteria decision-analysis method is suitable for the Risk assessment.

2.1.2 Multi-hazard risk assessment

The problem of the multi-hazard risk assessment is not just in designing a proper calculation to aggregate all hazard risks in one area (Fleischhauer et al. 2005), but also to take into account hazards mutual correlation (Liu et al. 2017), because one hazard can trigger creation of another hazard. For instance, the fires are usually spread after the earthquake, and the earthquake can produce tsunami, thus flooding the area. All this must be taken into account when assessing multi-hazard risk.

The second problem of the hazard risk assessment, both in multi-hazard and single-hazard approach, is dealing with low-probability – high-consequences events (Mignan et al. 2012). This issue represents a huge problem, since earthquakes can have high intensity but their frequency is usually very low, so the risk calculation of multiplying intensity and frequency will result with low risk level. Therefore, additional factors need to be taken into calculation to emphasize the risk from earthquakes and similar hazards which are low-probability – high-consequences events.

2.1.3 Vulnerability analysis

As mentioned above, the vulnerability is one of the important inputs (factors) in the risk assessment. Namely, high vulnerability of the area can result with severe losses during low intensity hazard and low vulnerability of the area can result with minor losses during the high intensity hazard. Many different criteria are used for vulnerability calculation, because criteria set is also defined by the type of the hazard (Kappes et al. 2012). However, assessing vulnerability to natural hazards such as earthquakes can be regarded as an ill-structured problem or a problem without unique, identifiable, objectively optimal solution. A review of the literature indicates a number of contrasting definitions of what vulnerability means, as well as numerous conflicting perspectives on what should or should not be included within the broad assessment of vulnerability in cities (Rashed et al. 2003). For instance, some authors also include coping capacity (emergency units) of the area in the vulnerability analysis (Greiving et al. 2006). But this is not necessarily good approach since coping capacity is something that can dynamically change each year and other common vulnerability criteria (building age, building structure, building height, etc) are less or more static.

Regarding the vulnerability analysis, it is important to mention that different vulnerability analysis are used at different scales (Vicente et al. 2011), Figure 2. The different criteria sets (parameters or factors) are used and sometimes different methods must be used as well.

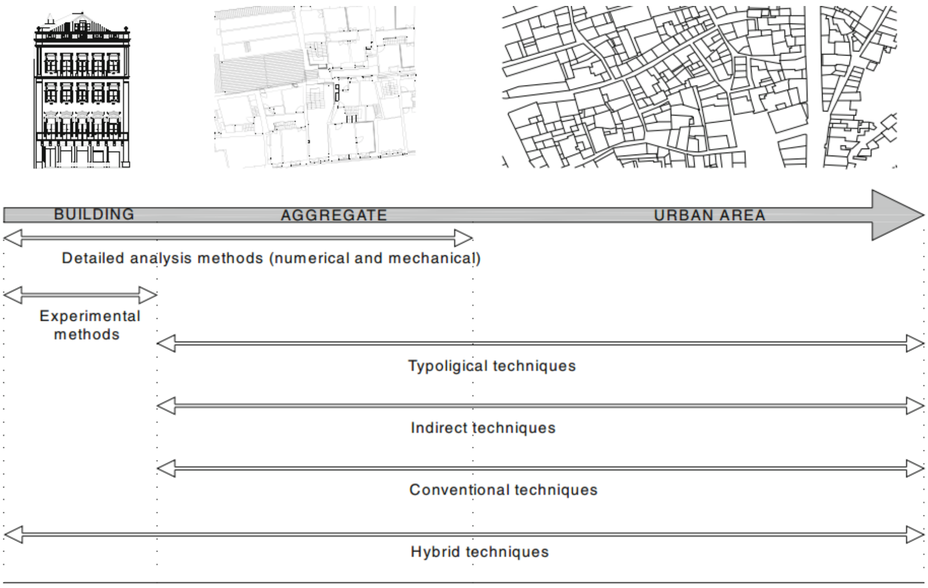


Figure 1. Different type of vulnerability calculations on different scales (Vicente 2011)

The initial set of data for building a methodology based on multicriteria analysis has a starting point in WP3 of PMO-GATE project where vulnerability analysis starts on a building scale in order to estimate vulnerability of each object that is potentially exposed to individual hazard. An analysis will be performed for the potential exposure of buildings to earthquakes, extreme sea waves, and flooding due to sea level rise induced by climate change. The result of vulnerability analysis on a building scale will be vulnerability index expressed on a 0-1 scale. Vulnerability index scale will be categorized to explicitly express the expected state of buildings after being exposed to some type of hazard.

Seismic vulnerability is calculated by methodology for vulnerability assessment (PMO-GATE Deliverable 3.3.1 Guidelines of the assessment procedure for earthquake vulnerability in HR test site). It consists in filling in a survey form composed of 11 parameters, calculations of those parameters and finally, calculation of the vulnerability index for the building. Vulnerability of buildings is estimated mostly based on the structural properties of an object as well as geometry and current state of examined building, which in total express the vulnerability (or resistance, inversely) to seismic impact. Similar, vulnerability of buildings for extreme waves' impact will be estimated based on the building capacity to withstand a hydrodynamic force induced by an extreme wave on the coastline. This type of vulnerability depends on the structural properties of buildings, geometrical proportions and building material. Vulnerability of buildings to coastal flooding due to long-term sea level rise will be estimated similarly, by taking into consideration the potential effect of the flooding impact. Vulnerability is estimated based on the supporting structure material (foundations, floors, walls) that can be damaged if exposed to sea water. In addition, number of floors and geometrical proportions of some object play additional role in estimating vulnerability.

Estimation of vulnerability of objects gives an important information to decision makers (further description within deliverables of WP3), which can be used to define priorities of potential reconstruction measures and list of objects to be improved. However, this analysis is insufficient when analyzing potential hazard impact on a larger spatial scale. Vulnerability index can provide useful information but the vulnerability analysis on a larger spatial scale implies inclusion of additional vulnerability effects in order to provide appropriate information. Since vulnerability analysis on a larger spatial scale is intended for a larger group of stakeholders, especially emergency managers, additional criteria are identified that lead to potential damage on some endangered area. Those criteria are specific for each particular area, and their estimation is based on the expert assessment as well as local stakeholders' opinion. This means that each municipality, city or region defines their own vulnerability criteria based on their preferences and priorities.

2.1.4 Multi-level GIS approach to Risk assessment

Geographic Information System (GIS) serves as a perfect tool for the visualization purposes (Figure 3) and spatial decision making in the Risk assessment (Rashed et al. 2003; Vicente et al. 2011).

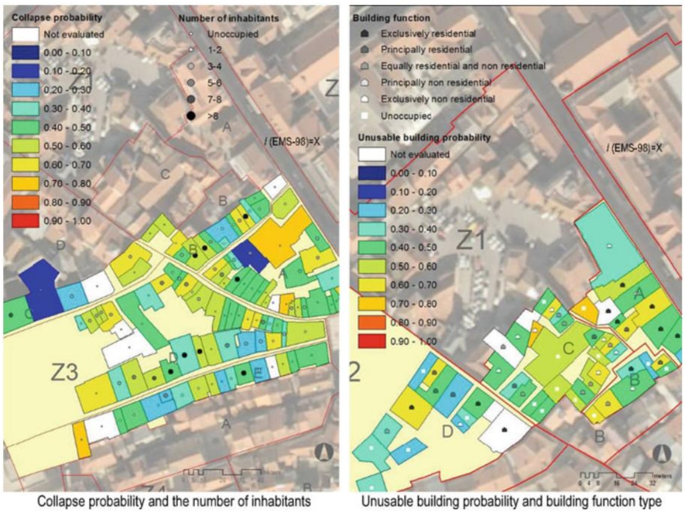


Figure 2. GIS analysis and visualization of buildings data (Vicente et al. 2011)

Generally, by using multi-scale approach and different criteria sets, the vulnerability analysis could be made for a building, its settlement, settlement's municipality, and, at the end, for the whole region. This kind of multi-level and multi-criteria approach is presented in Figure 4.

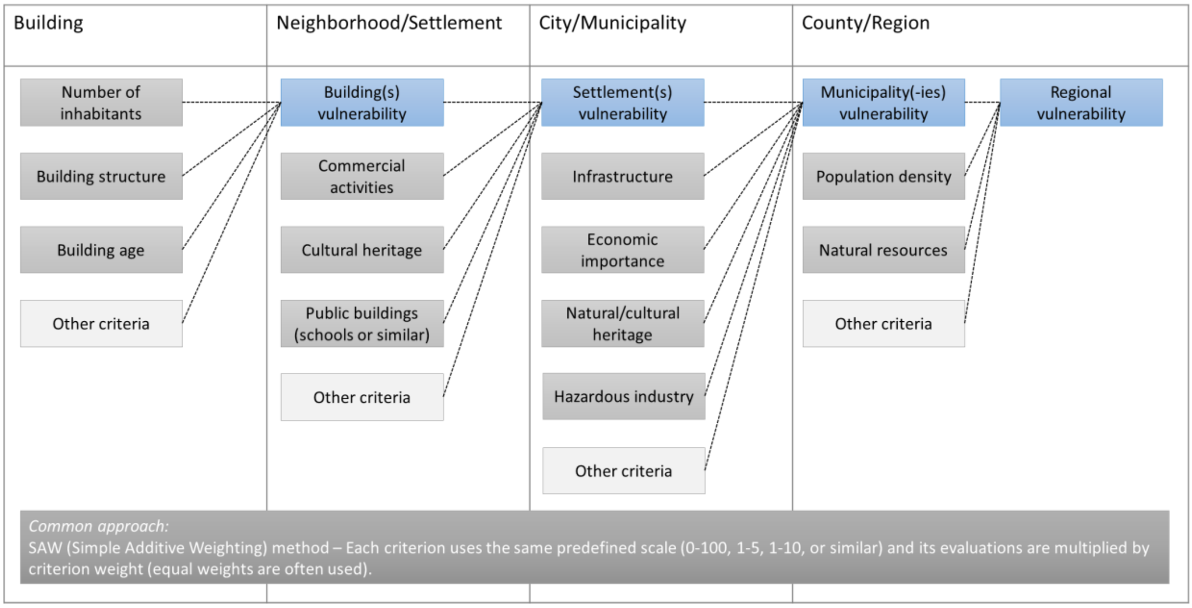


Figure 3. Vulnerability analysis at different scales with multi-criteria approach

The PMO-GATE project proposal defined that the data and risk plans will be integrated on a cross-border level with a bottom-up approach respectful of the real IT-HR territorial challenges. This is ushering for Risk assessment and Vulnerability analysis on different scales and multi-level GIS approach. The objectives of the PMO-GATE project are to define vulnerability and assess risk on the level of buildings and areas or settlements.

Since risk assessment will be made for particular assessment area, these areas need to be defined by mutual spatial characteristics or by some already defined urban entity. HR test site is a small area and it represents one urban entity (one cadastral municipality), therefore it is very important how to define these assessment areas: as "working units" or as "homogeneous zones".

One of the possible approaches is the definition of assessment areas as "working units" by using grid of blocks. The working unit is the geographical entity in which the calculations will be computed, hereby controlling the geographical resolution of the study. The definition of the working unit depends strongly on two factors: the geographical unit in which the original data are expressed and the scale of the study. In the urban-scale seismic risk study for city Almería, a 200 m squared grid was considered appropriate to cover the entire city of Almería, totalling an amount of 400 equal cells or working units (Rivas-Medina et al. 2013).

The second approach is to define assessment areas as "homogeneous zones" which are generated by intersecting relevant thematic layers. For HR test site, part of Kastela City (Figure 7), the approach of “homogeneous zones” is used. The thematic layers for definition of “homogeneous zones” have been selected for each single-hazard.

Figure 4. PMO-GATE: HR site – Kastel Kambelovac

2.1.5 Multi-Criteria Analysis and Decision-Making approach to Risk assessment

In order to develop the methodology for assessment of single and multi-hazard exposure in coastal and urban areas, an algorithmic approach has been made for evaluation of "***Provision assessment index***" (PAI) based on Spatial Multi-Criteria Decision-Making and presented on the Web Map.

Provision assessment index (PAI) is an indicator of the exposure to the various natural hazards so that represents total exposure to the risk of different areas and that through single and multi-hazard exposure.

In the analysis of natural hazards, impacts are often expressed in terms of vulnerability and exposure. Vulnerability (V) is defined as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. Exposure (E) is the totality of people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses. Therefore, the risk is a function in dependence of vulnerability and exposure:

$$\text{Risk} = f\,(E, V)$$

In the PMO-GATE project, the exposure (E) that corresponds to the measure of hazard will be presented by Intensity (e.g. Peak Ground Acceleration (PGA) for the earthquake) and Area Impact (e.g. area exposed to earthquake, flooded area for sea flood). Furthermore, vulnerability will be evaluated on multiple levels (for the particular buildings, for the settlement, for the city, etc.) with the use of different criteria for different level. Function *f* represents mathematical PROMETHEE (*Preference Ranking Organisation METHod for Enrichment Evaluations*) method (Brans et al. 1984) that will connect all criteria and asses the risk for observed area.

Using the concept of vulnerability makes it more explicit that the impacts of a hazard are also a function of the preventive and preparatory measures that are employed to reduce the risk. Depending on the particular risk analysed, the measurement of risk can be carried out with a greater number of different variables and factors, depending inter alia on the complexity of the chain of impacts, the number of impact factors considered and the requisite level of precision.

The scheme of assessment of single-hazard and multi-hazard exposure for HR test site is shown in Figures 8 and 9.

