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Resilience assessment: Methodological challenges and applications to critical infrastructures

Proceedings of the 63rd ESReDA Seminar
Joint Research Centre, Ispra, Italy
25-26 October 2023

Kopustinskas, V., Foretic, H., Asensio Bermejo, I.

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Abstract

These proceedings are the outcome of the 63rd ESReDA Seminar on "Resilience assessment: Methodological challenges and applications to critical infrastructures" that took place at the European Commission's Joint Research Centre's (JRC) premises in Ispra, Italy, on 25-26 October 2023. A broad spectrum of resilience topics were covered, with sessions addressing different infrastructure sectors: energy sector (electricity, gas, hydrogen), transport sector (rail, road, air and maritime), other critical infrastructures, networks and entities, urban development, public sector and government. The seminar aimed at addressing resilience due to different hazards or threats, such as: disruptions of infrastructures due to aging or technical failures, natural events, intentional attacks or emerging threats, hybrid being an example. This seminar brought together researchers, practitioners and decision-makers from academia, operators, industry, governing bodies, to discuss theories, concepts, and experiences of resilience assessment methodologies and applications. The proceedings include 3 plenary speeches and 25 full papers or extended abstracts.

Acknowledgements

The organisation of the 63rd ESReDA Seminar was a huge effort of many JRC staff and ESReDA members. The authors of this report are particularly thankful for full support of the JRC Directorate C Director Habil dr. Piotr Szymański and his office team, Unit C3 – Energy Security, Distrbution and Markets hierarcy – Head of Unit Kristine Vlagsma and her deputy Gianluca Fulli. The authors are very thankful for the time and attention from ESReDA Board of Directors and in particular ESReDA President dr. Mohamed Eid.

The Seminar would not be a successful event without dedication of the JRC Ispra Conference Service Team, Catering, Logistics, Security and Procurement Services. All and each service member deserves a big thank you!

We would like to thank every participant for attending and contributing to the 63rd ESReDA Seminar. We hope that the seminar provided a platform for stimulating discussion and debate and that participants were able to take the opportunity to form new, collaborative links and share their knowledge of resilience techniques and their applications in practice, with like-minded engineers and scientists.

Special thanks goes to Virginie Petitjean, Unit secretary, for her full dedication, extreme efforts and creativity that made a lot of last minute requests happen.

The last, but not least 'thank you' goes to the Technical Programme Committee for their efforts during the review process of the seminar contributions.

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2.10 A territorial view of the infrastructure resilience

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Abstract

The challenge to make cities and, more in general, the territories inhabited or exploited by humans safe, and resilient, includes mitigation and adaptation strategies against disaster, as a central issue in achieving sustainability. A tool to measure local vulnerability from a multi-risk approach is proposed and discussed. The tool consists of a mathematical framework for the territorial vulnerability assessment that integrates multiple indicators clustered into three factors defined as sensitivity, pressures, and hazards, weighted according to a participatory procedure. These include the infrastructures at the service of the territories and the effects of their disruption. Cascade effects can be also considered in the model, as mutual influences among factors, to keep into account, as an example, climate change related phenomena. Space-dependent analyses using the Geographical Information System were developed from the multiple nested indicators to project the vulnerability index onto a homogeneous grid in the territory of interest. Thematic maps referring to the systemic vulnerability by different sensitivity components were generated. The tool contributes to increasing the awareness of territorial vulnerability and offers support to resilience-based decision-making in designing technical measures of policies at a local scale, whose managers are potentially disoriented by more complex models. A municipality in North-West Italy was used as a case study, concerning the process/energy infrastructures, within the research activities of the Responsible Risk Resilience Centre from the Polytechnic of Turin to test the vulnerability matrix. Further research is required to implement the framework in different scenarios and develop the model's temporal behaviour.

