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Assessing resilience at different scales: from single assets to complex systems

Clemente Fuggini[1] · Celina Solari[2] · Rita De Stefano[2] · Fabio Bolletta[1] · Florencia Victoria De Maio[3]

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Abstract

Nowadays, critical infrastructure and systems are getting more and more interconnected, while facing increasing and more intensive hazards: from man-made to natural ones, including those exacerbated by effects of the climate change. The demand for their robustness and resiliency against all these threats is finding ground to organizations or states' ambitions, implementations, and policies. Moreover, their distributed network spanning from local areas to cities, from regions to cross-country extension, make them a target for malicious actions aimed to damage or even disrupt their critical supplied and therefore the availability of the service they deliver. The paper focuses on a review from an engineering perspective of past efforts (namely those related to the H2020 Secure Gas project) and provides evidence of application cases where the network/system dimension of the critical infrastructure is a key point to be taken into account and to be safeguarded. Finally, an outlook on future perspectives and potentials in the application of resilience at local, urban and territorial/national level is described, with incoming and emerging threats at local and global level.

Keywords Infrastructure · Complex systems · Resilience · Hazards · Scales

1 Introduction

The significance and the crucial role of the well-tempered function of critical infrastructures (CIs) and systems is ever-increasing the recent years, as their key role in the businesses', societies', and states' continuation and sustainability is emerging in a daily basis. The main reason for this upgrade is the severe repercussions to economic and societal level of the countries due to damages of CIs, caused by reduction of their functionality, potential disruptions of their services or even their destruction (partial or total). The severity of the damages is increasing from both the exposition of CIs to more hazards due to their inevitable interconnection and the hostility of the man-made threats, but also to the amplifying magnitude of the natural hazards due to the climate change. As climate change and its consequences are already causing damages estimated at billions of dollars annually (Hallegatte et al. 2019), and the future projections are predicting an increase of these costs the forthcoming years and decades (Neumann et al. 2015; Shiklomanov et al. 2019; Twerefou et al. 2015), the states and the societies have started the shifting to a more resilient behaviour of them towards these phenomena and dangers. The countries are now aligning more eagerly to the respective frameworks (United Nations 2015a) and international agreements (United Nations 2015b) on the reduction of the climate change's impact and their resilient profile building, by robusting and empowering the resilience ability and capacity of their CIs and Systems. The necessity of this shifting is also depicted in a decisive manner, regarding the built environment and the construction sector, as the extra cost of building resilience into the built environment (buildings + infrastructures) is approximately the 3% of overall investment needs worldwide. Thanks to fewer disruptions and reduced economic impacts, the overall net benefit of investing in the resilience of infrastructure would be \$4.2 trillion over the lifetime of new infrastructure, a fact that can be translated into \$4 benefit for each dollar invested in resilience (Hallegatte et al. 2019).

✉ Clemente Fuggini
clemente.fuggini@rina.org

[1] RINA Consulting S.p.A., Via Gran S. Bernardo Palazzo R, 20089 Rozzano, Italy

[2] Rina Consulting S.p.A., Via Cecchi 6, 16129 Genoa, Italy

[3] Rina Consulting S.p.A., Via del Fiumicello 7, 80142 Naple, Italy

The scientific and research community has responded to these demands and necessities, by investigating and developing resilience assessment frameworks for various levels (i.e. single infrastructure, regional, territorial) and various hazards (i.e. natural, man-made), along with design methodologies and tools for the resilience enhancement of the CIs and systems. The initial conceptualization of resilience was of course qualitative, and its historical roots as notion and term can be found back to 1430, by making a broader study on the transfer history in the genesis of the resilience notion and concepts (Gößling-Reisemann et al. 2018). A very insightful and targeted to the critical infrastructures (including the community and the urban resilience level) review on qualitative research approaches is conducted by Cantelmi et al. (2021), providing information and categorizing numerous approaches that have a complete qualitative dimension, or that can be used as entry points for semi-quantitative analyses. The qualitative expression of the resiliency concept and the respective frameworks developed were necessary for the step ahead and the development of a more technical and quantitative approach, in the scope of the assessment and enhancement of the resilience capacity.

The initial and most common approach to the implementation of resilience assessment methods is the targeting of a single asset or system of CIs regarding the protection mainly towards natural hazards. To this category, many types of critical infrastructures are included, some of them are presented via exemplary and extended reviews on water infrastructure systems (Shin et al. 2018), transportation infrastructure systems (Faturechi and Miller-Hooks 2015) and power systems (Mokhlis et al. 2021). But they don’t limit only to these, as recent events of global interest like the Russian–Ukrainian war and the COVID-19 pandemics, which caused severe disruption on the states’ and supply chains’ functions and continuity, led to the examination of the healthcare systems (Trump and Linkov 2022; Galaitsi et al. 2021; Sfakianakis et al. 2021) and peacebuilding (Mitoulis et al. 2023) or war (Jermalavičius et al. 2023) under a resiliency prism. The quantitative approaches for the modelling of the supply chains’ resilience have been investigated before (Mersky et al. 2020; Ribeiro and Barbosa-Povoa 2018), but these events spotlighted further the significance for enhancing these tools and methodologies in order to be more capable and efficient as global community in the future.

As a preliminary step to the expansion of the factors considered and the scale level of these assets or systems, the interconnection of the infrastructures has been started to be formulized (Little et al. 2010) and then studied (Ouyang 2014; Zhang et al. 2019), also taking into consideration threats related to cyber-security (Palleti et al. 2021; Wilson and Perret 2023) and to hybrid nature (Linkov et al. 2019). The level of spatial expansion of the resilience frameworks is expanding also to community, urban and territorial scale. Regarding the community level, extended research has been conducted in the community-based resilience towards natural hazards and climate change (Koliou et al. 2018), while in respective frameworks, the CIs interdependency is taking into consideration (Blagojevic et al. 2022) and implementation of resilience methods and analysis in real communities have taken place (Feofilovs et al. 2016; Deshkar and Adane 2016). The community-based resilience design can be considered also as part of the broader built environment (Masoomi and van den Lindt 2018), associating this way the local with the urban level of design. At the urban level, the resilience capacity and ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales (Meerow et al. 2016) are under examination. The dimensions, criteria and indicators for the resilience assessment are multiplied (Yamagate and Sharifi 2016), advancing the respective design methods chosen to include multi-risk scenarios (Critto et al. 2022), while the risk factors are becoming more heterogeneous (Galderisi 2013) and real case studies in urban level have started to conducted (Wang et al. 2022; Qalati et al. 2022). As it was expected, many suggestions for increasing the urban resiliency capacity focused on the role and the enhancement of the infrastructures via the concepts of green (Liu et al. 2020), sustainable (Bobylev et al. 2012) and hybrid (Andersson et al. 2022) infrastructures, but most of the attempts limited to offer solutions on the urban level. Finally, the territorial resilience is starting to be considered a key goal of the spatial planning (Salata et al. 2019), as its adaptation and prism are contributing to study the economic perspectives of cities and regions more adequately (Antonescu and Bogdan 2018). Also on this level, the crucial role of the infrastructures is exhibited as studies carried out on their resilience capacity towards multi-natural hazards (Elms et al. 2021) and their security-related hazards (Krimgold 2012), and respective assessment methodologies of them have been developed (CISA 2021). Real case studies are now examining whole provinces (Arvin et al. 2023), metropolitan regions (Peng et al. 2022) and warfare territories under the scope of peacebuilding (Mitoulis et al. 2023).