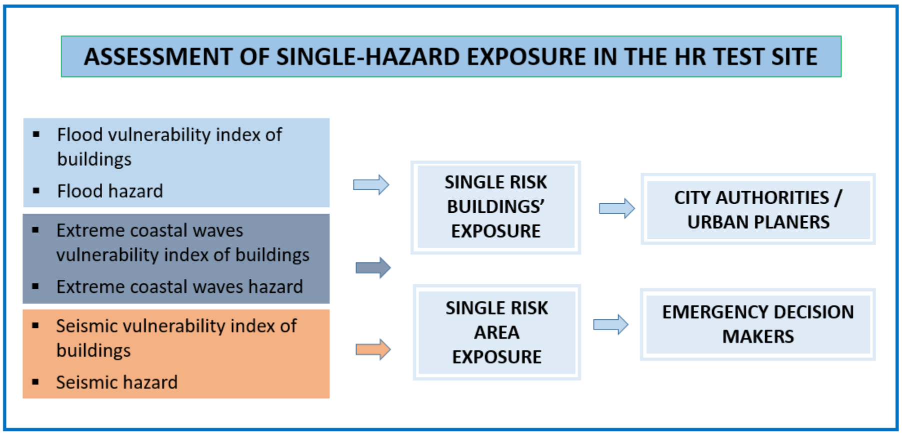


Figure 5. Assessment of single-hazard exposures for HR test site

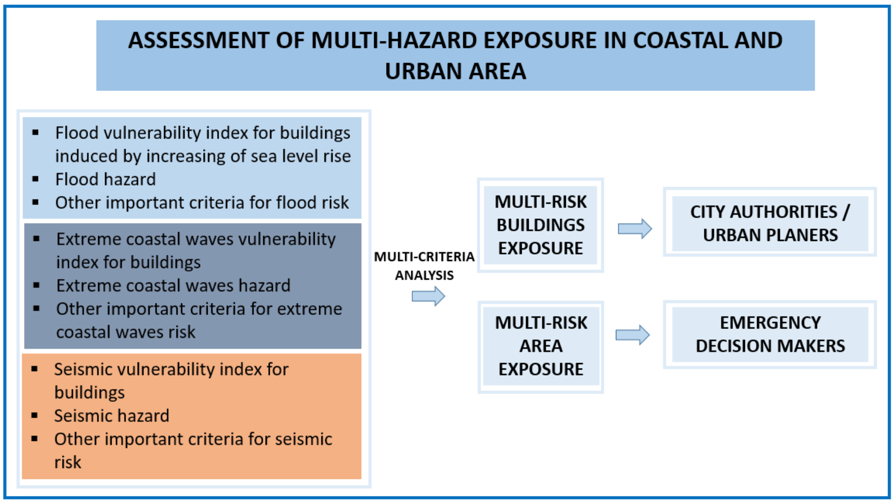


Figure 6. Assessment of multi-hazard exposures for HR test site

The **individual risk assessment** will be done for different levels, starting from the lowest level (micro level), i.e. an individual building.

At this **micro level risk assessment of single-hazard exposure** is based on calculation of vulnerability indexes of buildings for individual natural disasters:

- Flood vulnerability index for buildings $V_{f(b)}$
- Extreme coastal waves vulnerability index for buildings $V_{cw(b)}$
- Seismic vulnerability index for buildings $V_{s(b)}$

as well as on assessment of the single hazards:

- Flood hazard $H_{f(b)}$
- Extreme coastal waves hazard $H_{cw(b)}$
- Seismic hazard $H_{s(b)}$

For instance, *seismic vulnerability index* $V_{s(b)}$ of building is calculated by using approach and criteria presented in Table 2. An example of seismic vulnerability indexes of buildings for one part of HR test site is presented in Figure 10.

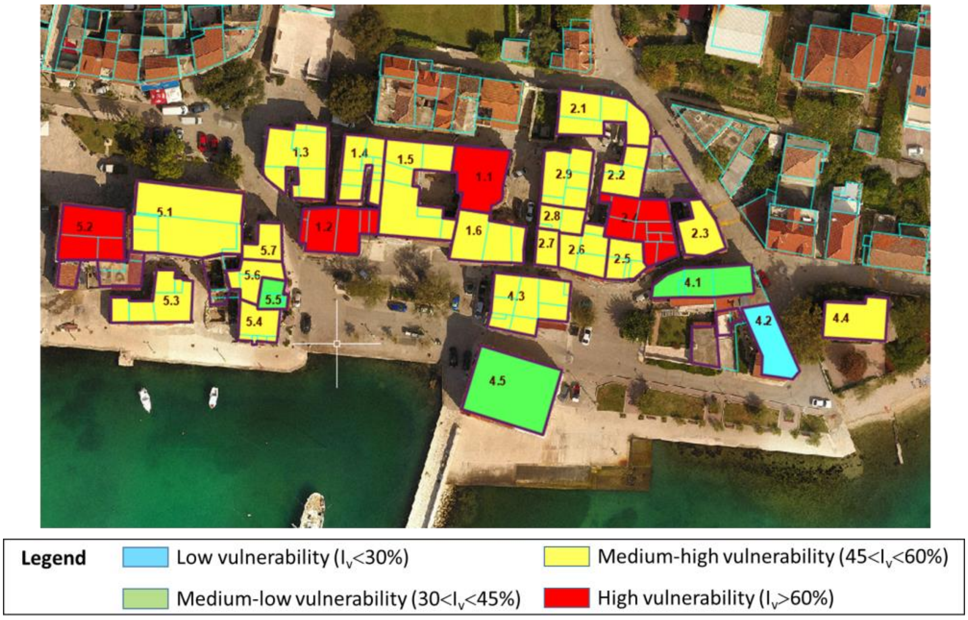


Figure 7. Seismic vulnerability index for buildings $V_{s(b)}$ for one part of HR test site

Flood vulnerability index and *extreme coastal waves vulnerability index* are calculated in similar way. The approach was specifically designed to cope with the vulnerability on the basis of a multicriteria vulnerability analysis of the buildings. Vulnerability index for each building is calculated as the weighted the sum of a set of parameters, which are individually evaluated through four classes of growing vulnerability.

Flood hazard due to sea level rise is determined in according to EU Flood Directive, where it states that for each area under flood hazard at least three flooding scenarios should be considered; high probability scenario, moderate probability scenario, and low probability scenario. The chosen high, moderate and low probability scenarios correspond to the return periods of 25 years, 100 years and 250 years respectively. For the chosen probabilistic scenarios, a sea level values are estimated using the probability distribution.

Extreme coastal waves hazard is determined on the basis of evaluation of wave heights and their propagation toward the coast. The methodology for computing the wave hights by using values of wind speeds in critical wind directions for HR test site is developed, where Probability Distribution Function is used to fit wind speed histograms and to evaluate return period values.

Seismic hazard for Croatia, was presented with two maps, expressed in terms of the peak horizontal ground acceleration during an earthquake for return periods of 95 and 475 years. The maps have been accepted as a part of the National Annex in HRN EN 1998-1:2011. The map, which is used in designing earthquake resistant buildings, shows the reference peak ground acceleration on type A for the return period of 475 years with a probability of exceedance of 10% in 50 years. According to HRN EN 1998-1:2011, soil type A is defined as ground where the velocity of propagation of seismic waves exceeds v > 800 m/s is composed of rock or other rock-like geological formations, including at most 5 meters of weaker material at the surface. This map is used for determination of seismic risk in Croatia. Another map, for the return period of 95 years with a probability of exceedance of 10% in 10 years is used in order to satisfy the fundamental requirements in damage limitation states. According to HRN EN 1998-1:2011, ground types A, B, C, D and E, may be used to account for the influence of local ground conditions on the seismic action. The site can be classified according to the value of the average shear wave velocity $v_{s,30}$. An investigation of the deep geology and characteristics of the terrains as regards of seismic risks, performed at HR test site by OGS, has shown that shear wave velocity $v_{s,30}$ is higer than 800 m/s at the whole HR test site. Therefore, there is no influence of local ground conditions to seismic hazard in the HR test site, i.e. the seismic hazard at the whole area is same.

After definiton buildings vulnerabilities and hazards for individual risks, by combining vulnerabity and hazard (multiplying them or placing them in another form of dependence), the Provision assessment index (PAI) is obtained as a risk measure for an individual object at the micro level $PAI_{(b)}$. $PAI_{(b)}$ can be a very useful source information for urban planning and management decision makers about exposure of the buildings to single risks which can be used for defining:

- Urban planning measures for future construction
- Construction measures to increase buildings resistance

At this micro level, other scenarios are also identified where combinations of other hazards (multi-hazard approach (mh)) are possible. Two main multi-hazard scenario will be analyzed:

(1) Risk assessment of combined flood-seismic hazards with the following parameters:

- Flood vulnerability index for buildings $V_{f(b)}$
- Flood hazard ($H_{f(b)}$)
- Seismic vulnerability index for buildings $V_{s(b)}$
- Seismic hazard $H_{s(b)}$

(2) Risk assessment of combined seismic – flood – extreme coastal waves hazards which will include the relevant parameters regarding:

- Flood vulnerability index for buildings $V_{f(b)}$
- Flood hazard $H_{f(b)}$
- Extreme coastal waves' vulnerability index for buildings $V_{cw(b)}$
- Extreme coastal waves hazard $H_{cw(b)}$
- Seismic vulnerability index for buildings $V_{s(b)}$
- Seismic hazard $H_{s(b)}$

Regarding the number of parameters included for this scenario, a multi-criteria approach could be used to obtain a multi-hazard (mh) provision assessment index provision assessment index ($PAI_{mh(b)}$) for an individual object (b), which of course depends on the available input data.

At the next (higher) level of processing, which is the **meso level**, the previously analyzed objects are grouped into spatial units (Assessment area), which we previously defined as "homogeneous zones". Since homogeneous zones have more complex characteristics, the above scenarios are repeated with defined parameters for vulnerability and hazard, and the inclusion of additional criteria for both single-hazard and multi-hazard approach. As in the previous case, Seismic vulnerability indexes for individual buildings ($V_{s(b)}$) are used to calculate average seismic vulnerability index ($V_{s(hz)}$) for homogeneous zones (hz), with one of the statistical methods, where the simplest procedure is to sum (sum) the individual $V_{s(b)}$ and divide with the number of objects in a homogeneous zone.

Additional criteria

Inclusion of additional criteria for obtaining Provision assessment index for individual homogeneous zones $PAI_{(hz)}$ indicates the need to use more complex mathematical (multicriteria) models, or approaches, in order to evaluate the impact of each of the parameters (criteria) on the overall risk of the analyzed homogeneous zone.

It can be seen from the literature that the level of risk to the community, which is to be determined, depends on a number of other parameters whose activation in a particular hazard reduces the "resistance" to extraordinary events. Of course, each area and the difference in size of the analyzed area requires a special approach in identifying the relevant parameters, but for sesmic hazard the most common parameters (criteria) are grouped into area characteristics (geology, soil, slope, historical earthquake events, fault line, etc.), then the characteristics of human intervention in space (land use, built communal infrastructure and roads, etc.), and social characteristics such as housing density, social purpose of buildings (Occupancy Category), social structure, etc.).

For the HR test site at the mezzo level, only a few additional parameters (criteria) that can be quantified and which are different for each homogeneous zone are noticeable, and they are:

- communal infrastructure
- road network
- construction density (distance between buildings)
- inhabitation density
- importance factor (public building, school, etc.)
- historical buildings, etc.

Criterion **Communal infrastructure** can be presented as a unified indicator or, for easier quantification, can be divided into individual content, such as: electricity supply, water supply and sewerage, gas network, telecommunications network, etc. Electricity supply is of great importance for the HR site and will be treated as a separate criterion. The possible procedure for quantifying this criterion will be explained below. The following power buildings can be identified in the wider area of the town of Kaštela: electrical substations (TS 110/35 kV, TS 35/10 kV and TS 10 / 0.4 kV), transmission lines (OHL 110 kV, OHL 35 kV and OHL 10 kV), cables KB 35 kV and KB 10 kV), and overground and underground low voltage electrical network. The table shows the division of this criterion into individual elements that are integrated into the electricity supply system, and expert assessments of the impact of the vulnerability of each element are added on the total vulnerability of the electricity supply system.

By simply multiplying of the assessment of the degree of threat level of an individual element by its "density" in a particular homogeneous zone, the final value of the parameters of this criterion is obtained. Figure 8 shows the power supply system of the wider HR site area.

The next important segment of communal infrastructure is the water supply and drainage including the storm sewer network. Similar to the electricity supply criterion, the elements of the system can be divide in this criterion in order to simplify the process of quantifying this criterion. Table 4 shows the division of this criterion into individual elements that are integrated into the water supply and drainage system, and adds expert assessments of the impact of the vulnerability of each element on the total vulnerability of the water supply and drainage system (sewerage network including storm sewers).

Table 2. Criterion Communal infrastructure - electricity supply system

Mark	Type of infrastructure of the electricity supply system	Expected damage and description of the consequences of earthquake damage	Assessment of the degree of earthquake hazard	Symbol in GIS
A	DV 110 kV and DV 35 kV and DV 10 kV	demolition of poles and falling of conductors on buildings and ground, which poses a threat to buildings, people and animals (mechanical damage, fatal injuries, danger of electric shock to people and animals, fire due to short circuits).	**2,5**	
B	TS 110/35 kV and TS 35/10 kV	in case of damage to TS 110/35 kV and TS 35/10 kV, there would be an interruption in the power supply of the area of Kaštela, there would be difficulties in water supply (engine of water pumps!)	**1,5**	
C	TS 10/0.4 kV	in case of damage to TS 10 / 0.4 kV there would be a (local) interruption in the supply of electricity to the consumption area of the subject TS	**0,5**	
D	KB 35 kV and KB 10 kV and	due to faults (landslides) KB would crack because they do not have mechanical protection.	**1,5**	
E	overground low voltage network	there is mechanical damage of the conductors and the possibility of fire	**3**	
F	underground low voltage network	there is mechanical damage of the conductors and the possibility of fire	**1**	

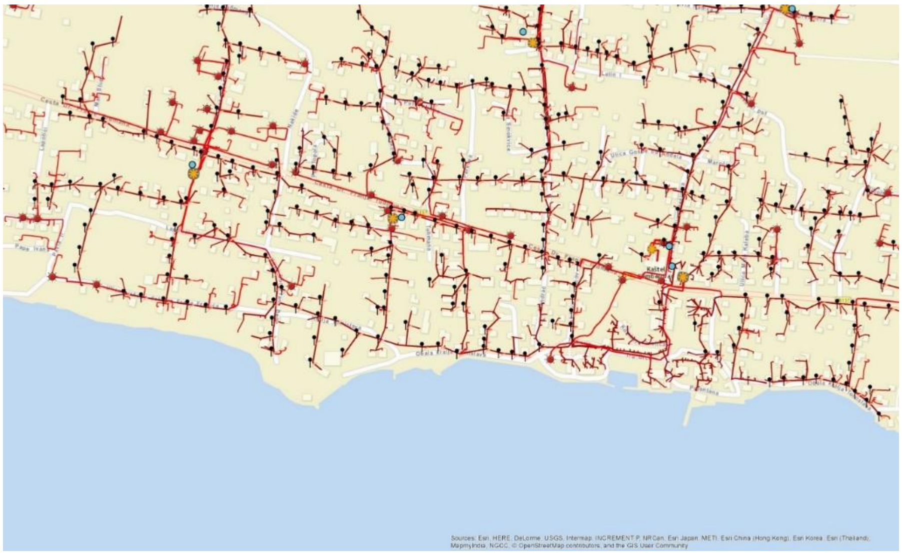


Figure 8. Electricity supply system of a wider area of HR site

Table 3. Criterion Communal infrastructure - water supply and drainage

Mark	Type of water supply and drainage infrastructure	Expected damage and description of the consequences of earthquake damage	Assessment of the degree of earthquake hazard	Symbol in GIS
A	Reservoirs and pumping stations	In the case of a devastating earthquake, pipelines and reservoirs would burst, causing water supply to be cut off.	**2,5**	
B	Water supply conductors – Main Distributive Hydrant conductor	Bursting of water supply lines would cause interruption of water supply and less flooding, especially of basements.	**3,0**	
C	Sewage network and collector	A strong earthquake could also cause damage to the drainage system. The expected consequences are dysfunctions, possible spillage of wastewater and flooding of the basement. The ultimate consequences can be endangering the health of the population	**4,5**	

By simply multiplying the assessment of the degree of threat level of an individual element by its length, that is "density" in a single homogeneous zone, the final value of the parameters of this criterion is obtained. Figure 9 shows the water supply and drainage system of the wider of HR site area.

