Chapter

Resilience of Infrastructures and Systems to Multiple Hazardous Events: Application Cases and Future Perspectives

Clemente Fuggini, Miltiadis Kontogeorgos, Saimir Osmani and Fabio Bolletta

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 and policies. The paper focuses on a review from an engineering perspective of past efforts and more importantly provides evidence of application cases the authors have developed in the past years. Finally, an outlook on future perspectives and potentials in the application of resilience is provided.

Keywords: resilience, hazards, complex systems, applications, impact assessment

1. Introduction

In today's landscape and emerging world, the significance of the Infrastructures and Systems (from Energy to Transportation ones) is becoming more and more critical for the well-tempered function of the states and communities. The increased demands in cities' energy consumption, the ever-expanding Transportation and Energy grids, the interconnection of these Systems and Infrastructures are some exemplary issues of this high criticality. In addition to these, the natural hazards due to climate change are appearing of higher magnitude and are causing more severe damages, estimating to billions of dollars worldwide annually [1], while future projections are predicting an increase of these costs the forthcoming years and decades [2–4]. Although the macroeconomic costs of the impacts due to climate change are highly uncertain, it is very likely to threaten development in many countries [5]. In addition, the man-made threats are always present for the global community, even expanding, due to terrorism, cyber-crime, and wars.

Under this prism, states and communities have already started to develop and set in force frameworks for robustness of their Infrastructures and Systems, both for their internal cohesion and uninterrupted continuity and for the more efficient co-operation among them in the international level. In the global sphere, cornerstones of global frameworks can be considered the Paris agreement [6] and the Sendai framework [7]. The Paris agreement is aiming to avoid more extreme natural phenomena and dangerous consequences due to climate change by taking measures in favor of global average temperature reduction, but also by enhancing societies' and states' capability to reduce the impacts of climate change. The Sendai framework has set up the priorities for actions for an effective disaster risk reduction and a resilient approach to these common threats, by understanding the disaster risk management to the enhancement of the disaster preparedness for effective response [7]. Furthermore, states or unions of countries (e.g., EU) have also developed their own frameworks [8–11], aligning simultaneously with the international agreements and goals, and showing special providence to cyber-resilience [12, 13].

The scientific and research community has faced the challenges and the demands for empowering the resiliency of Infrastructures and Systems. This was achieved by investigating many aspects of the resiliency planning against various hazards and developing in a scientific manner respective assessment and enhancement frameworks and tools. After the resilience conceptualization in a qualitative form, various quantitative metrics and approaches are suggested. Quantitative methods for assessing the resilience of Infrastructure Systems were proposed from many authors [14–16], also considering the interdependency of the Infrastructure Systems [17, 18] and expanding the field of study to the level of the communities [19]. Novel methodologies for analyzing Critical Infrastructure resilience were presented, with pilot implementation cases included as experimental part also [20]. As it was expected, studies were conducted also for examining the resilience capacity against specific hazards such as earthquake [21] or hurricane [22]. A special interest was shown for the resilience enhancement of Transport and Energy Infrastructures, due to their critical and multilevel meaning for the states' vitality and function.

The resilience of the Urban Transportation System was of interest for many researchers, and so many assessment methods were proposed [23, 24], including also multi-dimensional approach [25] and individual vertex-based and edge-based failure models [26]. The research has expanded beyond the Urban Transportation Systems, including also Railway [27, 28] and common Road and Transportation Systems [29, 30]. The factor of security has been highlighted, especially toward terrorism [31]. The Transportation Infrastructures and Systems have been tested also against various hazards, such as earthquake [32], extreme climatic and weather events [33, 34], and tsunami [35].

The vulnerability of Energy Infrastructures and Power Systems mainly to natural disasters due to climate change, but also due to manmade hazards, led the scientific community to develop assessment methods and solutions to increase the resilience capacity of these Systems. Frameworks and methods for the characterization of the resilience level of various types of Energy Infrastructures systems were proposed, such as for Nuclear Plants [36] and Hydrogen Systems [37]. Energy and Power Systems have been tested for their resilience capacity against various types of hazards such as hurricane [38], earthquake [39], or flooding [40]. In recent years, the resilience of the Energy Grids in the operational level [41], toward natural [42] or cyber [43] hazards, is being investigated thoroughly.

Although the multi-step progression in the definition of resiliency frameworks and the development of robustness' methods, Infrastructures and Systems are presenting a partial lack of efficient toolkits against multiple extreme events. Moreover, the cyber hazards are becoming more numerous and dangerous within the operational phase of the Systems, and the convergence of safety and cybersecurity has not been incorporated yet within the policies and the frameworks, which these Systems are following for their protection.