The multi-step progression in the definition and development of resilience assessment frameworks for the CIs and systems in different scale levels is beyond doubt, along with the awareness of citizens and communities towards the demand for the implementation of these methods on the purpose of societies’ benefiting. However, a partial lack is observed in the development and implementation of coherent and common resilience assessment methods and frameworks, which demonstrate the applicability to various types of CIs, systems and emerging hazards ranging from natural to man-made ones, providing simultaneously a feasibility range of extension from a single asset at a local level to complex systems at national and territorial level. The current study is addressing exactly this gap and necessity in the respective literature and practice.

2 Methodological approach

The most crucial element of every attempt to assess the resilience capacity of CIs and systems is the adopted methodology, especially in the case that the outer goal is the development of a common, concrete and applicable for various spatial levels assessment framework. The proposed methodological approach is having as philosophy cornerstone its applicability to all the spatial levels and the potentiality for covering most of the assets and the hazards that are needed to be investigated under the scope of a holistic resilience assessment. Figure 1 depicts this philosophy in terms of 3D chart, where the three axes are presenting the resilience dimensions, the time and the spatial level. The resilience dimensions are including many factors, but the most interested in the scope of this article is the physical infrastructures. The analysis can be targeted to examine the operational phase of an infrastructure or system, but also the emergency and post-recovery phase after a disruptive event, and it is presented via the time axis. The most critical option that this framework provides is its applicability towards scalable spatial levels, by beginning from a single building/structure (i.e. cultural heritage building towards seismic hazard) and extending to a whole province or country (i.e. the national gas transmission or transport network). The unified and common assessment framework promotes the feasibility towards the complete spatial level, spreading and implementing its philosophy from local to urban, and then to territorial/national level.

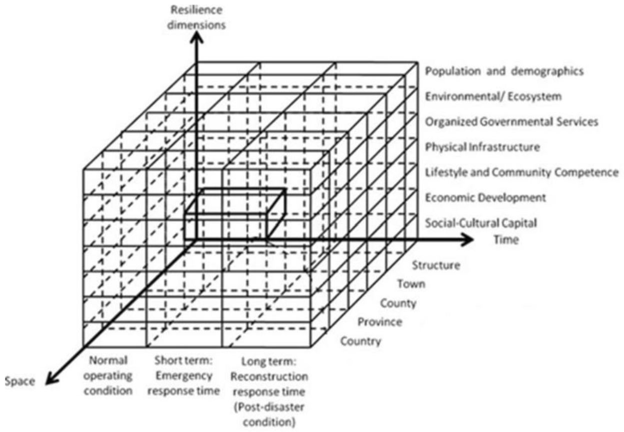
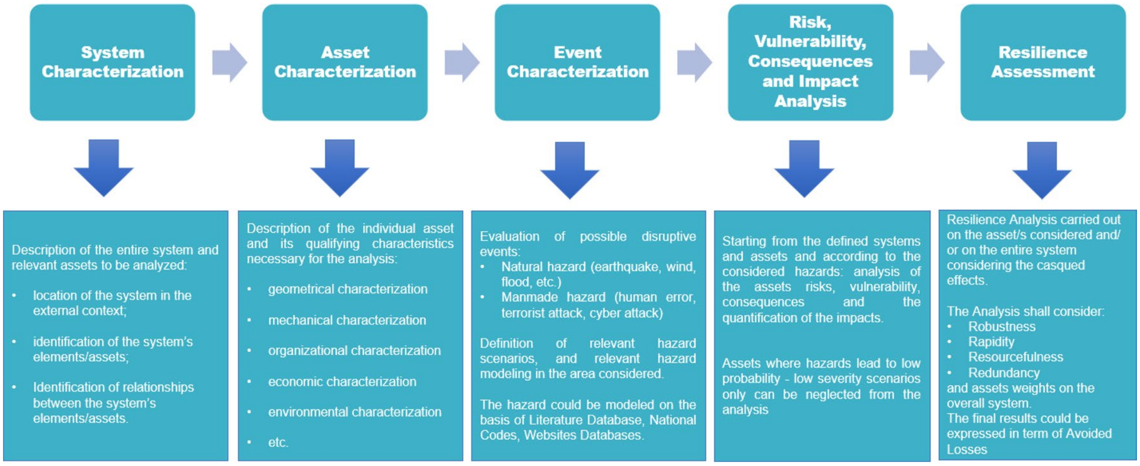


Fig. 1 The philosophy of the developed methodological approach, presented as 3D chart and showing the three directions of this suggested framework, which are the resilience dimensions, the space and time of the analyses

The suggested resilience maturity assessment framework is aiming at becoming a tool, for providing to different users (e.g. public agencies and authorities, city officials and policy makers, private entities providing services for the built environment) a comprehensive maturity assessment of the resilience of the asset/s they own or operate (e.g. a city, an infrastructure, a building, etc.) in face of natural, climatic and man-made hazards. The framework is consisted of a five-step approach, and it is presented schematically in Fig. 2.

The initial step includes the description and the characterization of the entire system (i.e. power system, transportation system), collecting all the necessary information for the resiliency analysis. Based on these, the definition of the resilience goals and the objectives for planning resilience will be set. The objectives will serve as the baseline for assessing the actual current level of resilience as well as possible measure to improve to, the "to be" condition. The assigned objectives will provide an assessment of the level



Description of the entire system and relevant assets to be analyzed:

- location of the system in the external context;
- identification of the system's elements/assets;
- Identification of relationships between the system's elements/assets.

Description of the individual asset and its qualifying characteristics necessary for the analysis:

- geometrical characterization
- mechanical characterization
- organizational characterization
- economic characterization
- environmental characterization
- etc.

Evaluation of possible disruptive events:
- Natural hazard (earthquake, wind, flood, etc.)
- Manmade hazard (human error, terrorist attack, cyber attack)

Definition of relevant hazard scenarios, and relevant hazard modeling in the area considered.

The hazard could be modeled on the basis of Literature Database, National Codes, Websites Databases.

Starting from the defined systems and assets and according to the considered hazards: analysis of the assets risks, vulnerability, consequences and the quantification of the impacts.

Assets where hazards lead to low probability - low severity scenarios only can be neglected from the analysis

Resilience Analysis carried out on the asset/s considered and/or on the entire system considering the casqued effects.

The Analysis shall consider:
- Robustness
- Rapidity
- Resourcefulness
- Redundancy

and assets weights on the overall system.
The final results could be expressed in term of Avoided Losses

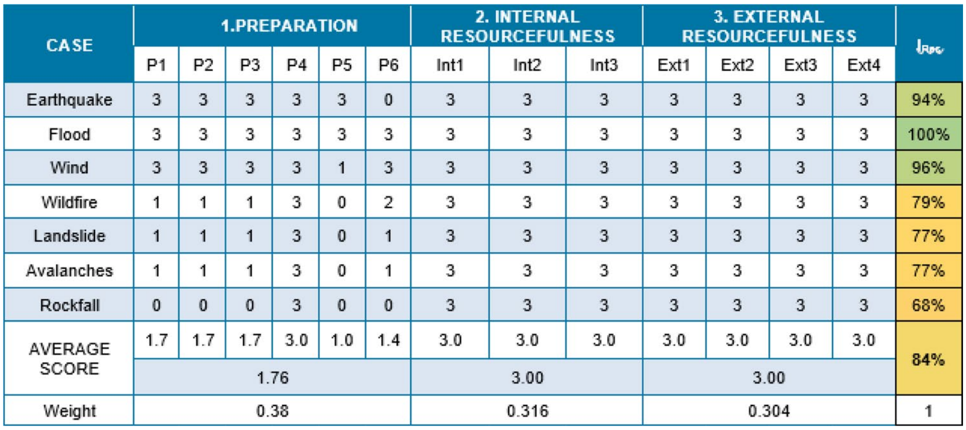
Fig. 2 Schematic representation of the five-step methodological approach, including in summary actions considered in each step of awareness of the user on the topic of resilience, the risks associated with the user’s current level of awareness and the resilience actions or plans which have already been implemented (and their availability).