Figure 9. Water supply and drainage system of a wider area of HR site

A gas network has not yet been built in the analyzed area of Kaštel Kambelovac, although it is planned, and the telecommunications network does not pose a significant threat at this level of problem processing.

Road network is part of the built infrastructure, but it is also treated as a special criterion due to its importance, because firefighters accesses are very important element of the system for assessing the vulnerability of urban units. Firefighters access intended for one-way movement of fire vehicles should be at least 3 m wide. The rise or fall in the firefighters access must not exceed 12% of the slope. Eventual stairs at the fire escapes must not exceed 8 cm in height, and the distance between the stairs must be at least 10 m. Also, if the fire access to the facilities is longer than 100 meters, and in the end there is no space to turn the vehicle, it is unusable and is excluded from the analysis. Based on these limitations, the road network is analyzed for each homogeneous zone and an expert assessment of the "quality" and availability of firefighter's accesses is made. And with this criterion, GIS helps to valorize the road network. Image 10 shows the valorization of the suitability of a particular road network segment for possible use in emergency situations. Roads that are narrower than 3 m or longer than 100 m are marked in red, and there is no possibility of turning emergency vehicles. Roads that can be used are marked in green, and roads are wider than 6 m in blue, and enable simultaneous two-way passage.

Here, too, an expert assessment valorizes each homogeneous zone the suitability of an individual road network segment for in an emergency situation.

Construction density or distance between buildings as a way of building is an important criterion from the aspect of the organization of the rescue, especially in cases of earthquakes of higher intensity. Freestanding buildings certainly allow easier access and do not require specialized mechanization, unlike buildings that lean on each other.

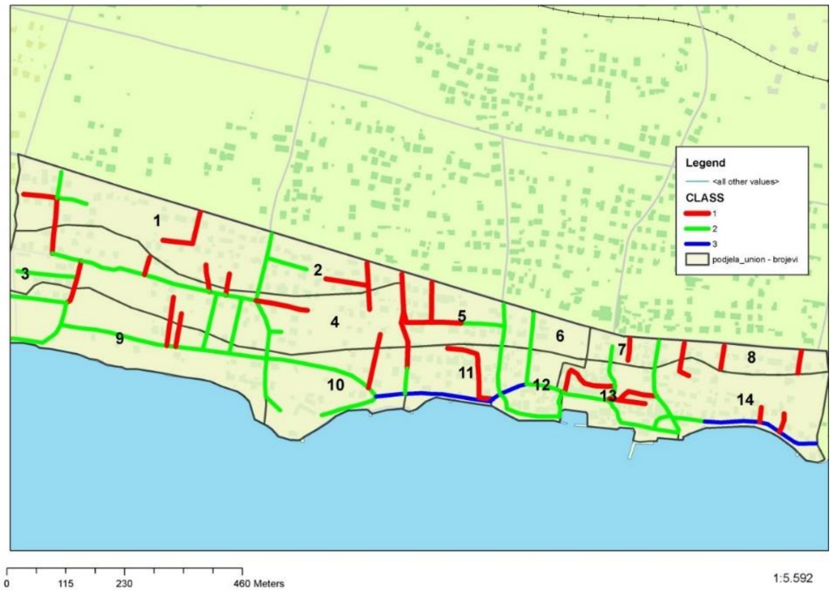


Figure 10. Valorization of road network suitability for intervention in an emergency situation

Inhabitation density is a very common criterion used to have an insight into the expected number of victims or vulnerable persons. Data for this criterion can be generated from a digitized view of the census or from communal databases for garbage collection charge. If these data are not available, the GIS can calculate the number of inhabitants in each homogeneous zone by multiplying the number of buildings and the number of stories of buildings with the average number of persons per family, which for HR test site is 4.5.

Importance factor is a criterion that indicates buildings that have social importance (content) such as schools, churches, kindergartens, libraries, sports halls, shopping centers, etc. This criterion is valorized in the way by determining the number for each homogeneous zone and the importance of the content in which a large number of residents reside or stay.

Historical buildings is a criterion that indicates the presence of important historic buildings in a particular homogeneous zone. It is possible to valorize the importance of historic buildings with respect to their cultural importance or century of construction.

For a higher macro level (Region or County), a number of additional parameters (criteria) are available, given that this is a larger area and a more complex impact on possible events. Provision assessment index for region ($PAI_{(r)}$) can provide useful information but the risk analysis on a larger spatial scale implies inclusion of additional vulnerability aspects in order to provide appropriate information. Since risk analysis on a larger spatial scale is intended for a larger group of stakeholders, especially emergency managers, additional criteria need to be identified. Namely, those criteria are specific for each particular area, their estimation is based on the expert assessment as well as local stakeholders' opinion. This means that each municipality, city or region defines their own set of vulnerability criteria based on their preferences and priorities.

The stakeholders preferences can be defined through criteria weights in the PROMETHEE method. It is one of the reasons why the PROMETHEE method was chosen as multi-criteria analysis and decision-making method for the PMO-GATE project.

2.1.6 Multi-Criteria Decision-Making method

The techniques of multicriteria analysis and multicriteria decision-making (MCDM) originate in the early 1980s. The main objective of the methods developed since then has been to help decision-makers solve complex problems concerning criteria that are usually conflicting and qualitative. The idea of multicriteria decision-making is nowadays implemented world-wide in tackling a wide range of problems involving selection, sorting, and ranking, as well as in various fields of research: social sciences, economics, environmental issues, technology, and many more.

Multi-Criteria (Multi-Attribute or Multi-Objective) Decision-Making is characterized by a set of alternatives (actions) *A*, a set of criteria (objectives) *G*, and evaluations of each alternative on each criterion which represent evaluation set *F*. Decision-making consists of the selection of the "best" alternative, comparison and ranking of alternatives, or comparison of alternatives with some reference points (sorting of alternatives). Usually, there is also set of weights W, which consists of a weight value for each criterion, i.e. criteria are not equally important.

Generally, Multi-Criteria Decision-Making methods can be divided into the following groups based on their characteristics: based on utility functions, outranking methods or interactive methods. Popular MCDM methods are (Guitouni and Martel, 1998): based on utility functions – Multi-Attribute Utility Theory (MAUT), Measuring Attractiveness by a Categorical-Based Evaluation Technique (MACBETH), outranking methods – Analytic Hierarchy Processes (AHP), Elimination and Choice Expressing Reality (ELECTRE), Preference Ranking Organisation Method for Enrichment Evaluations (PROMETHEE),

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and interactive methods – Visual Interactive Method for Decision Analysis (VIMDA). Among various multi-criteria methods, due to its good performance (Guitouni and Martel, 1998), the PROMETHEE method was chosen (Brans and Mareschal, 1991). PROMETHEE is accepted by decision-makers because it is comprehensive and can present visualized results as proven in the application of this method in other engineering problems (Mladineo et al., 1987; 1992).

2.1.7 PROMETHEE method

In the last 40 years, several multi-criteria decision aid methods been proposed. Among them, one of the most popular (with more than 2.200 scientific papers), applied in almost every field is the PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations) method (Brans and Mareschal, 1991). This method is known as one of the most efficient and the most robust, but also one of the easiest in the field. The PROMETHEE method is accepted by decision-makers because it is comprehensive and has the ability to present results using simple ranking.

An input for the PROMETHEE method is a matrix consisting of set of potential alternatives (actions) *A*, where each a element of *A* has its *f(a)* which represents evaluation of one criteria (Figure 11). Each evaluation $f_j(a_i)$ must be a real number.

	$f_1(.)$ $f_2(.)$ …… $f_j(.)$ …… $f_k(.)$
a_1	
a_2	
…	
a_i	$f_j(a_i)$
…	
a_n	

Figure 11: Input matrix for the PROMETHEE method

PROMETHEE I ranks actions by a partial pre-order, with the following dominance flows (Brans and Mareschal, 1991), for leaving flow (Brans et al. 1984):

$$\Phi^{+}(a) = \frac{1}{n-1}\sum_{b\in A} \Pi(a,b)$$

and for entering flow (Brans et al. 1984):

$$\Phi^{-}(a) = \frac{1}{n-1}\sum_{b\in A} \Pi(b,a)$$

where *a* denotes a set of actions, *n* is the number of actions and *Π* is the aggregated preference index defined for each couple of actions. PROMETHEE I gives a partial relation, and then a net outranking flow is obtained from PROMETHEE II method which ranks the actions by total pre-order calculating net flow (Brans et al. 1984):

$$\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a)$$

In the sense of priority assessment, net outranking flow represents the synthetic parameter based on defined criteria and priorities among criteria. Usually, criteria are weighted using criteria weights w_j and the usual pondering technique (Brans et al. 1984):

$$\Pi(a,b) = \frac{\sum_{j=1}^{n} w_j P_j(a,b)}{\sum_{j=1}^{n} w_j}$$

Furthermore, different sets of criteria weights can be used and then each set represents one scenario, thus making it suitable for SWIFT and Scenario analysis.

Since during the evaluation of the optimal policies for risk reduction several groups are involved in the decision process, the activities in the process of problem solving are thus defined:

- definition of the characteristics, namely, the set of activities and the set of criteria (the definition of the problem scope);
- bringing together the sets of actions and criteria with 'partners' in the decision process (it is usual to add some of the criteria due to the partners' insistence, during the group decision making);
- definition of the weights and preference types for each criterion;
- bringing together (negotiating) criteria weights, in order to achieve consensus;
- definition of alternative scenarios of the criteria weights assessment, assessing more weight to certain criteria groups;
- sensitivity analysis, namely, checking the stability of criteria weights for each weight scenario;
- application of the GAIA method in order to visualize problem characteristics;
- presentation and elaboration of the multicriteria analysis results to the participants in the decision-making process, and evaluation of additional scenarios (criteria weight variations).

However, the problem with PROMETHEE II results for non-expert users is that they are presented on a scale with interval [-1, 1] where a higher number represents "better" action. Additional information is a rank of each action, but, the rank itself is usually insufficient information to make the right decision, because it is too coarse. It does not indicate how close actions are to each other, it uniformly distributes actions. This represents a problem in the application and implementation of PROMETHEE II in practice. The solution to this problem is changing of PROMETHEE II scale from [-1, 1] interval to [0, 1] interval i.e. [0%, 100%] interval. It is, so called, PROMETHEE II score or net score (Mladineo et al., 2017) and it can be calculated by using the following expression:

$$\Phi'(a) = \frac{1}{2}\left(\Phi^{+}(a) + \Phi^{+'}(a)\right)$$

where $\Phi^{+'}(a)$ can be calculated using expression:

$$\Phi^{+'}(a) = 1 - \Phi^{-}(a)$$

Another advantage of net score is that its calculation uses standard output of the PROMETHEE I method (positive net flow and negative net flow), so there is no need for additional calculations. An example with comparison of net flow and net score results is presented in the Table 4.

Furthermore, PROMETHEE II score can be interpreted as scale of grades, thus making the risk assessment more understandable (Table 4).

Using this grade interpretation of scores, it is even clearer to understand how much one action (homogeneous zones) is more exposed to the risk compared to another action. It makes it much easier to visualize the risk, no matter if it is a relative risk assessment or absolute risk assessment, or if it is a single hazard approach or multi-hazard approach.

Table 4. An example of risk assessment results for six homogenous zones

Action (homogeneous zone)	Possitive flow Φ^+	Negative flow Φ^-	Net flow Φ	Net score $\Phi'(\%)$	Rank	Visualization in GIS (Web map)
A1	0.2411	0.0951	0.1461	57.3 %	1	
A2	0.3179	0.1876	0.1303	56.5 %	2	
A3	0.2188	0.1454	0.0734	53.7 %	3	
A4	0.2173	0.2187	-0.0014	49.9 %	4	
A5	0.1242	0.2132	-0.089	45.6 %	5	
A6	0.0879	0.3472	-0.2593	37.0 %	6	

Table 5. An example of risk assessment through grades

Score	Grade	Description	Visualization in GIS (Web map)
90 – 100%	5	*very high risk*	
70 – 89%	4	*high risk*	
50 – 69%	3	*medium risk*	
40 – 49%	2	*low risk*	
0 – 39%	1	*negligible risk*	

For each of a single hazard, a specific set of criteria is defined which in a comprehensive way valorizes the available parameters that determine the level of risk, or on the basis of which the Provision assessment index (PAI) is calculated, that is, the risk of a particular area is determined.

The PROMETHEE method is also used to calculate the multi-hazard Provision assessment index (PAI), where for each of the listed hazards (floods and extreme waves exposure), in a particular area, the new multi-hazard matrix is entered as the criteria of the value obtained from numerical processing of single hazard and common criteria for the multi-hazard scenario are added. For example, housing density is one of the criteria common to all types of hazards. It is also necessary to determine the weights for each of the hazards concerning its impact on the global multi-hazard assessment.

2.1.8 Multi-level and Multi-criteria Risk assesment based on PROMETHEE method

It is important to note, according to European Commission's Risk Assessment and Mapping Guidelines for Disaster Management (EC 2010): "*the risk cannot be expressed simply as a product of two terms (hazard impact and probability of occurrence) but must be expressed as a functional relationship. Likewise, where the impacts are dependent on preparedness or preventive behavior, e.g. timely evacuation, there are advantages in expressing the impact indicator in a more differentiated manner.*" Therefore, PMO-GATE addresses these issues by presenting the exposure through hazard criteria and vulnerability through vulnerability criteria in the input matrix.

Criteria weights can be defined by using literature and with the help of experts. The advantage of the PROMETHEE method is that original criteria evaluations, qualitative or quantitative, can be used. They do not need to be normalized on some scale. Therefore, an input from GIS and other quantitative data can be directly used in combination with criteria weights which represent experts' judgements (Figure 12). In single-hazard approach, for each assessment area numerical evaluation, based on PROMETHEE method, results with provision assessment index (PAI). The assessment areas or "homogenous zones" represent input, i.e. alternatives, for PROMETHEE method. For these areas (Area 1, Area 2, Area 3, etc.) the matrix for Risk assessment should be created (Table 5). Criteria evaluations (columns of the matrix) are generated from GIS or they are calculated in the WP3 (single-hazard exposures).