2. Methodology

A crucial element for the design of an efficient resiliency planning for Infrastructures and Systems, aiming at their protection toward multiple hazardous events, is the adopted methodology. Due to the flexibility that demands in order to be feasible for implementation to various assets and against various hazards, the methodology is setting some standard steps toward the resilience design, and then it is focusing partially on the specific asset and threat for every case. The procedure followed is being described in the **Figure 1**.

The initial step refers to the description and the characterization of the entire System (i.e., Energy System, Healthcare system), including all the necessary information, which is needed in the resiliency analysis. These can be the placement of the System toward the external environment and the interdependency between the System's elements or assets.

The next phase contains the asset characterization. This step refers more to technical information for the asset of our interest. For example, if the resilience planning aims at Energy Infrastructures, the characterization is needed to include the type of the Infrastructure (i.e., gas transmission pipeline, refineries, power plants) and then the design details and the qualifying characteristics. In case of a bridge asset, it needed the type of bridge (i.e., suspended) and the design details of the project (i.e., type of foundation, reinforcement blueprints), and so forth, regarding every asset under resilience evaluation.

The third step is about the threat characterization. The identification of potential threats and hazards is carried out, after the evaluation of the disruptive event's magnitude and criticality, and the definition of relevant hazard scenarios is taking place. According to the examined hazards, a modeling of them is following, respecting the literature database and the national codes and frameworks. In this step are included calculations such as the creation of probabilistic seismic curves due to site characteristics or the probabilistic scenarios for landslides and floodings based on site and meteorological data available.

The first three steps were decided more as part of constructing the profile of the interested Infrastructure or System and then defining the problem. The fourth and fifth steps are closer to final goal of the methodology, and they are the core of the followed philosophy. So, the fourth step is devoted to the risk and vulnerability assessment, along with the impact analysis. A quantitative expression based on failure probabilities for the examined Infrastructure or System is conducted, under the form of a vulnerability curve. This step is connecting the existing situation and behavior of the asset toward multiple scenarios of the hazards' magnitude, by defining the failure limits of the asset. Furthermore, regarding the magnitude and the intensity of an event beyond the capacity's limits, an impact analysis is conducted. The impact analysis takes into account the economic, social, environmental, and human losses aspects of a disruptive event and determines the total direct and indirect losses caused to the stakeholders (i.e., energy operators, civil protection, state) and the society. Again, the analysis contains some general criteria and aspects covered, but is delving also into specific impact details and information, respectively, to the type of the asset.

Figure 1.
Schematic representation of the methodology's philosophy.

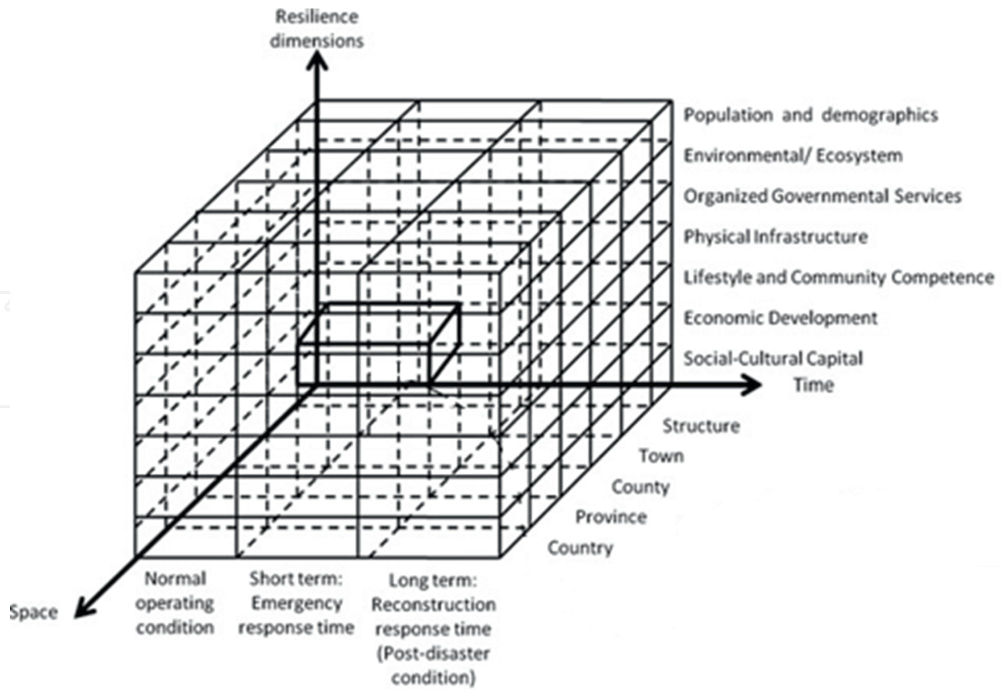

Figure 2.
Depiction of the resilience dimensions, in terms of space, time, and type of resilience analysis.