After this, the definition of assets, indicators and metrics follow, along with the description of the whole context (the boundary to limit all the physical, administrative, environmental, societal and financial consequences of a potential loss/disaster impact in the area of study). Each asset (i.e. the portfolio of facilities/assets/areas/critical buildings for which the level of risk needs to be quantified) is characterized according to the organizational, operational, economic and environmental dimension. Relationship and interdependencies, both tangible and intangible, are identified. For example, if the resilience planning aims at transportation infrastructures, the characterization is needed to include the type of the infrastructures (e.g. road or railway network) and then the design details and the qualifying characteristics. The same way, in the case of Energy Infrastructures, the type of infrastructure is needed to be find (e.g. electricity plant, gas plant) and then design details like the length and the structural characteristics of the grid or the technical characteristics of structures to be provided.

The third step is referring to the threat and hazards characterization, along with the applying models. The modelling of classical hazard events that could affect each asset is based on literature review, national codes and regulation, standards, common practice, existing frameworks and a systematic operator elucidation. The disruptive event’s magnitude and criticality are taking into consideration also. In this step, probabilistic scenarios and calculation are conducted, regarding the under-examination hazard (e.g. earthquakes, rainfalls). The spatial factor is highlighted explicitly here, as the building of the probabilistic scenarios are showing great dependence on the spatial level they refer to (from an asset location to a whole region).

The fourth step is containing the calculations of the vulnerability, exposure and risk, including impact analyses. The analyses of the vulnerabilities, risk and consequences at asset (e.g. single building) and systemic (e.g. city) level are quantitatively starting from the defined system and assets according to the considered hazard/threats. Family standards may be considered in the risk calculation, following and being in compliance with the reference frameworks, standards and high-level legislation. This leads to the risk assessment and a quantitative expression based on failure probabilities for the examined CIs or system, under the form of a vulnerability curve. The impact analysis takes into account the economic, social, environmental and human losses aspects of a disruptive event, calculating also the total direct and indirect losses caused to the stakeholders (i.e. energy operators, state authorities).

In the last and final step, the resilience assessment and the determination of the level of resilience (AS IS) are being carried out. These are expressed in a quantitative form, specifically via a resilience matrix based on specific indicators and particular scale. The resilience matrix integrates the robustness, rapidity, resourcefulness, redundancy sections and after the evaluation on these specific domains, a grading of the behaviour and response of the asset or the system is calculated towards a unique or multiple hazardous events (Fig. 3). In the case of a system, a quantitative assessment of each single asset is conducted and then is expanding to the whole system level, considering dependencies, critical supplies and cascading effects. This way, each asset weighs in a respective manner and level on the overall system.



CASE	1.PREPARATION						2. INTERNAL RESOURCEFULNESS			3. EXTERNAL RESOURCEFULNESS				I_{Res}
	P1	P2	P3	P4	P5	P6	Int1	Int2	Int3	Ext1	Ext2	Ext3	Ext4	
Earthquake	3	3	3	3	3	0	3	3	3	3	3	3	3	94%
Flood	3	3	3	3	3	3	3	3	3	3	3	3	3	100%
Wind	3	3	3	3	1	3	3	3	3	3	3	3	3	96%
Wildfire	1	1	1	3	0	2	3	3	3	3	3	3	3	79%
Landslide	1	1	1	3	0	1	3	3	3	3	3	3	3	77%
Avalanches	1	1	1	3	0	1	3	3	3	3	3	3	3	77%
Rockfall	0	0	0	3	0	0	3	3	3	3	3	3	3	68%
AVERAGE SCORE	1.7	1.7	1.7	3.0	1.0	1.4	3.0	3.0	3.0	3.0	3.0	3.0	3.0	84%
	1.76						3.00			3.00				
Weight	0.38						0.316			0.304				1

Fig. 3 Example of a resilience assessment matrix in which the score of an asset towards each hazard is calculated and then the holistic response of the asset towards multiple hazards in terms of resilience behaviour is evaluated. In the herein example, the section of preparation refers to the planning in advance, those of internal resourcefulness to effectiveness and availability of resources and those of external resourcefulness to the external agreement and coordination plans with other subjects (e.g. public units and local government institutions)

After the five-step approach, the identification of resilience improvement's measures and the estimation in terms of cost and time for their implementation may follow. The identification of innovative solutions (e.g. advanced materials, digital solutions) for resilience improvement and then the determination of their impacts in terms of costs and time of implementation may be offered regarding the project and its specific needs. These solutions are intended to improve the current level of resilience and/or to maintain the level of resilience in view of future climate changes (e.g. increase in occurrence and frequency of a give hazard in a long-term run) or an increased hostility of the surrounding environment (e.g. increase of terrorism, warzones). If it is possible, the determination of the level of resilience (TO BE) in case of improvements applied will be attempted.

Moreover, the term of that resilience pay-off or payback can be also acknowledged and inserted in this step. The route towards the spotlighting of this crucial aspect for the resilience design and its adaptation from the users (e.g. cities, states, systems like healthcare) should be modified into two main levels, the entry and the advanced. In the entry level, the methodology via its implementation and verification in research and real-life projects generate a return for the resilient philosophy in term of confidence, trust, reputation and promotion. It can be considered as a key milestone for cities and end-users in the fight towards various hazards at city/urban/regional level, thus unlocking decision-based, data/fact-based resilience investments in terms of adaptation measures towards these hazards (e.g. towards climate changes). In consequence, the advanced level may reveal the return in terms of money saved for the entities (e.g. city, region, state) which invested in the resilience building. The calculation of the cost for the whole resilience building and the implementation of the rule that for every 1 dollar the payback is equal 4, can be conducted in the base of the results of the resilience assessment and then complete the technoeconomic appraisal of the proposed methodology.

2.1 The spatial scale of the methodology

The shift to the spatial scale of the proposed methodology requires the definition and the mapping of the system's (not those of a single asset anymore) ways, spaces, urban/territorial functions and strategic buildings/infrastructures for the urban/territorial response to the disruption event in the emergency phase, and for the maintenance and recovery of ordinary urban/territorial, economic-social and relational activities in the phase following the hazardous event. All the steps are taking into consideration the interconnectedness of the system's different assets and the case scenarios for a cascading chain of events diffused to many sectors of not coherent and same characteristics (e.g. the differences between residential buildings and energy plants).

In most of the cases, the definition of the system's emergency limit condition (CLE) is calculated and set. The CLE identifies that condition when it is exceeded (following the occurrence of a natural event), even with the occurrence of physical and functional damage such as to lead to the interruption of almost all the urban/territorial functions present, the operation of most of the strategic functions for the emergency, their accessibility and connection with the territorial context. An example of the CLE in urban level is given in Fig. 4, in terms of damage and magnitude.