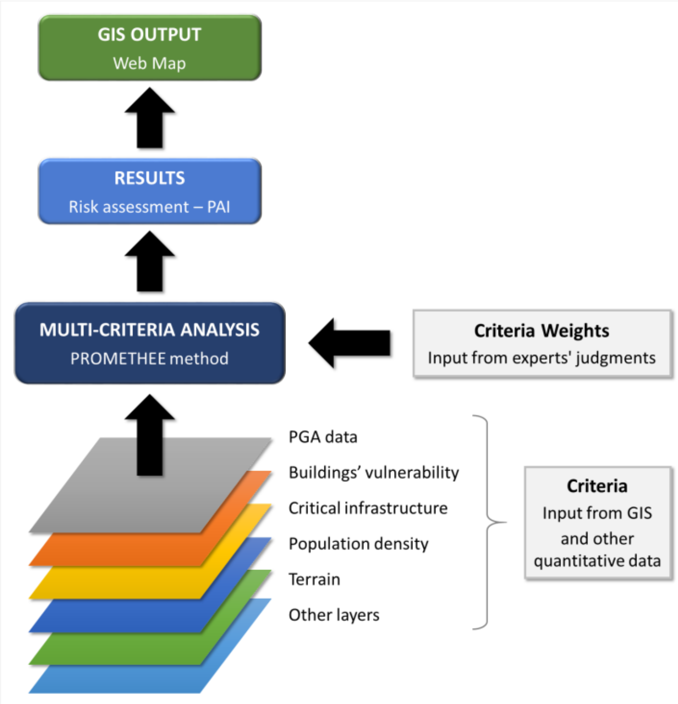


Figure 12: Inputs and output of the methodology for calculation of the provision assessment index (PAI)

The spatial data are collected and organized by using Geographic Information System (GIS) in the first step. Since risk assessment, i.e. evaluation of provision assessment index (PAI) will be made for particular assessment area, these areas need to be defined by mutual spatial characteristics or by some already defined urban entity. HR test site is a small area and it represents one urban entity (one cadastral municipality). The assessment areas are defined as "homogeneous zones", which are generated by intersecting relevant thematic layers selected for each single-hazard.

Alternative	Criteria						
	Hazard - Peak ground acceleration (PGA)	***Buildings' vulnerability (buildings characteristics)***	***Construction density***	***Importance factor (public, school, etc.)***	***Communal infrastructure***	***Population density***	***Historical buildings, etc.***
	Weight = # %	*Weight = # %*	*Weight = # %*	*Weight = # %*	*Weight = # %*	*Weight = # %*	*Weight = # %*
Area 1	###	###	###	###	###	###	###
Area 2	###	###	###	###	###	###	###
Area 3	###	###	###	###	###	###	###
…	…	…	…	…	…	…	…

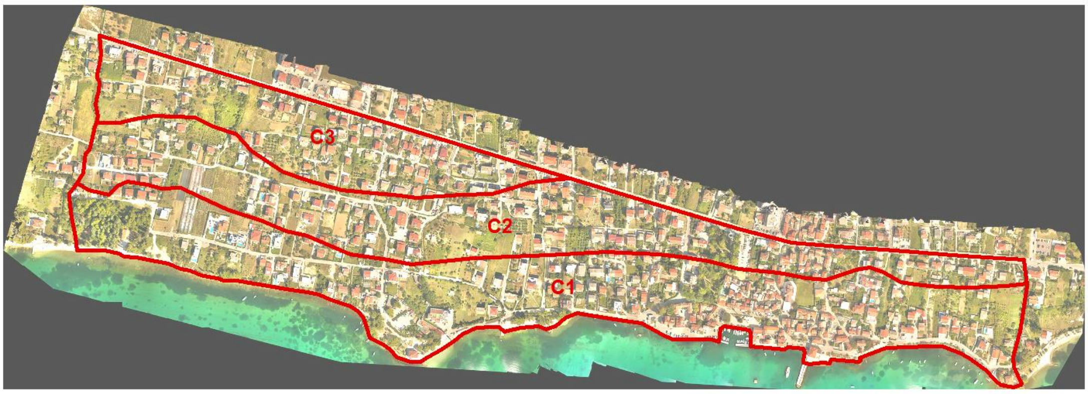
Figure 13: Proposal of the input matrix for Seismic Risk Assessment based on Multi-Criteria Analysis (PROMETHEE method) of the PMO-GATE project

For single-hazard exposures such as earthquakes, three thematic layers have been defined for definition of "homogenous zones":

1) Thematic layer which defines four areas (A_1, A_2, A_3 and A_4) with specific urban characteristics, population density and buildings density

2) Thematic layer which defines four areas (B_1, B_2, B_3 and B_4) according to main roads

3) Thematic layer which defines three areas (C_1, C_2, and C_3) according to terrain height (contours 5 and 10 m)



4) In the last step, these thematic layers are intersected and dozens (14) of polygons are created (Figure 14).

In this particular case, the 14 polygons are created and they represent "homogenous areas" or "homogenous zones". It is also possible to reduce the number of areas, by grouping some polygons, in order to have less number of areas in numeric analysis. Each of the 14 homogeneous zones generated is characterized by certain specificities that suggest a different approach to rescue services. Of course, multicriteria analysis, that is the PROMETHEE method, provides very important information, that is suggests priorities in rescue operations in emergency situations.

Figure 14. Homogeneous zones for HR site

2.2 Single-hazard Risk Assessment on HR test site

2.2.1 Generation of input data for seismic single-hazard risk assesment by using PROMETHEE method on HR test site

For the generated 14 homogeneous zones (hz) according to the defined criteria, the input data are calculated or expert estimates are given. In the previous chapters for calculating the "Provision assessment index" PAI (hz) for each homogeneous zone following criteria are validated:

- Peak ground acceleration (PGA) – Intensity
- Buildings' vulnerability
- Geology
- Communal infrastructure - electricity supply
- Communal infrastructure - water supply and drainage
- Road network
- Construction density (distance between buildings)
- Inhabitation density
- Importance factor (public, school, etc.)
- Historical buildings

Peak ground acceleration (PGA) and Geology have the same values in each of the 14 homogeneous zones and will not be included in the numerical processing. The input data are formed for the following criteria:

C_1: Buildings' vulnerability - For each homogeneous zone it is necessary to calculate average seismic vulnerability index (Vs(hz)), with one of the statistical methods, where the simplest procedure is to sum the individual Vs(b) divide with the number of objects in a homogeneous zone. This can be done automatically in GIS, and Figure 15 shows the buildings 'vulnerability index divided into 6 groups (different colors) and separated by the boundaries of a homogeneous zone.

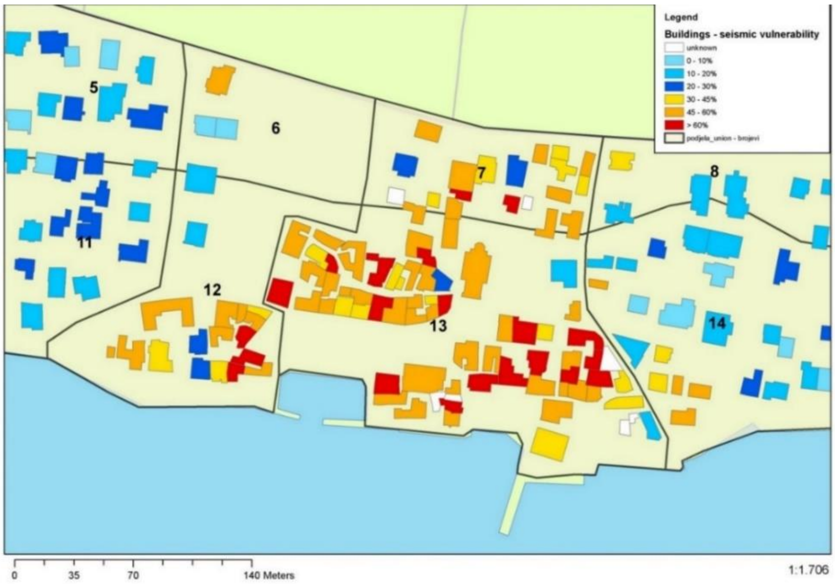


Figure 15. Buildings 'vulnerability index separated by homogeneous zone boundaries

Thus, the input data for this criterion are shown in Table 6.

Table 6. Input data for the Buildings' vulnerability criterion

Homogenous zone mark (hz)	Area of hz (m2)	Number of buildings	Seismic vulnerability index Vs(hz)
HZ_1	58627	56	0.133
HZ2	21865	29	0.174
HZ_3	57189	54	0.116
HZ_4	30925	25	0.120
HZ_5	26972	38	0.132
HZ_6	7763	4	0.194
HZ_7	7767	20	0.435
HZ_8	16168	19	0.162
HZ_9	60068	38	0.136
HZ_{10}	38133	14	0.171
HZ_{11}	24972	35	0.156
HZ_{12}	12696	17	0.448
HZ_{13}	24903	71	0.493
HZ_{14}	40782	48	0.187

C_2: Communal infrastructure - electricity supply

The parameter for this criterion is obtained by multiplying the assessment of the degree of threat level of an individual element by its "density" in a single homogeneous zone. Figure 16 shows a part of the power supply system separated by the boundaries of a homogeneous zone.

Figure 16. Overview of the power supply system separated by the boundaries of a homogeneous zone

C_3: Communal infrastructure - water supply and drainage

Similar to the previous criterion, multiplying the assessment of the degree of threat level of an individual element by its length or "density" in a particular homogeneous zone gives the final value of the parameters of this criterion for a particular homogeneous zone. Figure 17 shows a part of the water supply and drainage system separated by the boundaries of a homogeneous zone.

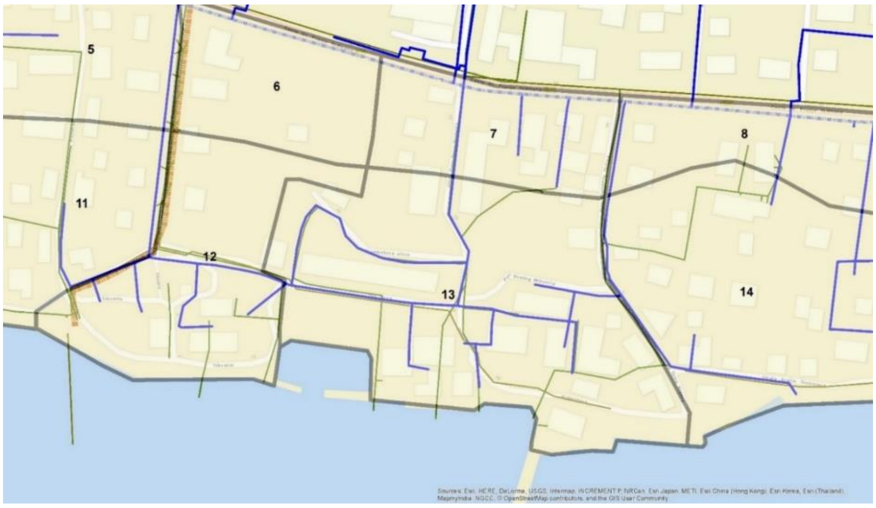


Figure 17. Overview of the water supply and drainage system separated by the boundaries of a homogeneous zone

C_4: Road network

With this criterion, for each homogeneous zone, the suitability of an individual segment of the road network for intervention in emergency situations is valorized, which represents the "quality", that is the availability of fire approaches to an individual facility. With this criterion, the choice was chosen to minimize the length of inadequate car access to facilities in relation to normal and possible two-way approaches in a particular homogeneous zone.

Figure 6 shows the valorization of the suitability of a particular road network segment for possible use in emergency situations. Roads that are narrower than 3 m or longer than 100 m are marked in red, and there is no possibility of turning emergency vehicles. Roads that can be used are marked in green, and roads wider than 6 m are in blue, and they enable two-way passage at the same time. The final valorization for each homogeneous zone is made in such a way that from the normal and possible two-way approaches (estimated with 1.5), that is green and blue roads, unsuitable roads marked in red are deprived.

C_5: Construction density (distance between buildings)

This is a very important criterion from the aspect of the organization of the rescue itself, especially in cases of earthquakes of stronger intensity. The freestanding buildings, which are mostly in the area of the HR site, certainly provide easier access and do not require specialized mechanization, unlike the buildings that lean on each other, which is the case in the old protected city core of Kastel Kambelovac. The valorization of this criterion is performed with respect to the average density of objects in a single homogeneous zone that is the number of independent objects. It can be seen from Figure 18 that a group of connected buildings has been identified, that is they are characterized by very high density (red color), and one group of high density buildings (brown color) and two separate groups of medium density buildings (yellow color).

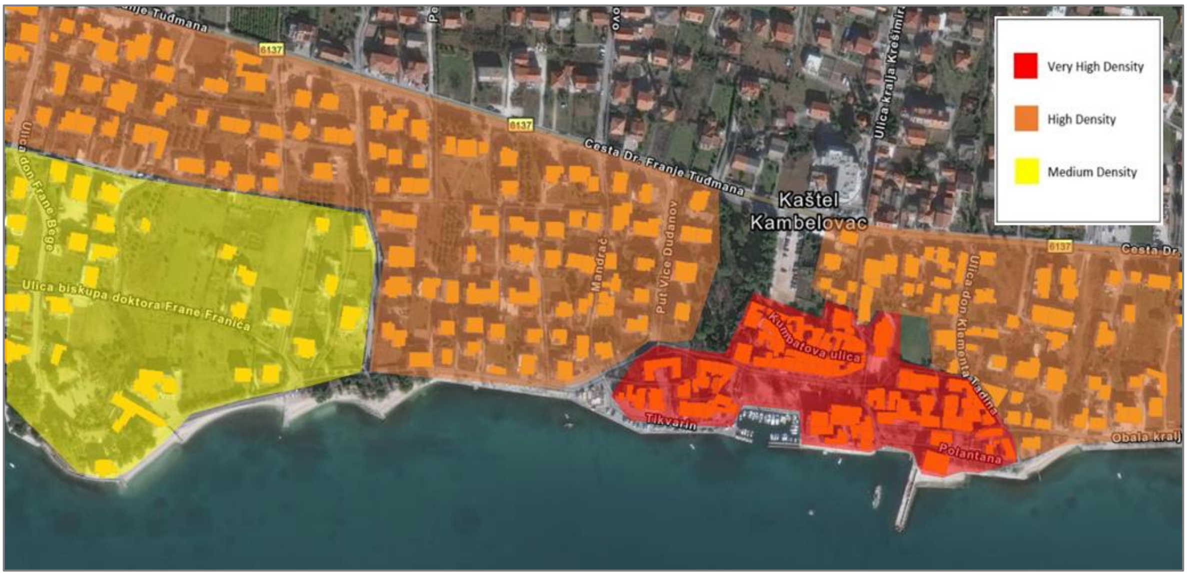


Figure 18. Representation of valorizations performed regarding to the average density of objects

C_6: Inhabitation density

Data for this criterion were generated from a digitized census and divided into homogeneous zones.

C_7: Importance factor (public, school, etc.)