The last and final step is including the desirable resilience assessment. After the processing of all the necessary information toward the asset and the investigated threats, the level of service and the resilience capacity are defined. These are expressed in a quantitative form, as for this step, a set of various resilience indicators and a resilience matrix have been developed and exploited. The resilience matrix contains the robustness, rapidity, resourcefulness, redundancy sections, and after the evaluation on these specific domains, a grading of the behavior and response of the asset or the system is calculated toward a unique or multiple hazardous events.

The range of applications for a methodological approach of this type, in terms of time, space, and aspects of resilience assessment, is depicted briefly in the **Figure 2**. 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. The space covered and examined in the resilience analysis can begin from a single building/ structure (i.e., cultural heritage building toward seismic hazard) and extend to a whole province or country (i.e., the national gas transmission or transport network). Finally, the aspects of resilience analysis that will contribute to the calculation of the total resilience capacity can include the social or the environmental factor, except those for the technical level of the System and the economic depiction of a disruptive event.

3. Application cases

The applications that are presented by the authors are selected in order to cover both Transportation Systems' and Energy Infrastructures' fields, by implementing the before-mentioned methodology approach and describing promising technologies for the increase of the resilience. The applications are derived or inspired from EU-funded projects. More specifically, the chosen application as an exemplary case for the Transportation Systems is describing the FORESEE project. This application is focusing on short- and long-term resilience schemes for rail and road corridors and logistics terminals. The Energy Infrastructure case is depicting the SecureGas project, which is dealing with the strengthening of the security and resilience of the European Gas Network, regarding the physical and cyber threats. Finally, the presentation of the INSPIRE project serves as an introduction to the beneficial use of potential meta-materials concepts within Infrastructures (especially Energy) and Systems, regarding their protection toward dynamic-nature hazards.

3.1 Transportation system

The main goal of the FORESEE application was to provide road authorities and managers, responsible for the rail and road corridors and logistics terminals, with a solution to anticipate, absorb, adapt, and rapidly recover from a potentially disruptive hazard or extreme event during the entire lifecycle of the transport infrastructure: planning, design, construction, operation, and maintenance [44]. In order to achieve this goal, the proposed methodology is implemented in all its five steps, and a toolkit, which is capable of collecting data for predicting the magnitude and the potential damage of various hazards to the asset of our interest, has been developed for that reason. The whole structure of the toolkit, which is aligned with the authors' methodological approach, is presented schematically in **Figure 3**.

3.1.1 System characterization

The first step is the system characterization. A whole Transportation System's network description is being conducted, also including its key elements, which are the bridges and the tunnels. Moreover, demand data (i.e., N° of vehicles/hour, traffic flow intensity, driving directions) are being collected from every available source and are being exploited as input data for the toolkit.

3.1.2 Asset characterization

In this phase, the asset characterization is focused on the network components (here bridges, tunnels, and road). The components' description is including the asset's