3 Application case studies

The applications that are presented by the authors are selected to cover both the targeting of a single asset at local level and how to allocate an asset in the context, by implementing the before-mentioned methodology approach and spotlighting the uniqueness of the method which can be implemented from asset to system. The applications are derived or inspired from EU-funded projects, and they are chosen between other related projects (e.g. LIFE-RESYSTAL, MEDIATE, FORESEE) where the methodology is applied, as they are showing in a more intuitive way the importance and the advantages of the methodological approach in the spatial field. The spatial character of each project justified their selection, as the first refers to local level and the second potentially to all the scale levels. Secure Gas was an ambitious project, which was dealing with the strengthening of the security and resilience of the European Gas Network, regarding the physical and cyber-threats at a single asset and local level. NEVERMORE is a research programme, aiming at evaluating climate change impacts at different scales via multi-risk analysis and proposing solutions for strengthening the resiliency at local and urban level.

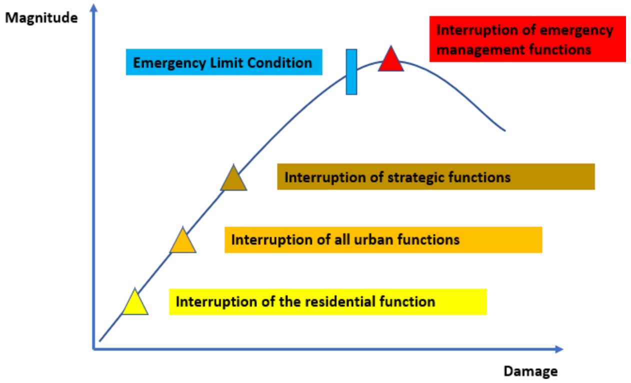


Fig. 4 Definition of the emergency limit condition in urban level, where the milestones in the characterization of the disruption's severity are set depending the actual results in the system's functions, which resulted in increase of the magnitude and damage of the event

3.1 Single asset/s from global to local level: the case secure gas

Secure Gas was a project with main technical goal to develop a blueprint on how critical gas infrastructure should be planned, designed, built, operated and maintained to cope with cyber-physical security threats and respond in a resilient way towards them. The application of the Secure Gas was referring more to a resilient design and management (Fig. 5), rather than to a resilience assessment or risk management of a gas transmission grid, but the methodology is adjusted, respectively, and it is tested for the case of a single asset at local level. The spatial character of this project may seem limited to the local level, but it is highly revealing on the process followed for the first step in the spatial scale of the resilience planning. The final goal of resilience enhancement is justified in practice. The current project follows the first three steps of the resilience assessment process, without the last two, as the subsequent upgrade of the overall resilient behaviour was considered granted. The schematic representation of the five-step approach is presented in Fig. 6, adjusted to the gas infrastructure.

3.1.1 System characterization

In the first step of the resilience assessment process, the system characterization for a typical gas network and plant at local level is conducted. This means that a special focus is given to the site characteristics (site location), geo-politics (hostility of the environment), climate-related data and any information regarding the surrounding environment. The system characterization is close to the threat characterization, as the necessary study of the relevance literature in order the hazards to be detected and prioritized is related to the system characterization of a gas transmission network. Within the Secure Gas, 3 different cases both in climate and in geopolitical levels were selected and are presented below in the Table 1. Every step on the gas value chain was taken into consideration (production, storage, transmission, distribution) to these cases, adopting a business case-driven approach by covering the entire value chain of gas from production (upstream) to transmission (midstream) up to distribution to the users (downstream) and with special emphasis on the detailed respect of the safety protocols.

3.1.2 Asset characterization

The collection of the technical and design detail of the single asset (i.e. here the gas plant and grid) is taking place in this step, especially those referring to the safety and the security of the gas plants and networks operational phase (e.g. maximum gas pressure in the pipelines). The asset characterization for every typical case is presented in Table 2.

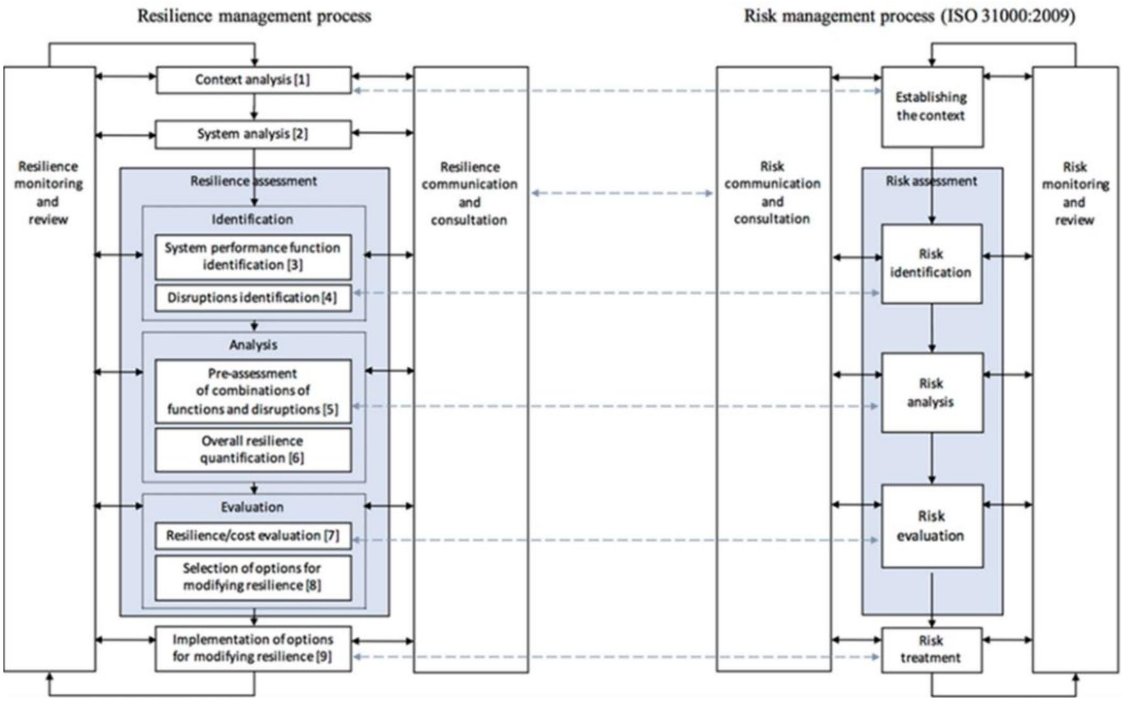


Fig. 5 The followed flowchart of resilience management process in Secure Gas, which is aligned with the proposed framework, as it has incorporated its basic steps and the final resilience assessment/quantification, while it follows standard procedures of the risk management process