This criterion indicates buildings that have social importance (content) such as schools, churches, kindergartens, libraries, sports halls, shopping centers, etc. This criterion is valorized by determining the number and importance of content for each homogeneous zone in which a large number of inhabitants reside or remain (Figure 19).

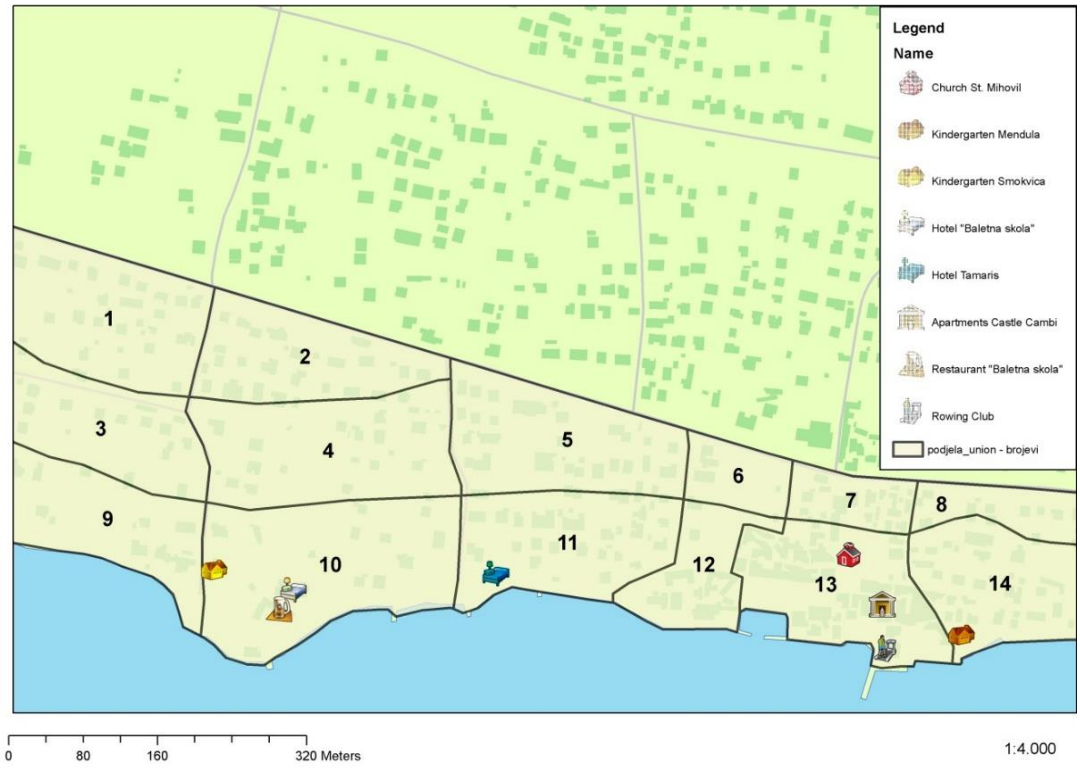


Figure 19: Overview of buildings of social importance (schools, churches, kindergartens, hotels, sports halls, etc.)

C_8: Historical buildings

The presence of important historic buildings in a particular homogeneous zone. It is possible to valorize the importance of historic buildings regarding to their cultural importance or century of construction (Figure 20).

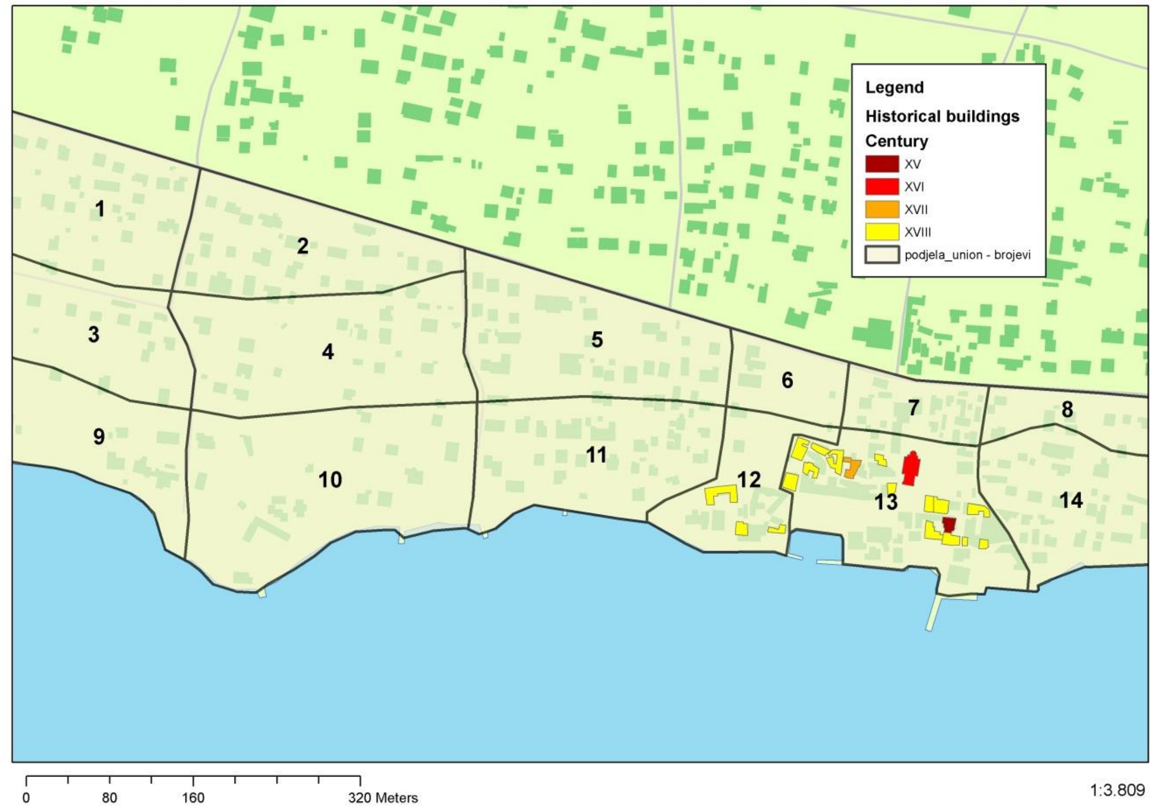


Figure 20. Overview of historic buildings regarding to their historical importance

Based on previously defined criteria, input table (Table 9) has been formed for numerical processing of seismic single-hazard risk, i.e. for calculation of "Provision assessment index" $PAI_{s(hz)}$ for HR site (Kaštel Kambelovac). In the Table 9, columns represent selected criteria (8 in total), and rows represent data or criteria evaluations of homogenous zones (14 in total). Each criterion has its own weight and objective (maximization or minimization).

The weight of criterion C_1 (Buildings' seismic vulnerability) dominates with 40% share in total weights, so rest of 60% is distributed on other 7 criteria. PROMETHEE method allows sensitivity analyisis of criteria weights to detect possible influence of one criterion weight on results. Sometimes, criteria weights are changed in iterative procedure based on sensitivity analysis. With proper software support all these analysis are visualized for successful interaction between the use and the model.

For numerical processing, Visual PROMETHEE software has been used (*http://www.promethee-gaia.net/*). Beside data from Table 7, it is important to define criteria preference function type and its parameters. The linear preference function with indifference and preference thresholds has been selected for this analysis. Advantage of Visual PROMETHEE is the statistical analysis of all the data, thus allowing better understanding of criteria evaluations and better definition of criteria parameters. Most of the time, several criteria weights sets are defined representing different Scenarios. For this first scenario (Scenario 1) the results are presented on Figures 21 and 22.

Table 7. Input data for numerical processing with PROMETHEE method

Homogenous zone (hz)	Criteria							
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
HZ_1	0.133	11	8	-216	0	252	0	0
HZ_2	0.174	13	7	80	0	130	0	0
HZ_3	0.116	11	8	492	0	243	0	0
HZ_4	0.120	9	11	-80	0	112	0	0
HZ_5	0.132	8	9	-121	0	171	0	0
HZ_6	0.194	2	2	60	0	18	0	0
HZ_7	0.435	5	4	39	0	90	0	0
HZ_8	0.162	7	9	-137	0	86	0	0
HZ_9	0.136	9	7	633	0	171	0	0
HZ_{10}	0.171	7	12	463	0	63	5	0
HZ_{11}	0.156	10	13	283	0	158	2	0
HZ_{12}	0.448	9	15	325	2	76	0	4
HZ_{13}	0.493	15	18	211	9	319	7	15
HZ_{14}	0.187	9	12	317	0	216	3	0
Criteria Weights	**40**	**10**	**8**	**8**	**14**	**10**	**4**	**6**
MIN/MAX	MAX	MAX	MAX	MIN	MAX	MAX	MAX	MAX

The display of numerical processing results shows a Phi value of 0.3993 for HZ_{13}, which means that the homogeneous zone 13 is the most endangered and that it's PAIs (hz) is almost 0.4, followed by HZ_{12} with a value of 0.0975 and HZ_7 with a Phi of 0.0302. Yet HZ_1 has a positive Phi value of 0.0025, while all other homogeneous zones have negative values, which means that their risk of earthquakes is significantly less compared to the three mentioned homogeneous zones. Figure 23 graphically presents the results of processing by the PROMETHEE I method, and the display shows the absolute dominance of HZ_{13} and a significant distance from HZ_{12}, which is very close to HZ_7. With such input results, the least risk of earthquakes is shown by the homogeneous zone HZ_6, and the zones HZ_9, HZ_3 and HZ_{10} are very close to it. A good visualization of the ratio of criterion weights as well as the results of multicriteria analysis is provided by the graphical support "Walking Weights" which enables interactive analysis of the impact of changes in criterion weights on the obtained rank (Figure 24). The weights of the criteria in Scenario 1 were obtained by consulting the available literature and especially in consultation with experts close to this issue. Visual PROMETHEE software also includes a special GAIA tool that is added a descriptive complement to the PROMETHEE rankings.

Visual PROMETHEE Academic - PMO-GATE_Kastela.vpg (saved)

File Edit Model Control PROMETHEE-GAIA GDSS GIS Custom Assistants Snapshots Options Help

Scenario1	criterion1	criterion2	criterion3	criterion4	criterion5	criterion6	criterion7	criterion8
Unit	unit	unit	unit	unit	unit	unit	unit	unit
Cluster/Group								
Preferences								
Min/Max	max	max	max	min	max	max	max	max
Weight	40,00	10,00	8,00	8,00	14,00	10,00	4,00	6,00
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	1,00	1,00	1,00	10,00	1,00	1,00	1,00	1,00
- P: Preference	100,00	20,00	20,00	1000,00	10,00	500,00	10,00	20,00
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics								
Minimum	11,60	2,00	2,00	-216,00	0,00	18,00	0,00	0,00
Maximum	49,30	15,00	18,00	633,00	9,00	319,00	7,00	15,00
Average	21,84	8,93	9,64	167,79	0,79	150,36	1,21	1,36
Standard Dev.	12,81	3,10	4,08	252,38	2,34	81,47	2,18	3,92
Evaluations								
HZ1	13,30	11,00	8,00	-216,00	0,00	252,00	0,00	0,00
HZ2	17,40	13,00	7,00	80,00	0,00	130,00	0,00	0,00
HZ3	11,60	11,00	8,00	492,00	0,00	243,00	0,00	0,00
HZ4	12,00	9,00	11,00	-80,00	0,00	112,00	0,00	0,00
HZ5	13,20	8,00	9,00	-121,00	0,00	171,00	0,00	0,00
HZ6	19,40	2,00	2,00	60,00	0,00	18,00	0,00	0,00
HZ7	43,50	5,00	4,00	39,00	0,00	90,00	0,00	0,00
HZ8	16,20	7,00	9,00	-137,00	0,00	86,00	0,00	0,00
HZ9	13,60	9,00	7,00	633,00	0,00	171,00	0,00	0,00
HZ10	17,10	7,00	12,00	463,00	0,00	63,00	5,00	0,00
HZ11	15,60	10,00	13,00	283,00	0,00	158,00	2,00	0,00
HZ12	44,80	9,00	15,00	325,00	2,00	76,00	0,00	4,00
HZ13	49,30	15,00	18,00	211,00	9,00	319,00	7,00	15,00
HZ14	18,70	9,00	12,00	317,00	0,00	216,00	3,00	0,00

Figure 21. Spreadsheet with Visual PROMETHEE software input data

A graphical representation of the multicriteria problem enables the decision maker to better understand the available choices and the necessary compromises he or she will have to make to achieve a best decision. **GAIA** can also be used to see the impact of the criteria weights on the **PROMETHEE** rankings.

GAIA starts from a multidimensional representation of the decision problem with as many dimensions as the number of criteria. Figure 25 spatially shows the data for Scenario 1 and there is a high correlation between the criteria, except for criterion C4, which is separated in the first quadrant of the "u, v" display. There is a particularly high correlation between criteria C1, C5 and C8 and they obviously have a dominant influence on the "decision axis" (red). In the "u, v" plane, a grouping of homogeneous zones is visible ($_{HZ1}$, HZ_8, HZ_4, HZ_7, HZ_6 and HZ_2), which means that they are very similar in terms of input data, while the other group is in the lower part of the plane (HZ_{12}, HZ_{11}, HZ_{14}, HZ_3, HZ_{10} and HZ_9). The homogeneous zone HZ_{13} has a completely separated position, which means that it has completely different characteristics with regard to the defined criteria.