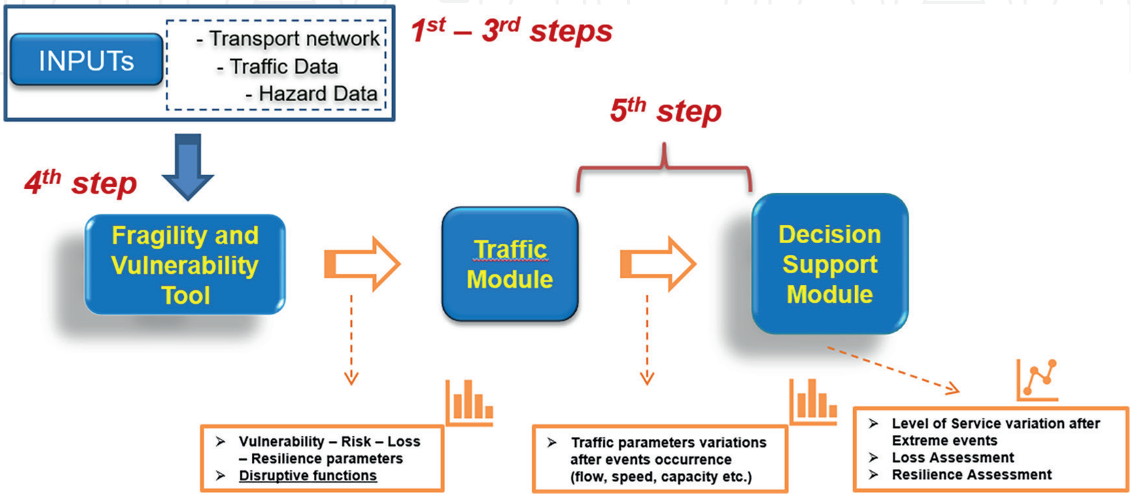

Figure 3.
Schematic representation of the toolkit's design philosophy, aligning with the followed methodology's steps.

main properties, mainly the technical details and the design data of the structures (e.g., N° of bridges' piers, deck length). The site conditions (e.g., soil properties, slopes characteristics) are taken also into consideration as they are very important data for the behavior of the asset and the hazard characterization.

3.1.3 Threat characterization

The third step is the hazard definition and evaluation. For this step, every resource available in literature, web sources, or data shared from the infrastructure's managers are being exploited. And one of the novelties is that the toolkit can integrate satellite and terrestrial data in the analysis and the assessment of the hazards. This way, the desirable data-driven diagnostic framework is strengthened sufficiently from the accuracy of the data input. It follows a definition of relevant hazard scenarios and relevant hazard modeling (e.g., seismic and rainfall curves) in the area considered.

3.1.4 Risk, vulnerability, and impact

The before-mentioned step is necessary for the calculation of the fragility (**Figure 4**) and restoration functions, along with the vulnerability curves, toward the investigated hazard. The fragility functions can be derived from methodologies, which are found to the existing databases or literature, or from a more targeted and accurate analysis, from the Finite Element modeling. The followed impact analysis consists of the operativity loss, risk quantification, loss curves, and expected annual loss. In this step, it is important, especially for the System's operators, the calculation of the Expected Annual Loss (EAL), as part of the impact analysis. It provides the annual loss of the asset, as percentage of the repair cost, for a given hazard. These losses are generated by the repair costs applied to the asset after a possible hazard occurrence.

3.1.5 Resilience assessment

The integration of all this information is leading to the creation of the multi-scenarios in which the Transportation System will be simulated, and the final resilience assessment will be conducted, under a specific framework with indicators and

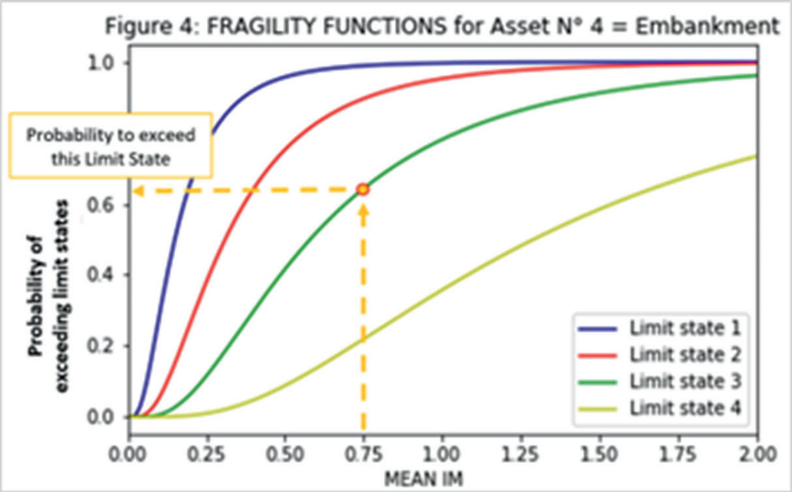

Figure 4.
Typical fragility function (e.g., for earthquake).