1 Introduction

The Sustainable Development Goals (SDGs) issued in 2015 for the United Nations Agenda, highlight the necessity to strengthen the resilience and the adaptive capacity in all sectors against the different natural hazards and disasters, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015a; 2015b). in this context, contemporary challenges and uncertainties expose cities and local communities to multiple and non-linear risk factors that require a spatial planning approach to integrate the dimensions of complexity and unpredictability. This situation calls for new methods and tools to frame territorial vulnerability (Brunetta et al., 2019) and thus enhance resilience (Galderisi, 2012) and adaptation in the context of sustainable development goals. Central to spreading awareness and building adaptation policies is the availability of specific data and analysis to measure resilience. In this sense, vulnerability assessment is the first part of operationalizing resilience, often interpreted as a buzzword and a term challenging to put into an operational context (Brunetta et al., 2020).

Vulnerability, often considered as the counter position to resilience, is to be understood as the predisposition of the elements of the system to be damaged by hazard events, punctuality, or continuous pressures over time (IPCC, 2012), while resilience is, in fact, the coping capacity of the elements of the system. Consequently, the measurement of vulnerability lends itself to using quantitative methodologies based on multivariate analysis of representative indicators.

New challenges faced by people involved in disaster risk management are the so-called high-impact and low-probability events (HILP), such as technological events triggered by natural hazards (Natech). Even if this kind of event presents a small likelihood (often neglected by operators), in case of occurrence, it may cause severe damage to individuals, infrastructure, environment, and society, being particularly complex because often it is the result of cascading events (Mesa-Gómez et al., 2020). Furthermore, there is some evidence suggesting that an increase in the frequency of certain types of Natech, may be linked to climate change (Ricci et al., 2021).

In this line, the Italian National Adaptation Plan serves as a notable instance of a climate change adaptation strategy advanced by EU member states. It acknowledges the issue of NaTech events as one of the sectoral vulnerabilities related to climate change and recommends sector-specific measures and best practices to ensure effective adaptation to climate change in the industrial sector (Centro Euro-Mediterraneo sui Cambiamenti climatici, 2017). Regarding the industries, they are no longer perceived as isolated facilities, but

as part of larger, interconnected socio-ecological and technological systems (SETSs), that consider the entire production process and its impacts on human beings and the environment.

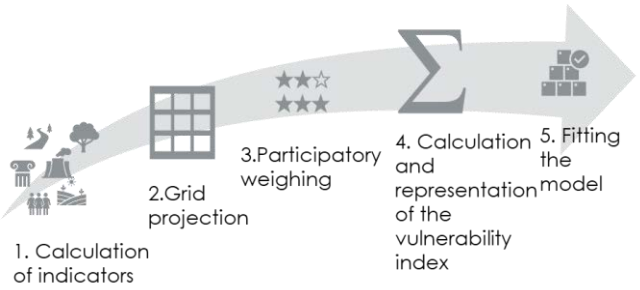
Considering everything described above, this contribution develops a territorial view of the infrastructure vulnerability, integrating elements of one industrial case study and the multi-hazard context where the facility is located. This case serves as a proof of concept to assist the decision-making process about the interaction among critical infrastructures and the multiple hazards belonging to the territories.

2 Tool for assessing the territorial vulnerability.

The tool proposed by Beltramino et al. (2022), to determine vulnerabilities at the local scale, represents the cornerstone of this case study. This multidisciplinary tool has been developed by the Responsible Risk Resilience Centre (R3C) from Polytechnic of Turin, to respond to the first objective of the project Measuring Resilience (Brunetta et al., 2019), which consists of the assessment and spatial representation of the systemic vulnerability of a territory.

In a nutshell, the multidisciplinary tool consists of a mathematical framework capable of quantifying the vulnerability in a territory, integrating multiple indicators clustered into three factors defined as sensitivity (S), pressures (P), and hazards (H), weighted according to a participatory procedure. It ensures not only the estimation of different stressors and hazards according to impacting sensible elements belonging to the location of interest, but also the necessities of the stakeholders expressed as a coefficient of interest. In addition, in the mathematical equation for the estimation of the systemic vulnerability consider factors for both, the impact of climate change, and the temporal character of the pressures. The vulnerability matrix follows five steps as depicted in Figure 1.

Figure 33. Steps to implement the vulnerability matrix.