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	HZ13	0,3993	0,4104	0,0111
2	HZ12	0,0975	0,1512	0,0537
3	HZ7	0,0302	0,1110	0,0808
4	HZ1	0,0025	0,0684	0,0659
5	HZ14	-0,0142	0,0518	0,0659
6	HZ2	-0,0269	0,0451	0,0720
7	HZ11	-0,0317	0,0395	0,0713
8	HZ5	-0,0318	0,0418	0,0735
9	HZ4	-0,0401	0,0387	0,0787
10	HZ8	-0,0420	0,0375	0,0795
11	HZ10	-0,0644	0,0349	0,0993
12	HZ3	-0,0654	0,0347	0,1000
13	HZ9	-0,0975	0,0166	0,1141
14	HZ6	-0,1156	0,0250	0,1407

Figure 22. Results of the PROMETHEE II method for 14 homogeneous zones (better rank represents higher risk)

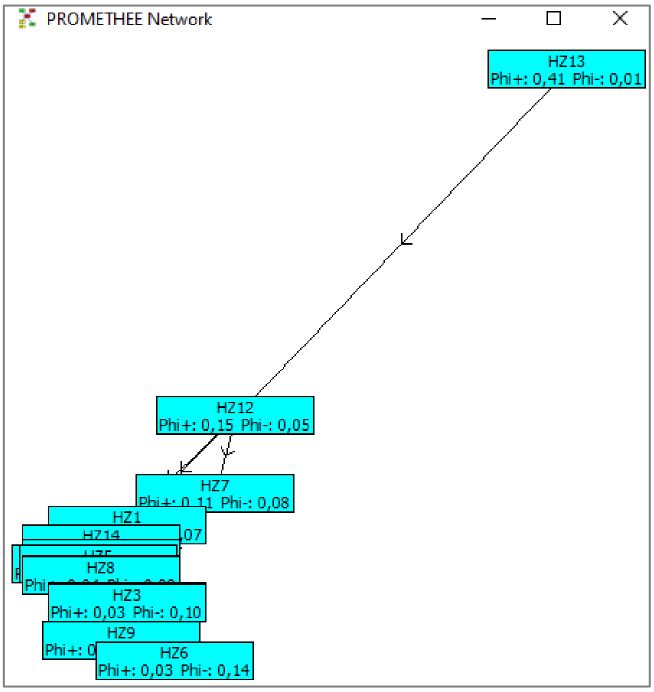


Figure 23. Results of PROMETHEE I method for 14 homogeneous zones (better rank represents higher risk)

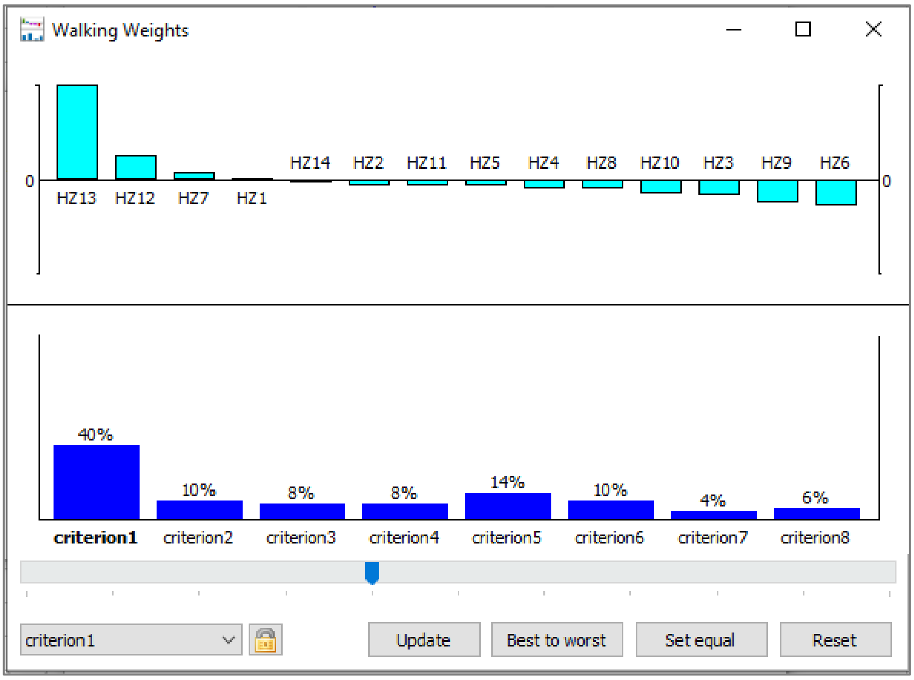


Figure 24: Graphic support "Walking Weights"

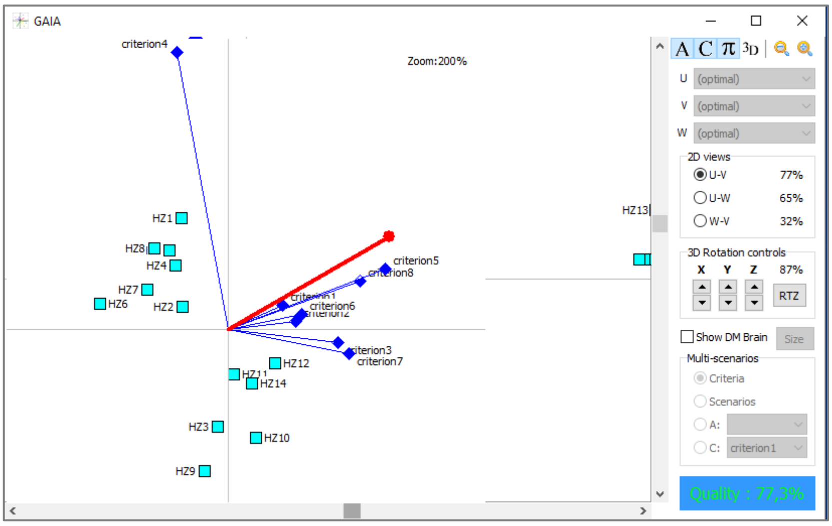


Figure 25: Graphic support for GAIA

In order to assess the impact of criterion weights on the obtained results, Scenario 2 was developed where all criteria have the same weight, which is 12.5. The results are best seen in Figure 26 where the rank of homogeneous zones remained almost unchanged except for H_{Z7}, which in this scenario is 11 by rank with a Phi value of -0.0594. HZ_1 also changed rank and is now second in line with a Phi value of 0.0361. From the analyzed results of Scenario 2, it can be concluded that the weights of the criteria do not have a significant impact on the obtained results, which is the weights of the criteria set in Scenario 1 are satisfactorily stable.

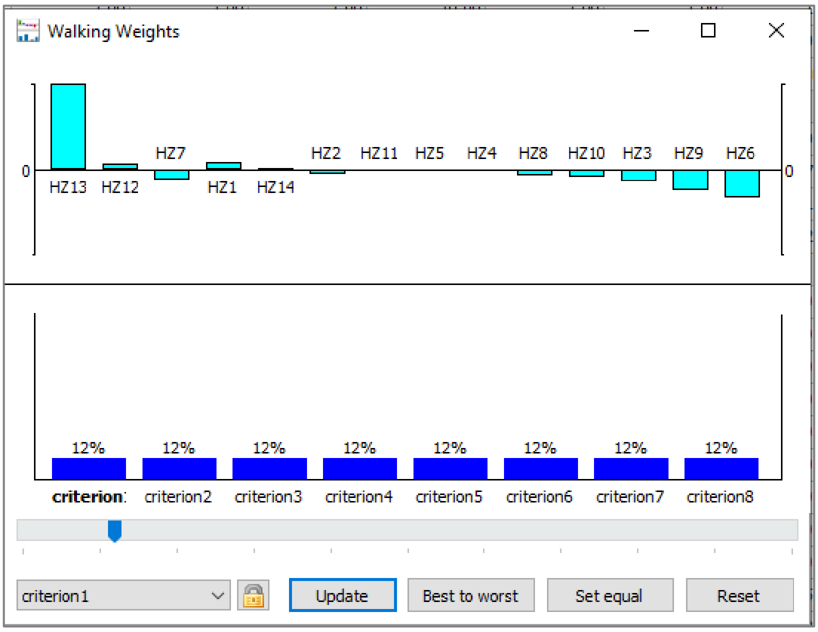


Figure 26: Graphic support "Walking Weights" for Scenario 2

In the next step, the obtained results of multicriteria analysis are "visualized" in the GIS so that they can be more easily used than services that operate in emergency situations. As described in the chapter on the PROMETHEE method, two ways of interpreting the results of multicriteria analysis are possible, namely to display net score values in GIS (Figure 27) or to form a scale of grades, thus making the risk assessment more understandable (Figure 28). These results are stored in GIS as separate thematic layers and can be overlapped with all other thematic layers shown earlier.

From Figure 27, it is clear that homogenous zones in historical center (HZ_{13} and HZ_{12}) have high risk, but zone HZ_1, which is populated with newer buildings, has high risk as well. Action profile of HZ_1 (Figure 29) shows the reason of such a high risk: criterion C6 (Inhabitation density) and criterion C4 (Road network) have high values and together with criterion C2 (Communal infrastructure - electricity supply) make this homogenous zone a high risk zone with rank 4^{th}. Regarding the scale of grades (Figure 28), this zone, together with zones HZ_7 and HZ_{12}, belongs to category of *medium risk*.

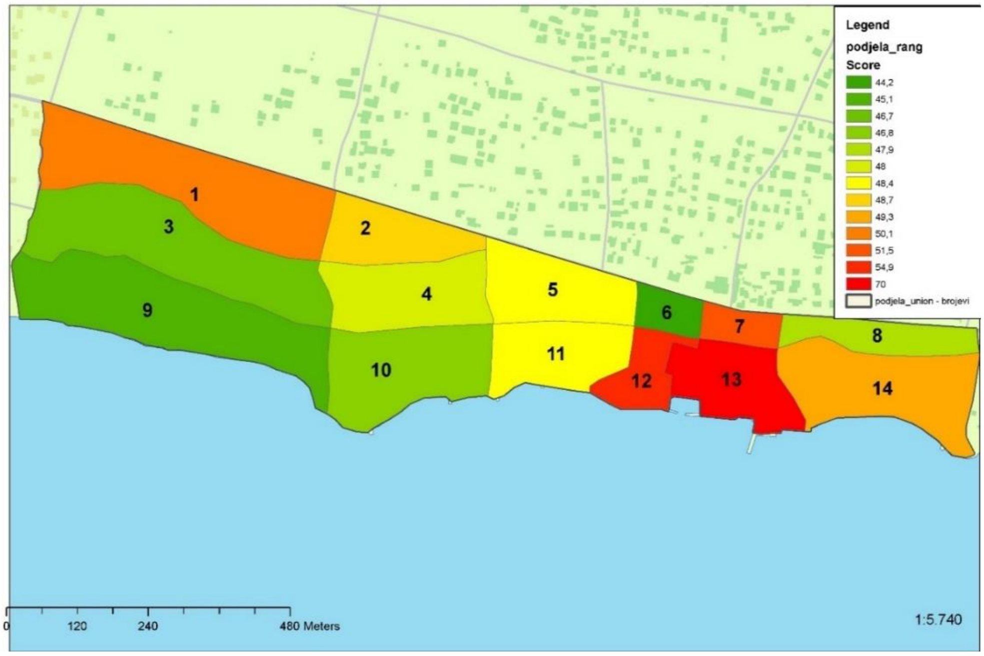


Figure 27: Presentation in GIS of the results of multicriteria analysis as a net score value

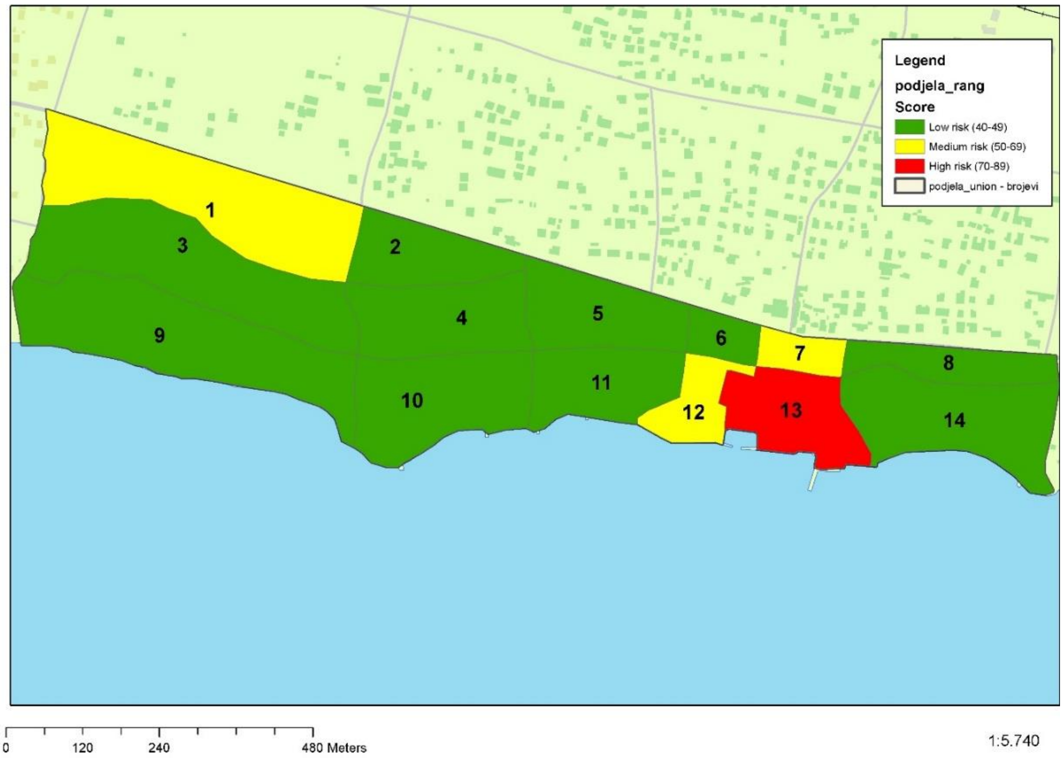


Figure 28: Presentation in GIS of the results of multicriteria analysis in scale of grades

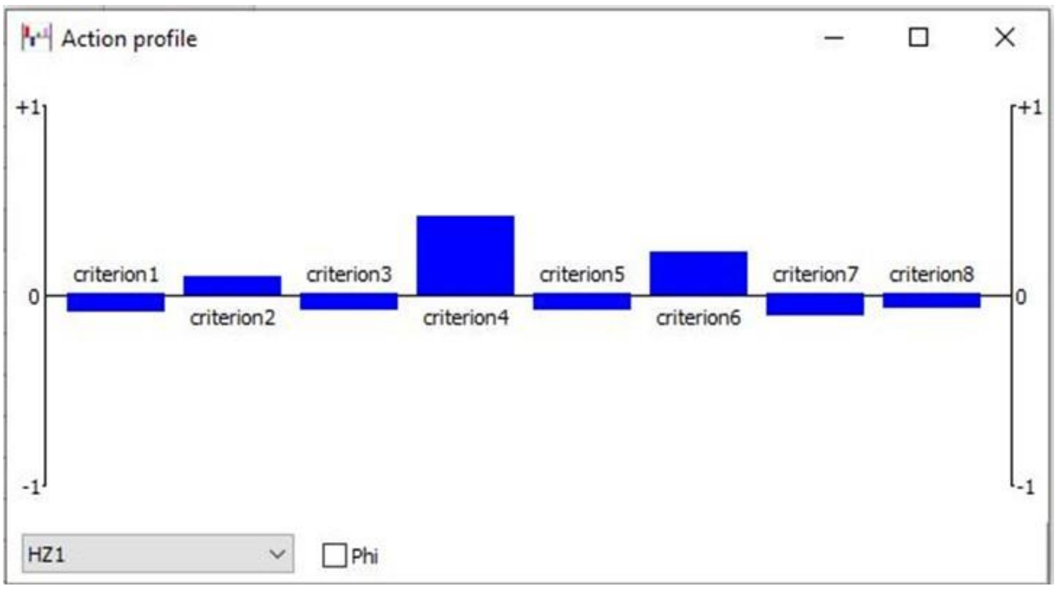


Figure 29: Action profile homogenous zone HZ_1

2.2.2 Generation of input data for flood single-hazard risk assessment by using PROMETHEE method on HR test site

The same approach of homogenous zones is used for flood single-hazard risk assessment. For each homogenous zone flood maps are used. The flood maps are made for three scenarios: year 2046, 2065 and 2100. In this risk assessment, flood data for the closest period – year 2046 – is used. Figure 30 shows homogenous zones affected by flood (HZ_9, HZ_{10}, HZ_{11}, HZ_{12}, HZ_{13} and HZ_{14}).