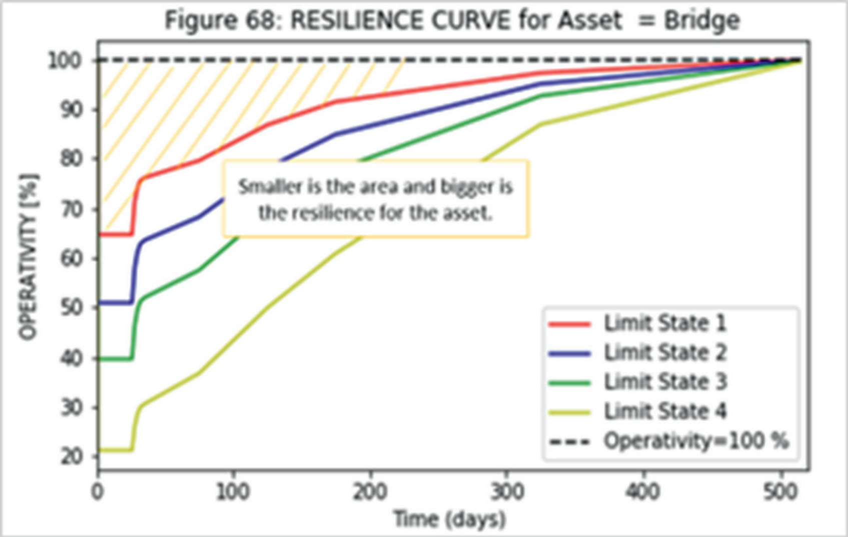

Figure 5.
Typical results presented for a resilience assessment of an asset (e.g., bridge).

different assumptions (i.e., deterministic or indeterministic approaches). The results are expressed in terms of operativity and time for the various limit states of the asset (**Figure 5**). The final goal of the resilience assessment is the creation of the necessary input for decision support tool, which is an instrument offered to Infrastructure managers about disruptive hazards impacting effects on their assets, and it enhances the overall operational phase of the Systems and Infrastructures.

3.2 Energy infrastructure

The application of the SecureGas was aiming more to a resilience design and management (**Figure 6**), rather than to a resilience assessment or risk management, of a gas transmission network. The methodology is adjusted respectively to the outer goal and this way, the desired adaptability is being justified in practice. The first three steps of the methodological approach are the same, and the subsequent upgrade of the overall resilient behavior was considered granted.

3.2.1 System characterization

In this initial step, the system characterization follows this of a typical gas network and plants, which means that special focus was given to the location (site characteristics), geo-politics, and climate. The first step was closely connected to the threat characterization, as the hazards were taken into consideration after the study of the relevance literature for the respective system characterization for a gas transmission network.

3.2.2 Asset characterization

Every technical and design details were collected in this phase, 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). Every step on the gas value chain was taken into consideration (production, storage, transmission, distribution), and the safety protocols were followed in detail.

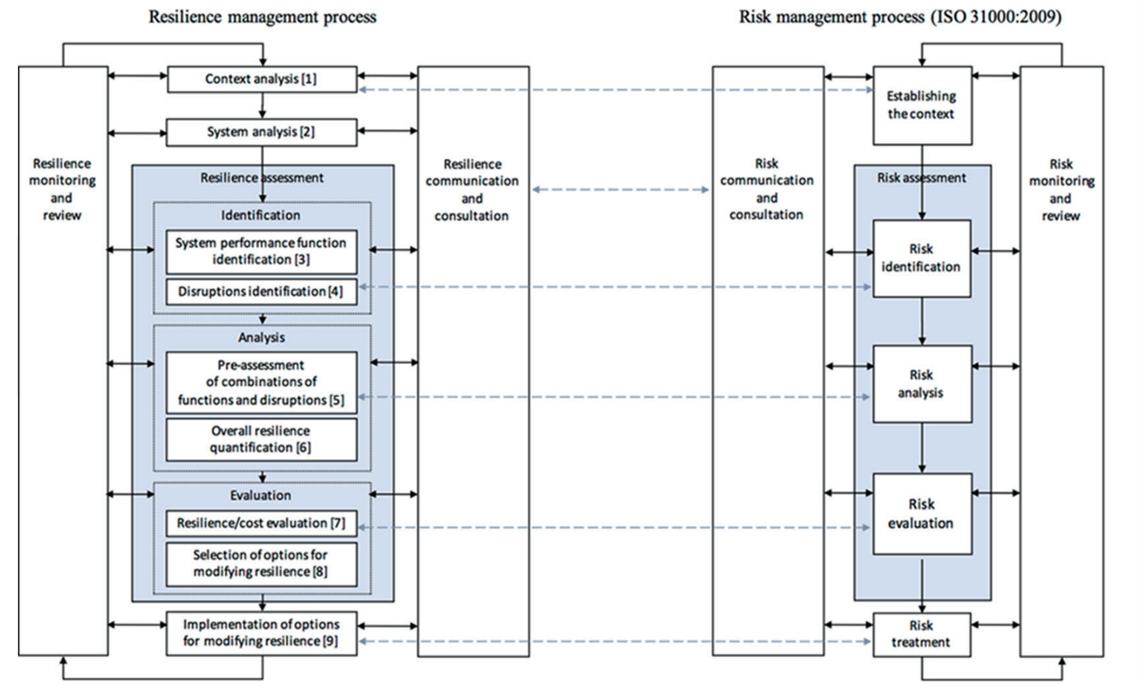

Figure 6.
A typical flowchart of resilience management process, which is aligned with the proposed methodology, as it has incorporated its basic steps and the final resilience assessment/quantification, also including the risk management of an asset and the monitoring of the resilience behavior.