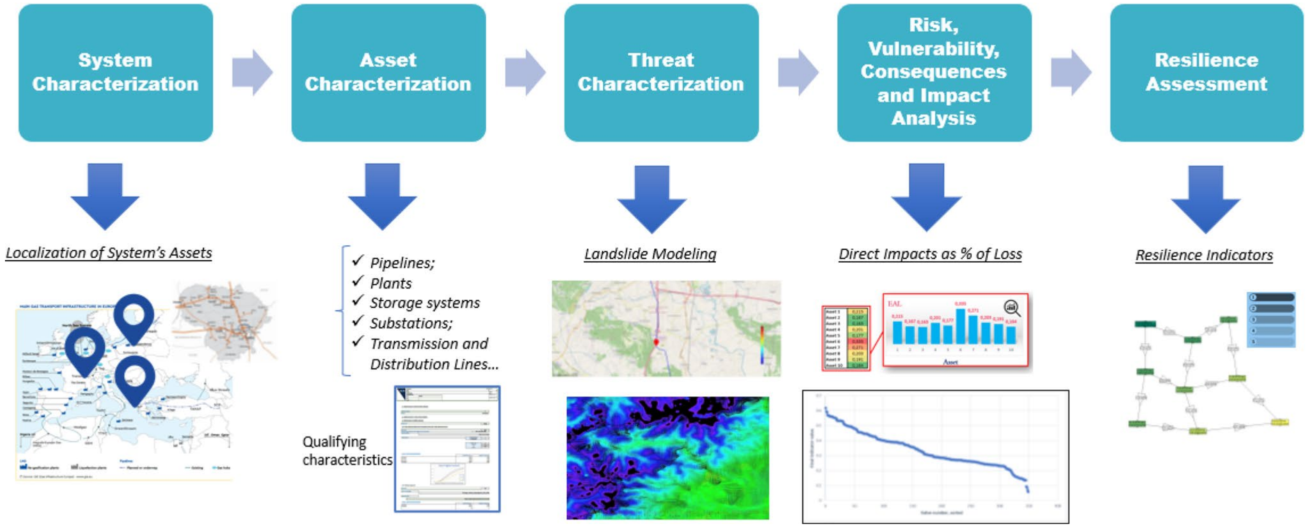


Fig. 6 The five-step approach for a resilience assessment of a gas infrastructure is presented here schematically. The final result is calculated with the use of respective resilience indicators, while every previous step is adjusted to the specific type of infrastructure. For example, landslide is a crucial natural hazard for pipelines, so it is going to be investigated and characterized in depth

Table 1 System characterization for the 3 typical Gas Plant and Network cases under examination within the Secure Gas project

Typical gas plant and network	Main challenges which characterize the system due to surrounding environment
Midstream and Downstream—South Europe	An all-hazards approach to be adopted addressing hazards and risks related to Geo-political (e.g. gas disruption from third countries) Technological (e.g. explosions/fires, ICT failure, cyber-attacks) Commercial/market/financial (e.g. unexpected peak demand; sharp price increase) Social (e.g. strikes in the gas sector) Sabotage, theft Natural (e.g. earthquakes, floods, fires) etc.
Midstream—East Europe	A comprehensive all-hazards, all-threats study based on detailed operational data, often not easily available. When the data were not available for specific events, expert judgement and expert solicitation techniques were exploited. The study combined natural hazards (which can be easily quantified in probabilistic terms like earthquake or flooding) and threats (which are not easy to quantify)
Upstream—South Europe	The main physical threats can be third-party interference (TPI), impact bending, spillages, and leakages due to corrosion, land sliding, fatigue, etc. Cyber-threats related to remote illegal actions on digital control system of pipeline network, causing closure of interconnection valves, unbalancing in transmission grid, up to the blockage of gas delivering or even cyber-remote control of gas metering with modified and wrong data

3.1.3 Threat characterization

The threat characterization was conducted based on the literature, searching for the most frequently classified threats, and the user requirements, which have been set with by the end-users, in order to align better with their needs in the real-life circle of the assets' operational function (Agrafioti et al. 2021). Among them are the external interference or third-party activity (including political/geopolitical interference), corrosion, construction defect and mechanical or material failure, natural hazards, operational error and cyber-attacks (Secure Gas project 2021).

3.1.4 Resilience assessment

The fourth and fifth steps here can be considered as the resilient design, which is resulting also to the operational management of the asset, and not only > the assessment phase. Within Secure Gas project, a toolkit based on high-level architecture (Secure Gas Project 2021) and the respective

Table 2 Asset characterization for the 3 typical Gas Plant and Network cases under examination within the Secure Gas project

Typical gas plant and network	Asset characterization
Midstream and Downstream—South Europe	A pipeline project, an offshore/onshore natural gas transmission pipeline, connecting resources via a gas hub, divided into an onshore and an offshore part. It refers to a pivotal infrastructure connecting the gas networks of two countries, enhancing the overall security of EU
Midstream—East Europe	A gas compression station and its nearby pipeline junction area, being of vital importance for the network operation, as well as strategic node of the gas of two countries
Upstream—South Europe	An upstream oil field with export gas onshore pipeline connecting joints within a national grid, an upstream offshore gas field with export gas pipeline connecting a platform to onshore terminals and to national grid and two downstream onshore pipelines

conceptual model followed was developed, aiming at the prevention, detection, response, and mitigation of combined physical and cyber-threats to gas transmission grid network.

The resilience management of the asset (Fig. 7) is enhancing and has become more robust towards any potential threat and hazards identified in the second step. The main goal and the novelty of this toolkit is the convergence between physical and cyber-threats or the so-called safety-security convergence. The range of implementation remains at the local level, but the philosophy of expanding towards higher spatial levels can be adopted accordingly. Specifically, a central and undivided platform was designed, which covers the user requirements and where all the threats (cyber, natural, and man-made) to the gas transmission network or the plant can be addressed and recorded. The inclusiveness for all the types of threats was achieved via the input data derived from the sensors placed to the network and the plant, the UAV inspecting the facilities and the software for the cyber-protection of the System's operation. This way, the surveillance and the control of the asset in the operational level are becoming more efficient, covering all the local area around the asset and the grid is enhancing its safety against multiple hazards. The real-time monitoring of the grid's condition is securing the high level of the situational awareness, and the early detection of disruptive event is leading to faster restoration of potential damage and a more targeted emergency management. The decision support system is based on the data acquisition and the threat evaluation, while the feature for the information sharing with the public is securing the safety of the communities. The spatial level of information sharing is one extra aspect regarding the potential of the current methodology, as it provides the opportunity to properly achieve citizen's awareness towards bigger spatial ranges.

3.2 From single assets to assets in a complex context: the case of NEVERMORE

The NEVERMORE (New Enabling Visions and tools for End-useRs and stakeholders thanks to a common MOdelling fRamework towards a climatE neutral and resilient society) project focuses on the modelling theory to take a significant step forward to overcome the current silo approach in favour of an integrated assessment one for evaluating impacts, risks, and interactions of climate change across sectors. This project composes an exemplary paradigm of how an asset can be allocated in the general spatial context and the process of implementing the current methodology for this scope. Specifically, the NEVERMORE approach integrates information from physical modelling of impacts and risk analysis methodologies and aligns them across different scales: from national, EU and global scales to local and regional ones. This means that the feasibility of the NEVERMORE approach and the methodology varies to all the potential scale levels. The goal of the risk assessment is to identify the

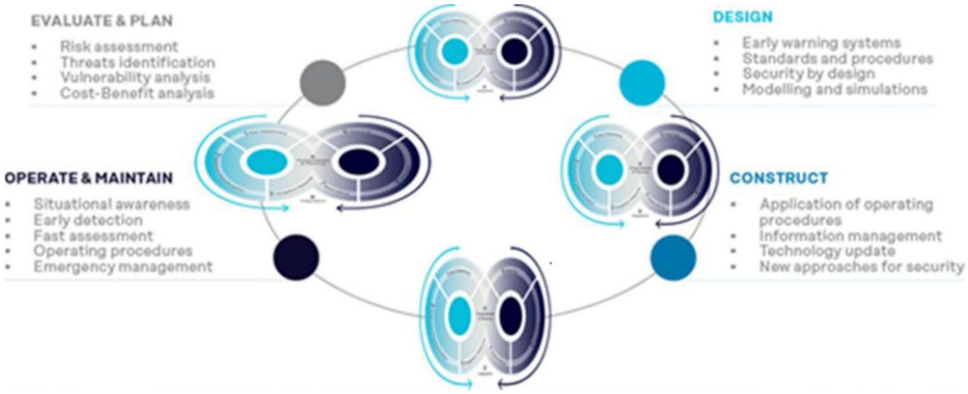


Fig. 7 Brief representation of the resilience management process across the life cycle of an infrastructure followed from RINA, where the proposed methodology is contributing to the design and evaluate and plan phase

most vulnerable and critical areas in each interested region; therefore, the resilience assessment and enhancement of the asset to achieved. In this project, the emphasis is given to the process of the threat characterization and the risk, vulnerability and impact analyses for every asset in a context of various scale levels, so there is no specific unit under study. The schematic representation of the five-step approach is presented in Fig. 8, focusing the flexibility towards local/urban/territorial scale.