2.1 Selection and Calculation of Indicators

The starting point for the creation of the tool is the selection of a set of sensitivity, pressure, and hazard indicators and their calculation using GIS tools. They were selected following a discussion with stakeholders from the area under study and a review of the principal spatial government plans and territorial instruments, highlighting the Municipality specificities.

The definition and calculation of the indicators is the most consistent and time-consuming phase of this work. Each of the 21 indicators selected has followed a process of data collection and calculation in a GIS environment. Further details about the description and calculation of each indicator can be found in Beltramino et al. (2022).

2.2 Indicators Grid Projection and Representation

These indicators were nested in layers onto a grid of homogeneous cells (200 x 200 m) which covers the municipality combining all the relationships and elements examined and allowing an overall reading of the critical territorial aspects. For their attribution into the grid, spatial join operations through a specific field identifier (FID) were assigned to each cell. Depending on the geometry of the input data (point, line, polygon) the attribution of the values obtained for each indicator to the grid was carried out according to five criteria: (i) point count (Cultural heritage consistency-B1, Floods-ALA), (ii) sum of the point values (Energy consumption intensity-A3, RES energy selfsufficiency-B3, Earthquakes-SIS), (iii) weighted sum of linear (Road infrastructure density-B5) or areal elements (Landscape sensibility-A1, Ecological Quality-A2, Building construction characteristics-B2, Communication infrastructure density-B4, Density of productive activities-C4, Soil consumption-CDS, Building obsolescence-OBS, Wildfires-IBO, Lands slides-FRA), (iv) average value of areas within the cell (Population density-C1, Elderly component-C2, Immigrant Component-C3, Aging population-OLD) and (v) intersection between input polygons and each cell (Flash floods-ALU, Major Industrial Risk-RIR).

2.3 Participatory weighing

The relationship between each sensitivity indicator and pressure and hazard indicator was weighted using a crossing matrix procedure (row by column). In this phase, a participatory methodology was used, involving a team of 13 researchers participating in the project, where an interactive version of the matrix, evaluated the degree of relationship between each indicator using an ordinal Likert scale, where: 0, no relationship; 1, weak relationship; 2, strong relationship; 3, very close relationship.

2.4 Calculation and Representation of the Vulnerability Index

The formula for determining the systemic vulnerability was implemented in a spreadsheet which involved not only the weights described in 2.3. section, but also the 21 columns corresponding to the indicators of S, P, and H, and the 2550 rows (one entrance for each 200x200 m cell that subdivides the territory). More details about the methodology and its mathematical framework can be found in Beltramino et al. (2022).