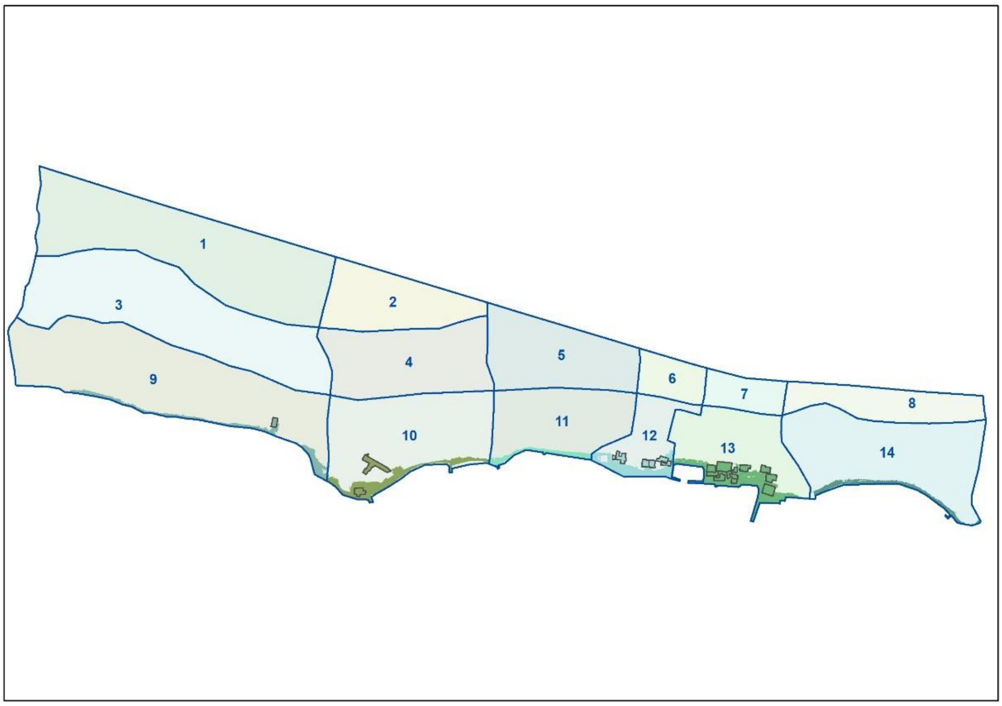


Figure 30: Area and buildings of homogenous zones affected by flood

Three criteria are generated from the flood map for each homogenous zone (Table 8): flooded area, are of buildings affected by flood, and number of buildings affected by flood. All other zones are not affected by flood, so their criteria evaluations are zero.

These data are used as an input for multicriteria method PROMETHEE with one additional criterion: flood vulnerability of the buildings affected by flood. For each homogenous zone, average flood vulnerability of the buildings affected by flood is calculated and used as a criterion evaluation.

The results of the PROMETHEE-method-based multicriteria analysis for flood risk are presented in Figure 31. From the analysis, it is clear that homogenous zones with highest risk are HZ_{13} and HZ_{12}. It represents a significant issue, since these zones are historical center of Kastel Kambelovac and represent its cultural heritage.

Table 8. Input data for numerical processing with PROMETHEE method for flood single-hazard risk assessment

Homogenous zone (hz)	Criteria		
	Flooded area	Area of buildings affected by flood	Number of buildings affected by flood
HZ_1	0	0	0
HZ_2	0	0	0
HZ_3	0	0	0
HZ_4	0	0	0
HZ_5	0	0	0
HZ_6	0	0	0
HZ_7	0	0	0
HZ_8	0	0	0
HZ_9	950	0	0
HZ_{10}	734	0	0
HZ_{11}	415.2	0	0
HZ_{12}	808	156	4
HZ_{13}	1188.1	1463.5	36
HZ_{14}	440.5	48.3	1
Criteria Weights	**33.3**	**33.3**	**33.3**
MIN/MAX	MAX	MAX	MAX

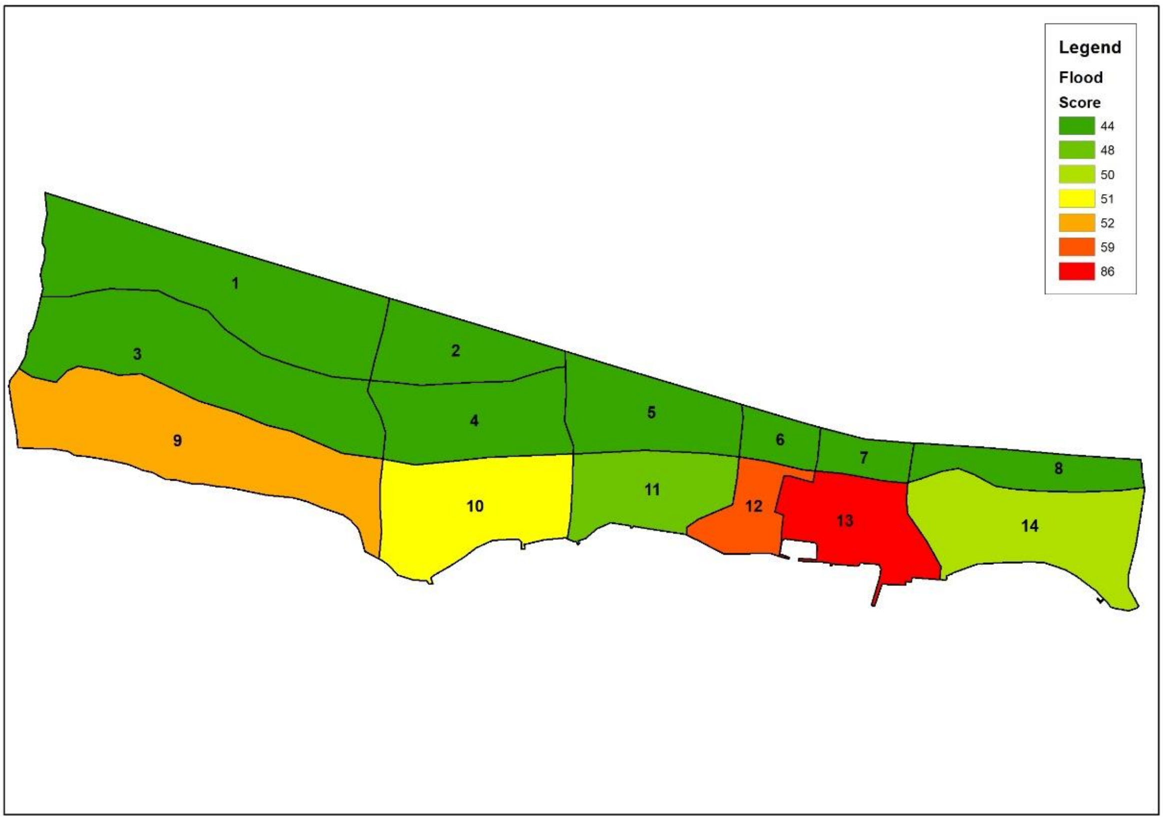


Figure 31: Presentation in GIS of the results of multicriteria analysis for flood risk (net score value)

2.2.3 Generation of input data for extreme waves single-hazard risk assessment by using PROMETHEE method on HR test site

The approach of homogenous zones is used for extreme wave risk assessment, as well. For each homogenous zone extreme waves maps are used. Figure 32 shows homogenous zones affected by extreme waves (HZ_9, HZ_{10}, HZ_{11}, HZ_{12}, HZ_{13} and HZ_{14}).

Again, three criteria are generated from the extreme waves map for each homogenous zone (Table 9): area affected by extreme waves, are of buildings affected by extreme waves, and number of buildings affected by extreme waves. All other zones are not affected by extreme waves, so their criteria evaluations are zero.

These data are used as an input for multicriteria method PROMETHEE with one additional criterion: extreme waves vulnerability of the buildings affected by extreme waves. For each homogenous zone, average extreme waves vulnerability of the buildings affected by extreme waves is calculated and used as a criterion evaluation.

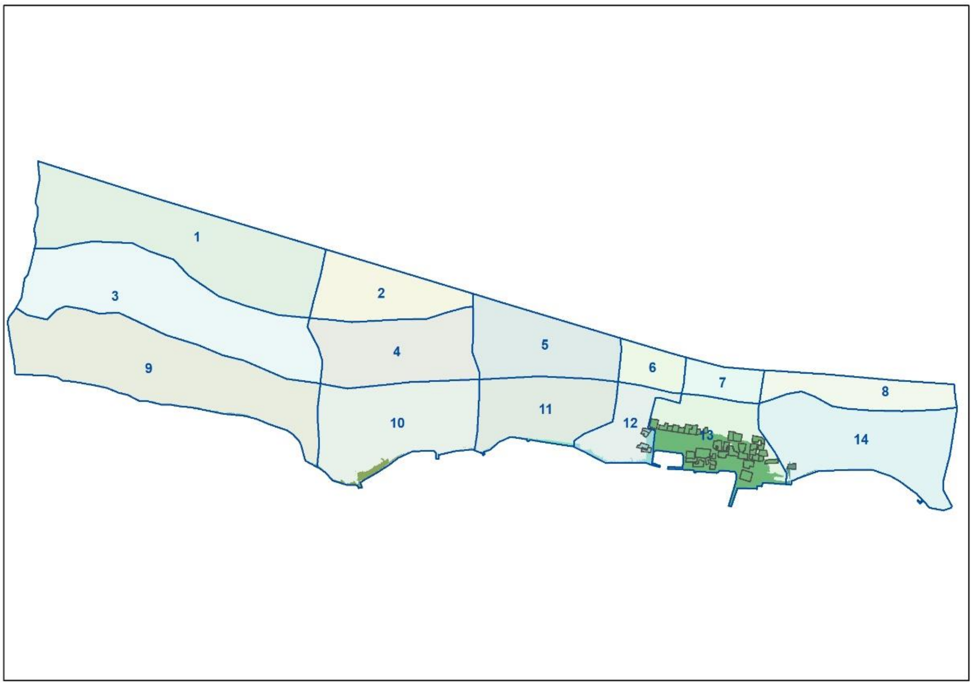


Figure 32: Area and buildings of homogenous zones affected by extreme waves

Table 8. Input data for numerical processing with PROMETHEE method for flood single-hazard risk assessment

Homogenous zone (hz)	Criteria		
	Area affected by extreme waves	Area of buildings affected by extreme waves	Number of buildings affected by extreme waves
HZ_1	0	0	0
HZ_2	0	0	0
HZ_3	0	0	0
HZ_4	0	0	0
HZ_5	0	0	0
HZ_6	0	0	0
HZ_7	0	0	0
HZ_8	0	0	0

HZ_9	2788.1	137	1
HZ_{10}	3260	730	2
HZ_{11}	1377	0	0
HZ_{12}	2466	716	6
HZ_{13}	4905.3	1935	12
HZ_{14}	1875	0	0
Criteria Weights	**33.3**	**33.3**	**33.3**
MIN/MAX	MAX	MAX	MAX

The results of the PROMETHEE-method-based multicriteria analysis for extreme waves risk are presented in Figure 33. From the analysis, it is clear that, same as in the case of flood, homogenous zones with highest risk are HZ_{13} and HZ_{12}. Again, it represents a significant issue, since these zones are historical center of Kastel Kambelovac and represent its cultural heritage.