3.2.1 System characterization

The standard procedure is followed in this step. Regarding the under-assessment asset, its site characteristics (site location), geo-politics (hostility of the environment), climate-related data and any information regarding the surrounding environment are collected. The location of each property at risk can use also advanced processes like geocoding, which is normally used to assign geographic coordinates such as latitude and longitude to each asset, as the spatial factor in this project is having a more crucial role. More specifically, within the NEVERMORE project, there are under examination 5 typical regions with different characteristics each and all presented in the Table 3.

3.2.2 Asset characterization

The collection of the technical and design detail of the asset is conducted here. For the example of a single building, these parameters include such features as its construction type, the number of stories and its age. In the case of a complex transportation system, again the ageing of the network or the technical conditions of the asphalt and the roads are of interest. In the current project, the scale is the regional/territorial so the characterization refers to whole regions/provinces, under the prism of which services and functions are more in danger and demand protection towards the hazards (Table 4).

3.2.3 Threat characterization

Heatwaves, droughts, floods, strong winds, heavy precipitation and changing temperatures are the most reported climate-related hazards and highly relevant for almost all countries (EEA Report, 2022), and these hazards are considered threats in the NEVERMORE project. The determination of the hazard alone cannot be directly used if not correctly correlated in space and time as defined by Basso et al. (2021), so the hazard/threat is considered through the definition of the relation between the frequency of occurrence and the relative intensity measure (IM) of a certain hazard/threat. The hazards considered to be strictly related to climate change events.

The hazard is often expressed in terms of exceedance probability, rather than in terms of exceedance rate (number of events per unit of time). The exceedance probability is the probability that a certain intensity will occur at least once in a given period. The two can be related using a concept called a Poisson process, which is a stochastic process which counts the number of events and the number of times in which they occur. The relationship is explained in the following formula:

$$\mathrm{MAF} = -\frac{\ln(1-p)}{t} \tag{1}$$

where MAF is the mean annual frequency, P is the percentage of exceedance, and t is the time.

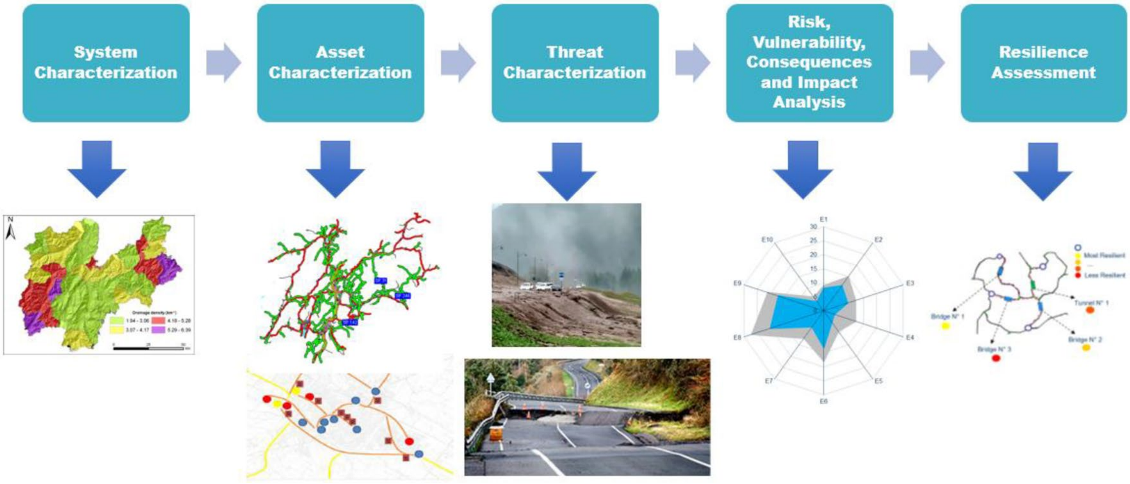


Fig. 8 The five-step approach for a resilience assessment is presented here schematically. The spatial factor is crucial from the beginning, as the system and asset characterization are referring to regional (territorial) scale, and the subsequent steps are adjusted to these types of spatial levels. (Trento drainage map, source: IRPI)

Table 3 System characterization for the 5 regions under examination of the NEVERMORE project

Typical region	System characterization
Island in the Mediterranean	The Mediterranean region selected as a most exposed to climate pressures, mainly due to heat and droughts, during summer periods because of tourism and agriculture. Besides, the projected sea level rise is over 1 m (by 2100) and storm surges will induce unexpected changes in the coastline due to coastal erosion. Intense local scale weather patterns due to highly complex topography and air-sea interaction are making a sound response very challenging
Mountain region	The selected case represents a mountain region most sensitive to climate change in southern Alps. Rising temperatures (+ 1.3 °C since the 40 s), more frequent heat waves, unpredictable precipitation patterns and modified seasonal snow-cover dynamics are the main climatic changes in the region. The effects of these changes are already visible: dramatic melting of glaciers, hydrogeological instabilities, landslides, floods and destructive windstorms
Boreal region	A boreal region where the forestry sector is affected by climate change, increasing the risk of forest fire, wind throw and insect and pathogen disturbance, however, tree growth increases due to an extended growing season. Agriculture is favoured by climate change due to an extended growing season. However, an increased need for pesticides and fertilizers is expected. Regarding fisheries, the habitat of warm water species is expected to grow at the expense of cold-water species, due to the mean temperature increase
Mediterranean region	Desertification (soil erosion) is mainly found in agricultural systems, especially in marginal agricultural areas on steep slopes and with bad agricultural practices and in intensively irrigated lands. The main desertification problem to this region is due to unsustainable water management. The current expansion of irrigated lands outside the areas suited for agriculture is increasing the intensity of aquifer exploitation, already causing serious problems of salinization, the loss of springs and wetlands and associated biodiversity and the exhaustion of non-renewable groundwater resources
Wetland	Extreme rainfall leads to extreme hydrological events, such as floods or droughts with a strong impact on the local economy and society. Floods are considered an important risk factor for the dynamics of the entire natural system, due to the severity of the recent events, entailing material damage, human losses and psychological stress for the inhabitants

Table 4 Asset (region) characterization for the 5 regions under examination of the NEVERMORE project