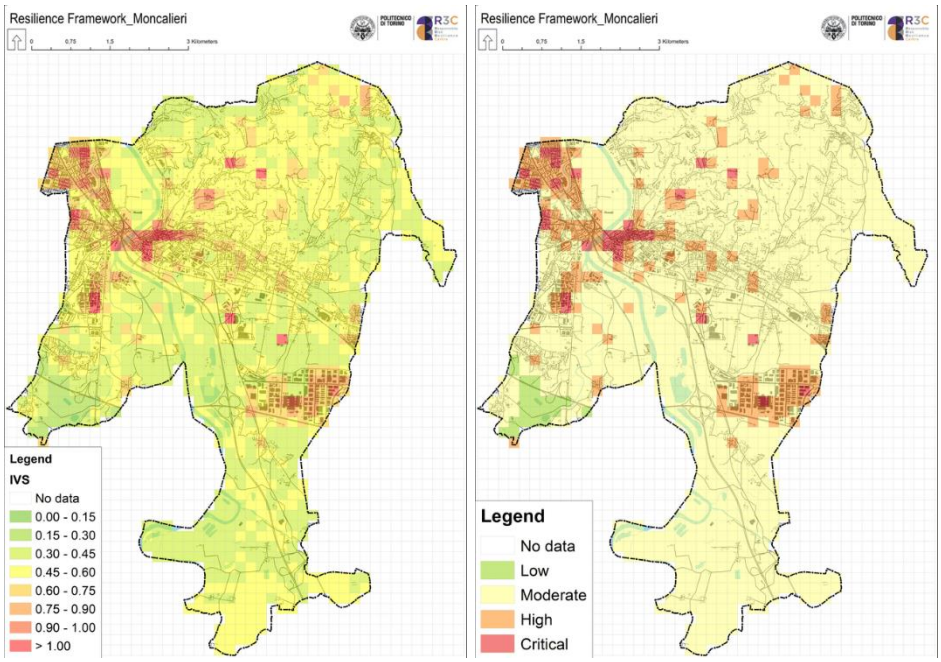
2.5 Fitting the model

Since the indicators depend on the availability of spatial data, and some assumptions should be made for the calculation and spatialization of the indicators, uncertainties are introduced to the model. Then, it is important to verify statistically as a single variable (central tendency, dispersion, shape, possible outliers, etc.) the behavior of each column (2550 values of each indicator). In addition, a representative sample of the 2550 values of each indicator and the critical points were spatially checked through the expertise of the planners and stakeholders in the territory under analysis.

3 Systemic Vulnerability assessment in the municipality of Moncaliery, Italy.

The principal output of this methodology consisted of colored maps using both, numerical scales (Figure 2 a), and qualitative scales (Figure 2 b), suitable for reading by non-experts, representing the systemic vulnerability through an ordinal scale of four categories (Low-green, Moderate-yellow, High-orange, and Critical-red).

Figure 2. Final systemic vulnerability map (a) numerical scale (b) qualitative scale.

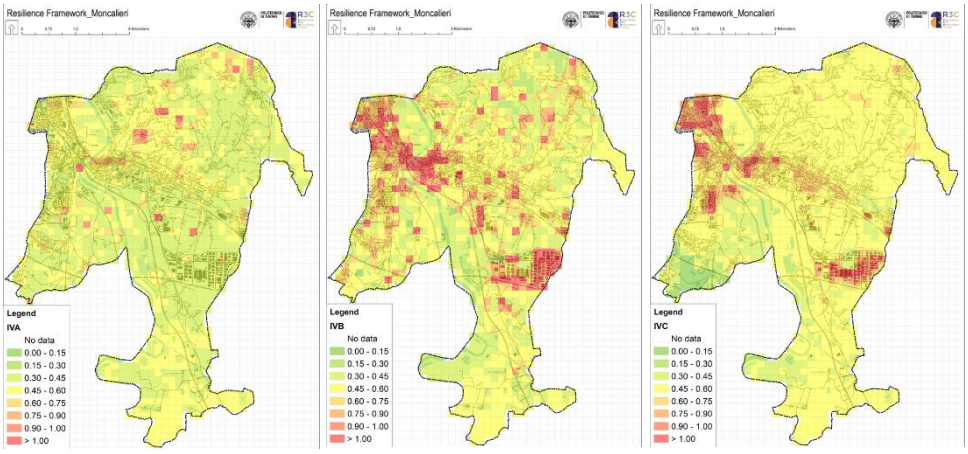


Source: Beltramino et al. (2022)

The three most vulnerable areas correspond to the historical center, the industrial areas, and the most anthropized area in the north-north-west. Other scattered areas identify situations characteristic of punctual elements of the territory. Indeed, during the step described in the 2.5 subsection, most of these areas were verified, providing consistency concerning the presence of elements that determined the territorial vulnerability.

Furthermore, the systemic vulnerability can be deployed by the three components of Sensitivity (Environment and Landscape-A; Building, Heritage, and Infrastructures-B; Economy and Population-C) as represented in Figure 3.

Figure 3. Systemic vulnerability maps (a) IVA: vulnerability index component A, (b) IVB: vulnerability index component B, (c) IVC: vulnerability index component C.



Source: Beltramino et al. (2022)

The values obtained, represented in the three maps, show the values of the vulnerability index divided according to the components IVA, IVB, and IVC.

Focus the analysis on component B (Building, Heritage, and Infrastructures) according to the scope of this article, the most vulnerable areas are those with the highest density of built-up areas, road infrastructures, and the presence of cultural heritage buildings, with a substantial impact on the pressure indicator OBS (obsolete buildings) and the presence of some industries.

The next section presents an application of the vulnerability matrix in an industrial context, to determine its vulnerabilities against the principal Natech factors.