3.2.3 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 [45]. Among them are the external interference or third-party activity (including political/geo-political interference), corrosion, construction defect and mechanical or material failure, natural hazards, operational error, and cyber-attacks [46].

3.2.4 Resilience management

The fourth and fifth steps here can be considered as the resilient design, which is shifting to the operational management of the Infrastructure, and not only the assessment phase. So, within SecureGas project, a toolkit based on High-Level Architecture [46] and the respective Conceptual Model followed was developed, aiming at the prevention, detection, response, and mitigation of combined physical and cyber threats to gas transmission grid network. Following this philosophy as an expansion of the proposed methodology, the resilience management of the asset (**Figure 7**) is enhancing and has become more robust toward 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. 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 input data are 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.

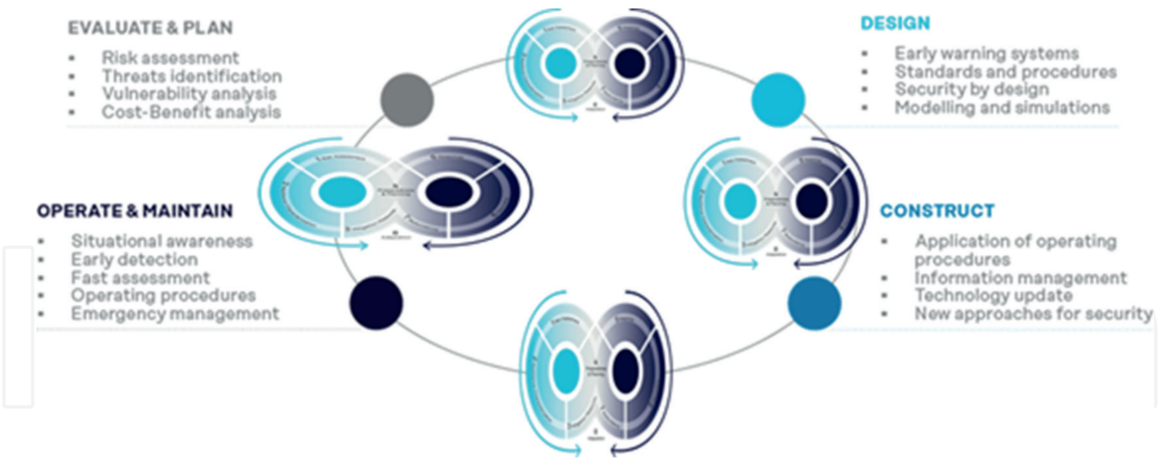

Figure 7.
Brief representation of the resilience management process across the life cycle of an infrastructure followed from RINA, where the proposed methodology is contributing to the design and evaluate and plan phase (source: RINA).

This way, the surveillance and the control of the asset in the operational level are becoming more efficient, 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.

3.3 Meta-materials and energy infrastructures

The notion of "meta-materials" refers to natural or artificial materials or structures, which exhibit extraordinary properties for inhibiting or conditioning wave propagation in all spatial directions over broad frequency bands [47], and this way, protecting the underlying structures toward dynamic-nature hazards. Due to the periodic structure of the meta-materials, the so-called band-gaps are being created, which are considered to be mitigation zones for specific frequency ranges of the transmitted waves (**Figure 8**). This way, the potential damage from dynamic-nature phenomena such as blast or seismic is mitigated, or in some cases, the structures are becoming isolated toward this hazard.

Meta-materials are relatively recent to the civil engineering design practices, but concepts based on this design philosophy for the protection of Energy Infrastructures have been already developed. Examples of them are the seismic protection of fuel storage tanks [48] and of nuclear plants [49] via the concept of a meta-foundation. Also, a meta-material concept for the blast protection of gas transmission pipelines has been proposed [50], and it is shown in **Figure 9**. It is worth noted that the already existing meta-material concepts such as the meta-concrete [51] or the meta-barriers [52] can be implemented for the increase of the resilience capacity of Energy Infrastructures and Transportation Systems, but the beneficial implementation of them has not yet been evaluated. Finally, meta-materials concepts can be exploited for the enhancing the resilience level of already constructed Energy Infrastructures, as they can be placed around the structure.