Typical region	Main policy sectors	Socio-economic context	Main challenges
Island in the Mediterranean	Water, biodiversity, agriculture	Agriculture (PDO products), tourism	Sea level raise, flooding, and droughts Preserve biodiversity, food chain and archaeology
Mountain region	Tourism, energy	Winter tourism, energy production	Rising temperature, unpredictable precipitation patterns, modified seasonal climate dynamics
Boreal region	Agriculture, forestry, fisheries, industry	Energy production, reindeer, tourism	Need of upgrading the energy system and allocation of resources for climate adaptation
Mediterranean region	Water, agriculture	Agriculture, tourism, industry	Desertification due to soil erosion in agricultural systems. Sustainable water management
Wetland	Water, tourism, agriculture, energy	Agriculture, low education level, economical dependency	Environmental and ethnic wealth protection Sustainable tourism and eco-agriculture promotion Land-use management

After this equation, the expression also for the return periods (Tr) can be given:

$$\mathrm{Tr} = -\frac{t}{\ln(1-p)} \tag{2}$$

For the data collection needed for the threat characterization, various sources can be considered like literature databases, national codes, websites databases and thematic maps on hazard distribution produced at the national level. As this framework is aiming at the assessment in the regional scale, it can consider information in a raster format, i.e. thematical maps, including indirect hazards (e.g. wildfire, drought, heatwaves). In this way, all the assets that relay in a certain region can be assessed together. Below, the methodology for the flood and wind hazard will be presented.

3.2.3.1 Flood hazard The flood hazard assessment is based on the estimation of the probability of occurrence of a certain damaging condition, represented by the depth of inundation. This selected intensity measure can be ease related to the fundamental properties of a stream, the discharge (National Research Council 2015) and the frequency of occurrence of a different kind of event should be defined. The information needed is simply the relation between the intensity measure and the probability of exceedance. In the flood case, this relation is built by knowing the values of average discharge and its variability per each region stream. Therefore, the average and the maximum discharges can be used to build up the cumulative distribution of the discharges (Fig. 9). The flood hazard assessment is based on the estimation of the probability of occurrence of a certain damaging condition, represented by the depth of inundation.

The values derived from the discharge cumulative distributions are needed in order the mean annual frequency (MAF) and the return period (Tr) to be computed, exploiting Eqs. 1 and 2. The data of the IM are based on a period of observation (e.g. 15 respect to 50 years). Thus, to have a homogenized risk analysis among the different hazards, the 4 probabilities (related to specific return periods in years) used are selected to have a comparable value of MAFs. This result to a typical hazard curve for flood, like in Fig. 10.

3.2.3.2 Wind hazard The analysis for the wind hazard is based also now on the IMs (e.g. m/s for wind) for the same 4 different percentage of exceedance in *t* years of the flood hazard. The MAF and Tr are computed also by the same 4-given percentage of exceedance in the *t* years.

Based on the (CNR 2018), the peak velocity of the wind can be computed as:

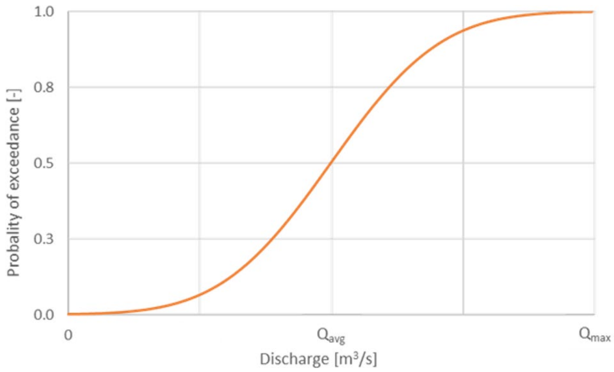


Fig. 9 Example of discharge cumulative distribution

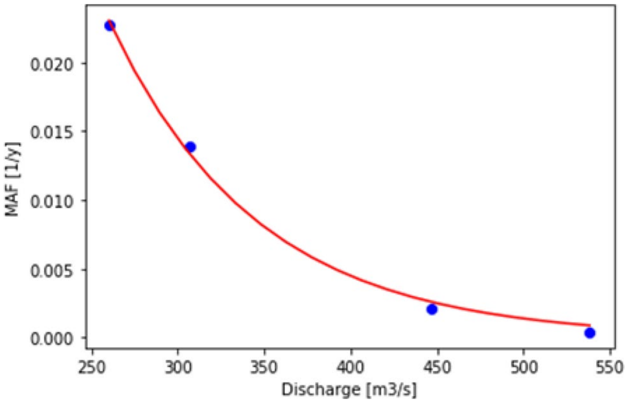


Fig. 10 Typical hazard curves for flood hazard

$$v_{\mathrm{p}} = v_{\mathrm{m}}(z) \cdot G_{\mathrm{v}}(z) \tag{3}$$

where G_{v} can be reasonably approximated each time based on (CNR 2018), and the v_{m} represents the average wind velocity for the selected return period.

Finally, the 4-speed associated related to the 4 percentage of exceedance can be evaluated, and so the wind hazard curve (Fig. 11) can be computed.

3.2.4 Risk, vulnerability and impact analyses

The definition of the vulnerability for an asset is inhere defined according to a set of 4 fragility curves. They are set following the main studies performed in the field of risk assessment, i.e. the Federal Emergency Management Agency (FEMA). The 4 curves are defined following the 4 damage states level defined to represent the most important damage scenarios, following the Hazus Manual subdivision of damage levels. The 4 levels are used in this analysis to reach a desirable level of simplicity, without losing the minimum level of accuracy required.

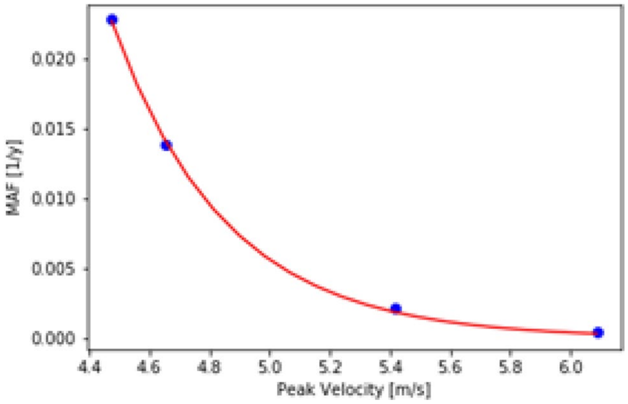


Fig. 11 Typical hazard curves for wind (direct) hazard

The first damage state (DS1) is associated with slight damage defined as flexural or shear-type hairline cracks in some beams and columns near joints or within joints. The second one (DS2) is associated with moderate damage, corresponding to the exhibition of hairline cracks on most beams and columns; for ductile frames, some of the elements have reached yield capacity, showing larger flexural cracks and spalling, while for nonductile frames, elements may exhibit larger shear cracks and spalling. The third one (DS3) is associated with extensive damage, corresponding to the reaching of the ultimate capacity of some elements; for ductile frames, large flexural cracks, spalled concrete and buckled reinforcement occur, while for the nonductile frames, elements may experience shear or bond failures at reinforcement splices, or broken ties or buckled reinforcement in columns, leading to a partial collapse. The last one (DS4) is associated to complete damage, which corresponds to the structure collapse or the imminent danger of brittle failure of nonductile elements or loss of frame stability. For the selection of the appropriate fragility curve, many parameters are considered, such as the principal construction material, construction typology, year of construction, the type of the code during the design phase and dimensions.