4 Vulnerability deployment focus in a Critical Infrastructure

4.1 General description of the plan

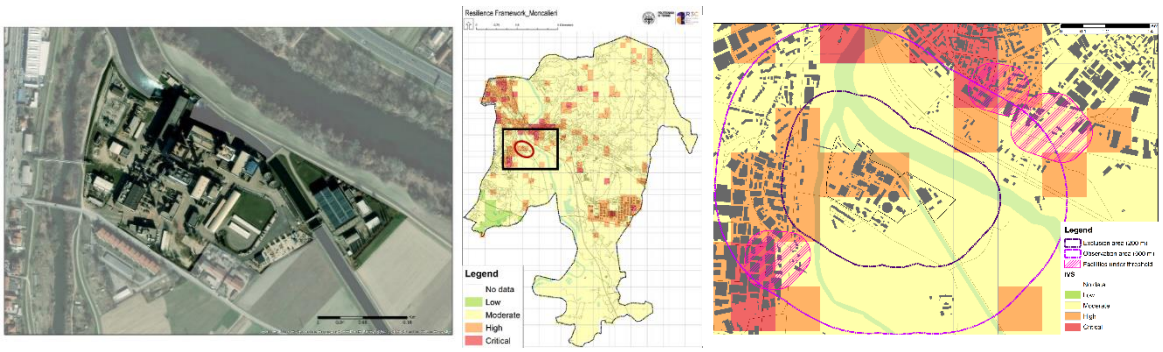
The establishment corresponded with a typical industrial typology clustered in the macro-sector "Power production" according to the description given by Casson Moreno et al. (2018). Its specific activity is the power production from the combustion of hydrocarbons. The unitary operations that are carried out in the plant are both chemical and physical. The activities also include auxiliary technical systems necessary for the production plant's operation, such as compressed air, treated wastewater, steam production, and warehousing. Within all the processes and functions of the plant, the following items were identified: atmospheric storage tanks, tall structures such as chimneys and process columns and equipment, heat exchangers, complex systems of pipelines, complex electrical networks, and water treatment organs.

4.2 Territorial Vulnerability Associated with an Industrial Context

The area of interest corresponds to an industrial context that not only includes the plant inside the fence, but also the entire environment with which the facility interacts, comprehending approximately 280 hectares and conformed by 70 exhaustive homogeneous cells. Figure 4 recreate some elements of interest for the industrial context.

Figure 4. Industrial context.

a) Industrial satellite view b) location of the industrial context within the municipality c) IVS for the industrial context.



Source: Castro et al. (2023).

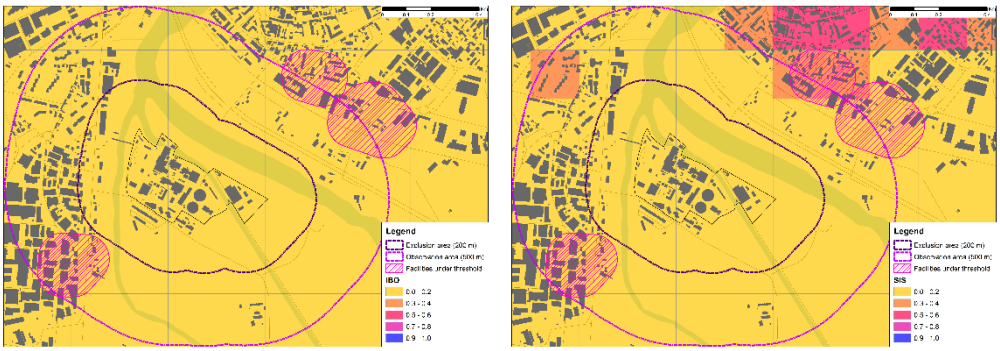
The systemic vulnerability analysis according to the visual field yielded approximately 65% of the cells with moderate vulnerability (yellow), 26% with high vulnerability (orange), and 9% with critical vulnerability (red). It is important to remark that the few critical vulnerability cells corresponded to areas that only partially intersect the observation area (farther than 500 m). In contrast, within the perimeter of the plant, more than 50% of the occupied area is found with a coloration corresponding to high vulnerability, while another 3 orange cells are included within the exclusion area in case a major accident occurs.