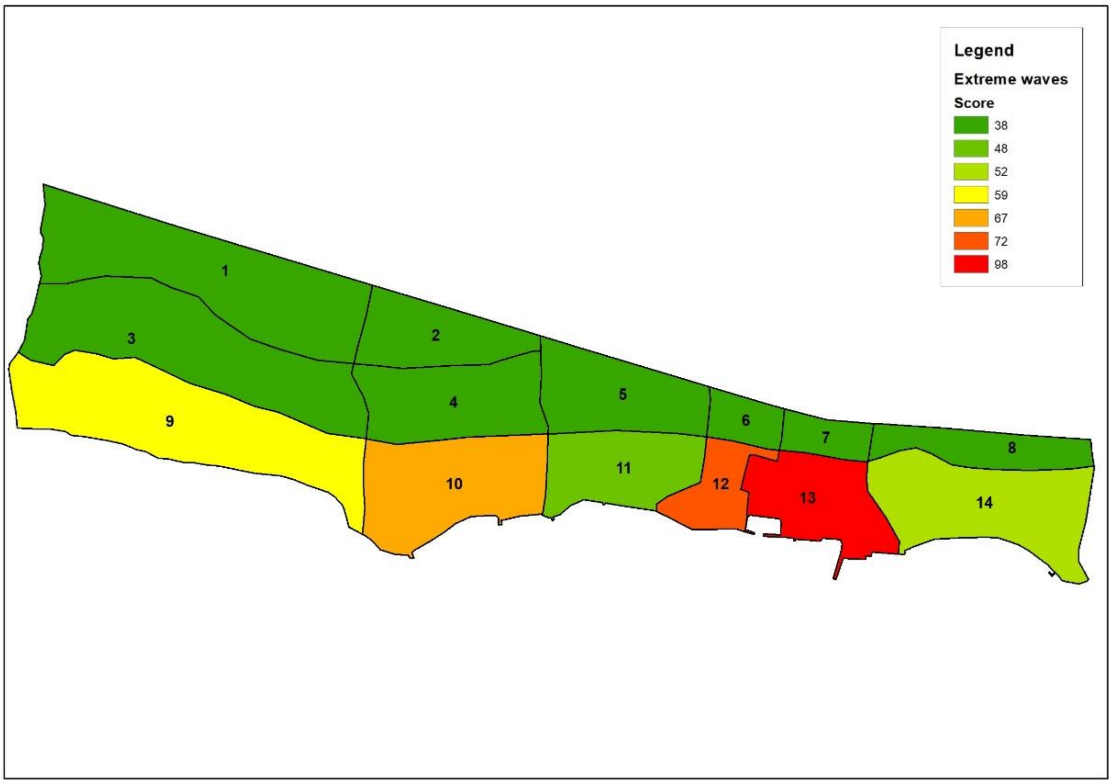


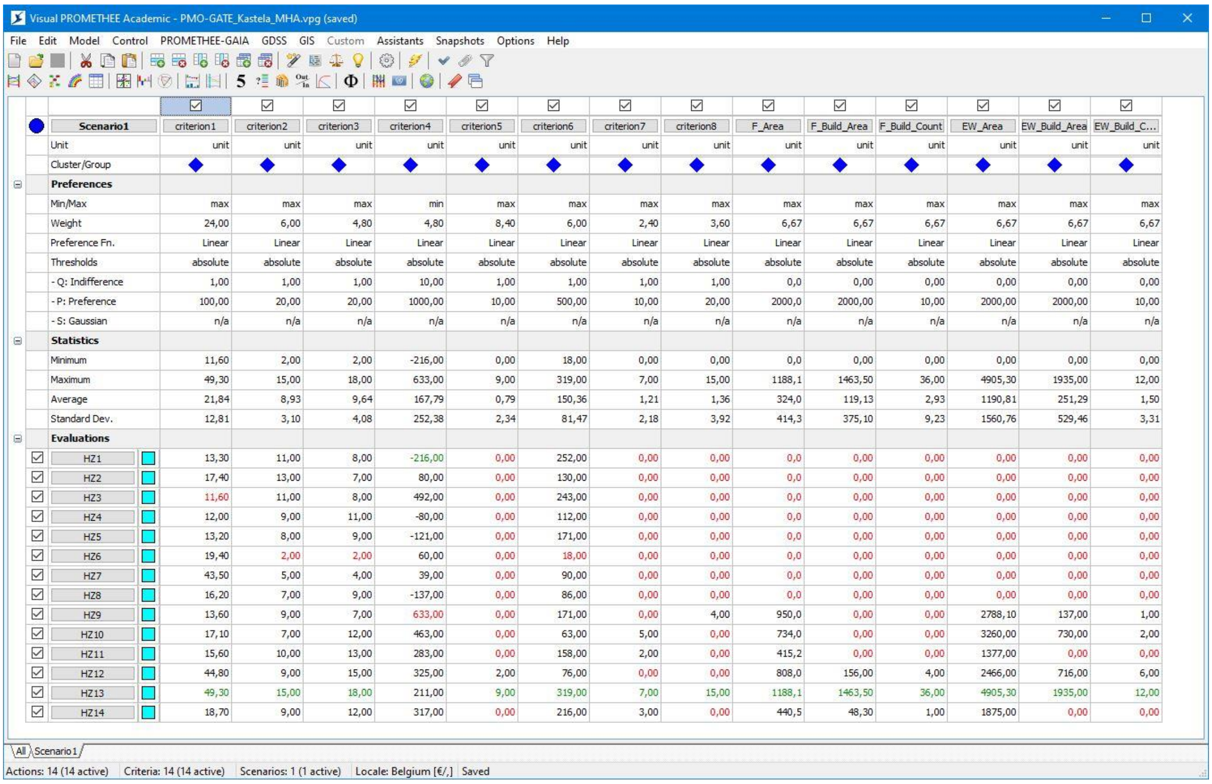
Figure 33: Presentation in GIS of the results of multicriteria analysis for extreme waves risk

2.3 Multi-hazard Risk Assessment on HR test site

2.3.1 Generation of input data for seismic, flood and extreme waves multi-hazard risk assessment by using PROMETHEE method on HR test site

Finally, the Multi-hazard Risk Assessment for HR test site can be made. Three natural-hazards are combined and evaluated together to assess the multi-hazard risk of each homogenous zone. The result of this multicriteria analysis will classify homogenous zones in accordance with multi-hazard risk.

In Figure 34, all criteria data for seismic (Table 7), flood (Table 8) and extreme waves criteria (Table 9) are combined into single multicriteria matrix of Visual PROMETHEE software.



Scenario1	criterion1	criterion2	criterion3	criterion4	criterion5	criterion6	criterion7	criterion8	F_Area	F_Build_Area	F_Build_Count	EW_Area	EW_Build_Area	EW_Build_C...
Unit	unit	unit	unit	unit	unit	unit	unit	unit	unit	unit	unit	unit	unit	unit
Cluster/Group														
Preferences														
Min/Max	max	max	max	min	max	max	max	max	max	max	max	max	max	max
Weight	24,00	6,00	4,80	4,80	8,40	6,00	2,40	3,60	6,67	6,67	6,67	6,67	6,67	6,67
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	1,00	1,00	1,00	10,00	1,00	1,00	1,00	1,00	0,0	0,00	0,00	0,00	0,00	0,00
- P: Preference	100,00	20,00	20,00	1000,00	10,00	500,00	10,00	20,00	2000,0	2000,00	10,00	2000,00	2000,00	10,00
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics														
Minimum	11,60	2,00	2,00	-216,00	0,00	18,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
Maximum	49,30	15,00	18,00	633,00	9,00	319,00	7,00	15,00	1188,1	1463,50	36,00	4905,30	1935,00	12,00
Average	21,84	8,93	9,64	167,79	0,79	150,36	1,21	1,36	324,0	119,13	2,93	1190,81	251,29	1,50
Standard Dev.	12,81	3,10	4,08	252,38	2,34	81,47	2,18	3,92	414,3	375,10	9,23	1560,76	529,46	3,31
Evaluations														
HZ1	13,30	11,00	8,00	-216,00	0,00	252,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ2	17,40	13,00	7,00	80,00	0,00	130,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ3	11,60	11,00	8,00	492,00	0,00	243,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ4	12,00	9,00	11,00	-80,00	0,00	112,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ5	13,20	8,00	9,00	-121,00	0,00	171,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ6	19,40	2,00	2,00	60,00	0,00	18,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ7	43,50	5,00	4,00	39,00	0,00	90,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ8	16,20	7,00	9,00	-137,00	0,00	86,00	0,00	0,00	0,0	0,00	0,00	0,00	0,00	0,00
HZ9	13,60	9,00	7,00	633,00	0,00	171,00	0,00	4,00	950,0	0,00	0,00	2788,10	137,00	1,00
HZ10	17,10	7,00	12,00	463,00	0,00	63,00	5,00	0,00	734,0	0,00	0,00	3260,00	730,00	2,00
HZ11	15,60	10,00	13,00	283,00	0,00	158,00	2,00	0,00	415,2	0,00	0,00	1377,00	0,00	0,00
HZ12	44,80	9,00	15,00	325,00	2,00	76,00	0,00	0,00	808,0	156,00	4,00	2466,00	716,00	6,00
HZ13	49,30	15,00	18,00	211,00	9,00	319,00	7,00	15,00	1188,1	1463,50	36,00	4905,30	1935,00	12,00
HZ14	18,70	9,00	12,00	317,00	0,00	216,00	3,00	0,00	440,5	48,30	1,00	1875,00	0,00	0,00

Figure 34. Spreadsheet with Visual PROMETHEE software input data for multi-hazard risk assessment

In Figure 35, single-hazard risk of homogenous assessment for seismic, flood and extreme waves natural-hazard is presented. The maps are similar for flood and extreme waves risk assessment since the coastal homogenous zones are affected by flood and extreme waves and inland zone are not affected. However, seismic map is different because all homogenous zones are affected by earthquake in a same way, so some of the inland homogenous zones have higher risk, as well.

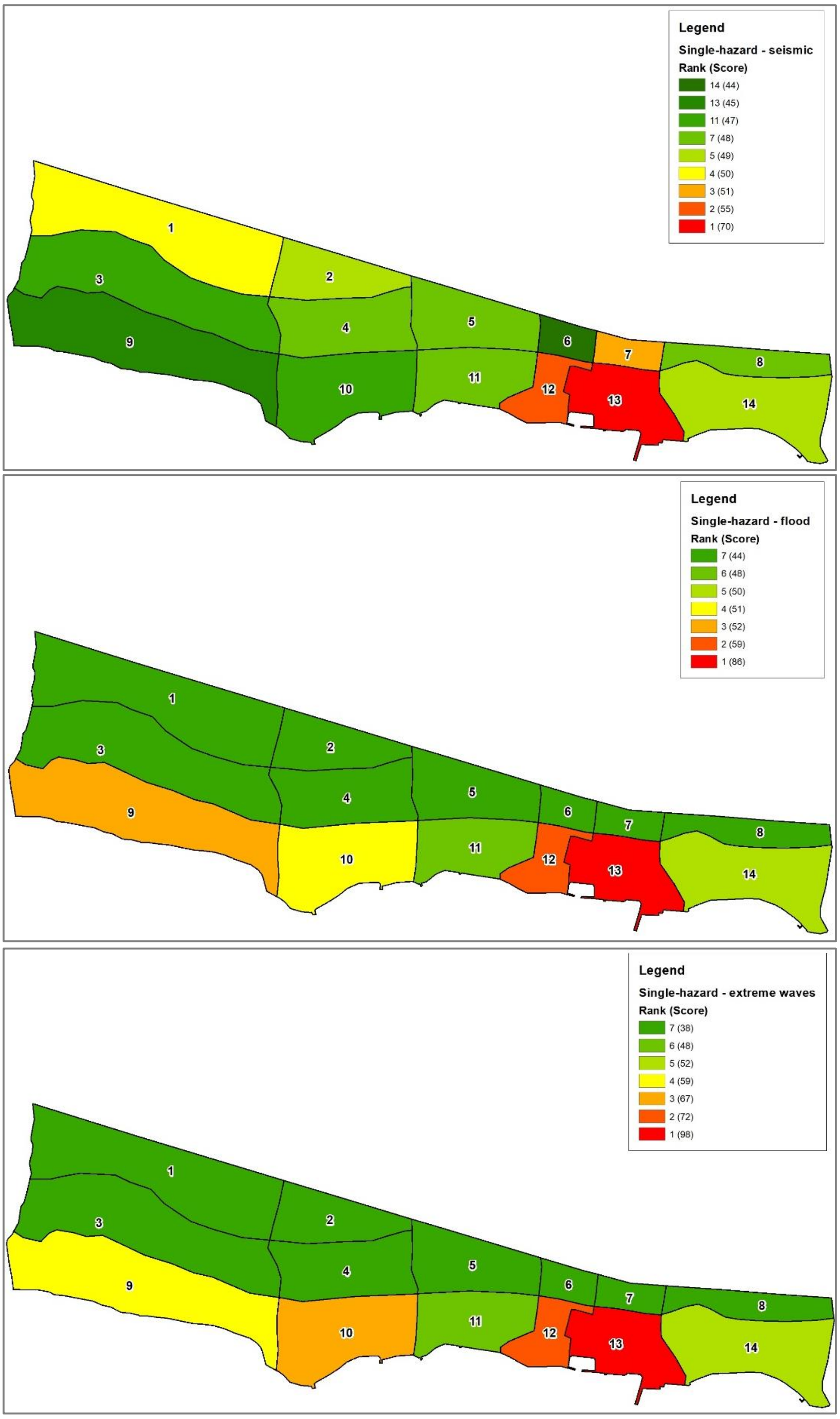


Figure 35: Single-hazard risk assessment of homogenous zones for seismic, flood and extreme waves

The next step is to define set of criteria weights. In this analysis, for each of three single-hazards their criteria weights are used (Table 7, 8 and 9). However, the set of seismic criteria got a total weight 60% in comparison to 20% for flood criteria and 20% for extreme waves criteria. Since the seismic hazard has highest probability, its criteria set is given a higher overall weight. This is just proposal, criteria weights need to be determine by an expert judgment.

Finally, the results of multi-hazard risk assessment for HR test site are presented in Figure 36.

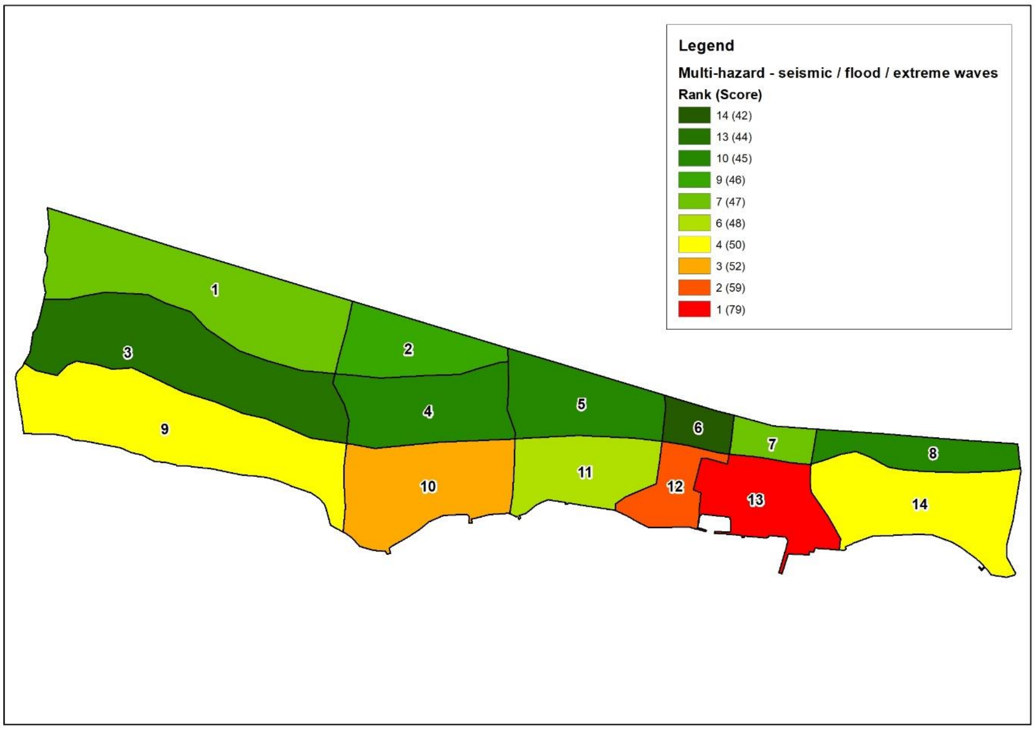


Figure 36: Multi-hazard (seismic/flood/extreme waves) risk assessment for HR test site

It is interesting to see that when taking all three hazards into calculation some of the coastal homogenous zones got higher multi-hazard risk (HZ_{14}), and some of inland homogenous zones with high seismic risk got lower multi-hazard risk (HZ_1 and HZ_7).

The possible issues of this approach is that PROMETHEE method is based on relative mutual comparison of alternatives, therefore in the case of change of total number of alternatives the result can vary. The solution of this issue can be in defining two reference points (low risk alternative and high risk alternative) to stable the comparison process. Nevertheless, it has been demonstrated that multi-criteria decision-making method PROMETHEE can be used for single-hazard and multi-hazard risk assessment with lot of topics for further research.

Conclusions

The multi-criteria decision-making method PROMETHEE and geographic information system have been used to create a spatial decision-making tool to assess the risk indexes for single-hazard and multi-hazard analysis. The homogenous zones have been identified as spatial area of the test site with some mutual spatial characteristics. The analysis of homogenous zones was enhanced with additional spatial criteria derived from GIS, in order to have proper risk analysis. The analysis has been made on two example as a proof of concept for single hazard risk analysis and combined risk analysis of multi-hazard.

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