Regarding the impact, the analysis is based on the analysis of three different categories, according to Sousa and Tsionis (2019): impacts on people (IP_{DSi}), impacts on the physical system/infrastructure (ID_{DSi}) and impacts on service continuity (IR_{DSi}). And the evaluation of each component is provided in economic terms. The analysis of the impact on the people (IP_{DSi}) is based on the evaluation of the number of fatalities and injuries due to the occurrence of a certain hazard. The methodology used is based on the definition on the three categories of death, slightly injured and severely injured. The impact on the physical system (ID_{DSi}) can be defined as the impact cost due to the direct damage experienced by the asset. Finally, the impact on service continuity (IR_{DSi}) can be related to the effects of the reduction of the service due to damage and its evaluation is based on the information on the average recovery time and service reduction per each damage state.

For the quantification of the risk level, the expected annual loss (EAL) is calculated. For the evaluation of the EAL, it is used a combination of the hazard and vulnerability. The results of this combination are representing the probability of damage occurrence of the impact. And the final value of EAL considers all the different components of the risk assessment theory, such as the probability of damage occurrence and the total impact (Fig. 12). Therefore, the EAL is the final measure of the risk per a certain asset, subjected to a generic hazard and a strong factor for associating the resilience assessment with the insurance practice.

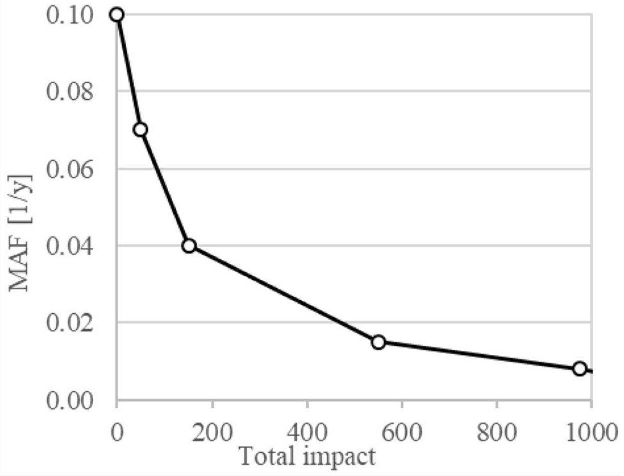


Fig. 12 Typical EAL evaluation curve

3.2.5 Resilience assessment

The final resilience assessment of the asset is expressed in terms of preparation, planning capacity and internal and external resourcefulness, measuring the impact on people and service continuity (like in Fig. 3). Regarding the impact on people, the evaluation of the casualties should consider the capacity of the people to evacuate in the best way and usually, this capacity can be related to the existence or not of emergency plans, its quality, and the training frequency. The community preparedness is expressed via a resilience coefficient which is very important to fit the real number of people heated by a hazardous event. Again, internal and external resourcefulness are expressed via coefficients, respectively, to the type of asset. For the example of a healthcare system, the coefficient for the internal resourcefulness considers the goodness of the internal coordination among facilities and departments, while for the external can be related to hospital redistribution capacity during an emergency. Regarding the impact on the service continuity, an important role is played by recovery efficiency; therefore, a recovery coefficient is set to consider the change in recovery performance. The recovery of economic loss is related to the unserved goods/services in a certain period, while the external resourcefulness is especially related to the institution efficiency.

Finally, based on the results of the resilience assessment and the adaptation and mitigation actions (i.e. disaster risk reduction measures) that in each case can be decided, an estimation of these measures' payback period is conducted. This is feasible via an extra technoeconomic assessment of the mitigation and adaptation measures decided for quantifying their resilience economic viability and profitability. This way, the economic aspect of resilience is highlighted and the connection with the insurance industry is more feasible and direct.

4 Future perspectives

The further expansion of the current knowledge and methodologies is crucial, as the need for expanding the resilience assessment and enhancement to territorial and national level is oriented from the future demands and landscape, in which the states and the societies will be part of. The proposed resilience assessment framework and the respective application cases which were represented are future-oriented, but their future exploitation is not limited to the so far produced results. Due to this reason, directions and suggestions potential concepts are given from the author at the Table 5, based on the investigated fields of interest and spatial level.

The work on Secure Gas project has spotlighted the significance of the convergence between physical and cybersecurity and the subsequent upgrade of the resilience capacity for the gas network grid. The need to expand this design philosophy in order to cover and tackle also hybrid threats and warfare is following subsequently. Moreover, the spatial level of these types of solutions must expand to territorial, in order to safeguard the continuous function of energy infrastructures in territorial and international level (i.e. European Union territory), especially within periods of huge uncertainty in states' safety and security, related to geopolitical changes and increased hostility in the borders of the territories. Regarding these, the further extension of the methodology to the so-called war resilience field will be of high interest, targeting initially to the protection and resiliency of the transportation Network.

As the consequences of the climate change are becoming more and more of higher magnitude and the damages are increasing for the communities and the states, a solution including a more efficient association of insurance industry with natural hazards is becoming a demand. The association of the resilience capacity level of CIs with the insurance cost can pave the way to operators, societies and states to better prepare and adjust to the new, hostile physical environment which emerges due to the climate change. Moreover, the recent experience with the COVID pandemic that affected in global level, the states and the societies can be the guide and the reason why the research should target also to the resilient behaviour of the healthcare systems, at local (in case of smaller towns or provinces) and urban (in case of big and metropolitan cities) level.

Finally, the next step in spatial level is the resilience assessment in national level. The compliance with the respective directives and regulations (e.g. in EU the CER and NIS2 directives) is necessary, while simultaneously the process of the inputs from the previous steps (of the five-step approach) will provide the level of criticality and a level of CIs at national level. To be this achievable, a national resilience assessment framework will have to take into consideration the systemic risks, the technological and non-technological risks, the cross-border dependencies and the non-national critical supplies of the CIs.

5 Conclusion

The aim of this study was to present a novel and holistic resilience assessment framework, applicable to various types of assets, towards various hazards and at different various scales. The methodological approach was specified, and the methodology's applicability towards all the spatial levels was highlighted and described. Two application case studies (based on EU-funded programmes) are presented, mainly referred to energy infrastructures and climate change hazards. The promising and efficient methodological approach is clearly presented in its general structure and then was

Table 5 Suggestions from the author for future exploitation of the resilience assessment frameworks

Type of asset	Spatial level	Hazard	Suggestions
Energy infrastructures	Territorial-National	Hybrid-nature hazards, also including hybrid warfare	Enhancement of Energy Infrastructures' resilience capacity towards hybrid hazards in territorial level and taking into account the interconnection
Transportation infrastructures and systems	Territorial-National	Man-made threats, warzone	Extension of the methodology to war resilience field, investigating the resilience capacity of transportation networks within warzones
Critical infrastructures	Local—territorial	Hazards related to climate hazards	Association of the CIs' resilience capacity towards climate change hazards with insurance measures, to mitigate the costs of the damages and enhanced preparation
Healthcare systems	Local—urban	Man-made threats, climate change hazards	Resilience assessment and enhancement measures for the healthcare systems, in case of pandemics or severe climate-related hazards

specified for every project. The application cases were chosen in order to demonstrate the ability of the methodology to adjust to different spatial levels and spotlight the need for inserting the spatial factor in the design philosophy for the resiliency planning and the robustness methods, regarding the current and future demands. Special mention was given to the demand for connection between resilience planning and the resilience payback in economic and insurance-related terms. The authors have also presented some of the potential future perspectives of the resilience assessment frameworks within a certain range of spatial levels and suggested specific concepts and directions for the further exploitation, with special mention to the resilience at national level.

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Author contributions All authors contributed to the writing of the document.

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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