The comparative advantage of the meta-materials is the upgrade of the resilience capacity from the design phase of a civil engineering project. Although, there are

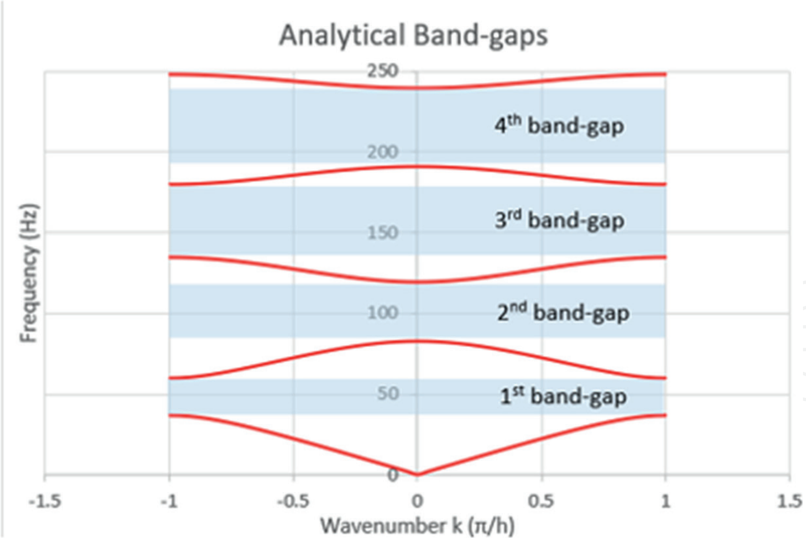

Figure 8.
A typical example of a band-gap, expressed in terms of frequency and length wavenumber, where the shaded regions are considered the mitigation zones for transmitting waves of these frequency ranges.

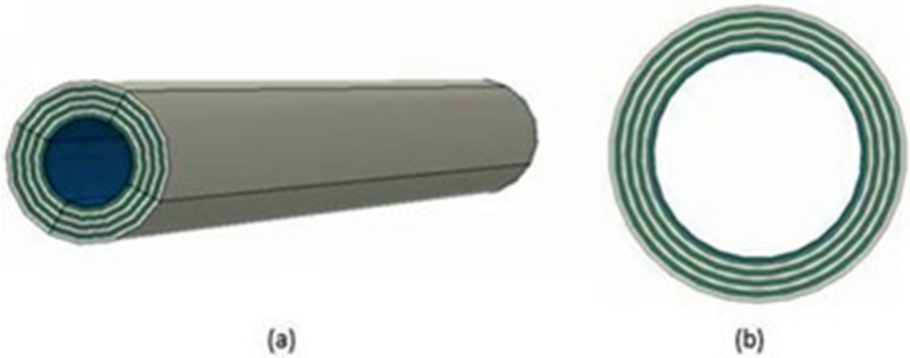

Figure 9.
The proposed meta-material concept for the protection of gas transmission pipelines, in a) exploded view and b) cross section [50]. The successive layers of the two different materials are leading to the creation of the band-gaps and the zones of energy mitigation.

solutions of this philosophy (e.g., meta-barriers) that can be exploited in order to reinforce the behavior of the System or a specific Infrastructure toward specific hazards. For both cases, the methodological approach can still be implemented and lead to a comparative study of the resilience level between solutions, which are including or not the existence of meta-materials in their scope.

3.3.1 System characterization

Regarding the type of the Energy Infrastructures, the system characterization will follow the standard procedure of collecting the necessary data and information.

3.3.2 Asset characterization

Regarding the type of the Energy Infrastructures, the system characterization will follow the standard procedure of collecting the necessary data and information.

3.3.3 Threat characterization

In the third step, except for the standard procedure regarding the type of the Energy Infrastructure, there will be included also the necessary information for the respective design of a meta-material concept, which means the frequency spectra of the dynamic-nature hazard.

3.3.4 Risk, vulnerability, and impact

Toward the fourth and most crucial step, the calculation of the vulnerability and risk assessment for the specific threat will take place and the results for the solution based on the meta-materials will reveal the beneficial presence of these concepts to the respective damage mitigation and risk reduction.