In addition, it can be also appreciated how different binding areas applied to other neighbor plants may interact with the observation area, being able to cause domino effects. Therefore, the zone analyzed is highly vulnerable to the mutual interaction between both industrial and external hazards, susceptible to suffering cascading events that may harm the environment, the population, and the infrastructure.

In this line, a components breakdown for IVS was carried out up to the pressure and hazards able to impact the industrial context.

Regarding the breakdown, this section just highlighted the contrast between the less relevant and the significative indicators as potential disruptive elements. Then, Figure 5 starts illustrating the vulnerability representation of two natural hazards that were not considered significant to the industrial context. On the other hand, Figure 6 presents a vulnerability representation of two significant indicators.

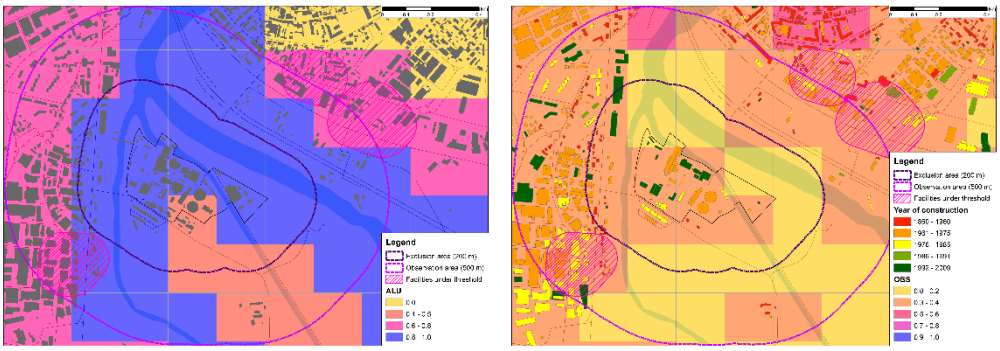
Figure 5. Vulnerability representation of natural hazards is not significant to the industrial context. a) Wildfires (IBO). b) Earthquakes (SIS).



Source: Castro et al. (2023).

It can be appreciated from the analysis that both hazards, earthquakes, and wildfires although they should not be completely disregarded, the industrial context vulnerability against these hazards is low.

Figure 6. Vulnerability representation of natural hazards and pressures significant to the industrial context. a) Floods (ALU). b) building obsolescence (OBS).



Source: Castro et al. (2023).

Moving to Figure 6 a), in contrast, it is not difficult to note how practically all the cells in the exclusion area, including those in the internal perimeter of the plant, are critically vulnerable to the impact of floods. The rest of the visual field in the industrial context alternates between critical and high vulnerability. The potential impact of this natural hazard is conditioned by the proximity of the plant location to the bed of a river which bifurcates on both sides of it. According to the European Commission (2022), this kind of natural hazard may trigger several damaged modes to industrial items such as buckling, rupture of pipes and connections, overfilling of process equipment, displacement and overturning of structures, and pushed objects against the equipment provoking the puncturing phenomena.

Moreover, Figure 3b shows building obsolescence as a linear and generalized trend that affects gradually the industrial context cells. In addition, it is important to note how the punctual elements in the plant area are categorized according to the year of construction. From this, it can be perceived that some process areas and the round structures corresponding to storage tanks had more than 50 years of construction. Then, a specific analysis should be done as proposed by Milazzo and Bragatto (2019).

5 Conclusions

The tool offers a comprehensive approach to measuring territorial vulnerability by integrating relevant indicators and considering systemic factors, territorial peculiarities, and stakeholder interests. Its multi-risk concept and spatial analysis enable scalable and replicable applications, fostering increased awareness and supporting detailed local policy planning.

The tool potentialities could be applied to assess the vulnerabilities of the critical infrastructure within territories of interest, such as Industrial contexts. The analysis enabled the systemic vulnerability at levels of components or indicators, individuating the most prominent to cause disruptions. The picture must be completed. From vulnerability to resilience. Data availability and quality is a criticality. This introduces uncertainties that must be addressed.

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