3.3.5 Resilience assessment

The subsequent enhancement of the resilience capacity will be verified, in the fifth and last step, following the before-mentioned resiliency framework and metrics.

In this case, the methodological approach is contributing, especially via the comparative calculation of the vulnerabilities and the impact analyses, to the highlighting of these meta-material-based solutions for the scope of the Infrastructures' and Systems' resilience. Under a more general prism, a way is being paved for respective advanced methods of design, which are derived from the latest research achievements, to be transferred in the real-world projects, serving the goal of resilience.

4. Future perspectives

The further expansion of the current knowledge is crucial, and it is needed to be oriented in the future demands and landscape of Infrastructures and Systems. The proposed resilience methodology and the respective application cases that were presented are future-oriented, but their future exploitation is not limited to the so far produced results. For this reason, the authors are giving directions and are suggesting potential concepts, based on the investigated fields of interest.

4.1 Transportation systems

The methodological resilience assessment process, which was followed in the Transportation System's application, and the toolkit, which led to a decision support system, are needed to be expanded in other types of Infrastructures, such as these in the sector of Energy. Also, the current range of applications can include the resilience assessment of Transportation Systems during war or the so-called war resilience assessment. The authors' suggestions are being presented in **Table 1**.

4.2 Energy infrastructures

The Gas Energy Infrastructure's toolkit has spotlighted the significance of the convergence between physical and cyber security and the subsequent upgrade of the resilience capacity for the gas network grid. It is needed also to expand its feasibility for tackling hybrid threats and warfare. Furthermore, the whole function and the

Type of infrastructure or system	Hazard
Transportation Systems	Expand the existing resilience assessment methodology of the Transportation Systems to the war resilience field
Energy Infrastructure	Expand the existing resilience assessment method to the Energy Infrastructures (including power plants and transmission grids)

Table 1.
Authors' suggestions for future exploitation of Transportation System's application.

Type of infrastructure or system	Hazard
Gas Network	Upgrade the existing resilience toolkit for facing the hybrid threats and the subsequent hybrid warfare
Energy Infrastructure	Expand the existing resilience toolkit to other types of Energy Infrastructures (including electricity and hydrogen power plants)

Table 2.
Authors' suggestion for future exploitation of the Energy Infrastructure's application.

Type of infrastructure	Hazard
Gas Transmission Pipelines	Surface & Underground Explosion
Underwater Transmission Pipelines	Underwater Explosion
Offshore Wind Turbine	Underwater Explosion
Electricity Plants	Seismic Protection
Geothermal Energy Plants	Seismic Protection

Table 3.
Authors' suggestion for future exploitation of meta-materials concepts for the resilience upgrade of Energy Infrastructures.

capabilities of the specific solution (indicated by the proposed methodology) can inspire respective toolkits for other types of energy plants or transmission grids. The authors' suggestions are being presented in **Table 2**.

In the field of advanced materials' exploitation for the scope of the resilience enhancement, the future perspectives and the range of applications are more. Various meta-material concepts can be exploited for the purposes of upgrading the resilience profile of existing or new Energy Infrastructures. They can also be implemented to numerous types of Energy Infrastructures such as electricity plants or underwater pipeline grid, against various types of hazards such as blast or seismic. The authors' suggestions are being presented in **Table 3**.

5. Conclusion

The aim of this study was to demonstrate novel approaches for the enhancement of the resilience for the Infrastructures and Systems, via a specific methodological approach, which has been followed within three applications, mainly cases referred to

Transport Systems and Energy Infrastructures. The promising and efficient methodological approach is clearly presented in its general structure and then was specified for every project. The application cases were chosen in order to spotlight the need for upgrade in the design philosophy for the resiliency planning and the robustness methods, regarding the current and future demands. A powerful toolkit is developed in order the methodological approach to be followed in the technical level, in scope of Transport Systems' resilience assessment. The convergence of safety and cyber-security is of high importance for the Infrastructures and Systems resilience management, and it is needed to be considered in every approach for the robustness of a resilience planning. Advanced technologies such as meta-materials can upgrade the resilience capacity of various projects (e.g., Energy Infrastructures) even from the design phase, and it paved a way in order the research-based technical solution to be integrated in resiliency frameworks. The authors have also described the future perspectives of the methodology in the studied sections and suggested specific concepts and directions for the further exploitation.

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Conflict of interest

The authors declare no conflict of interest.

Notes

Due to confidentiality reasons, it was not allowed to share specific results and values in some of the application presented. Whoever will be interested into more details about the applications can contact the author for further questions.

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