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Risk assessment of critical infrastructures: A methodology based on criticality of infrastructure elements

Inga Šarūnienė [a,b,*], Linas Martišauskas [a,b], Ričardas Krikštolaitis [a,b], Juozas Augutis [b], Roberto Setola [c]

[a] *Lithuanian Energy Institute, Kaunas, Lithuania*
[b] *Vytautas Magnus University, Kaunas, Lithuania*
[c] *Università Campus Bio-Medico, Rome, Italy*

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ABSTRACT

The assessment of risk for critical infrastructures (CIs) is a crucial aspect in ensuring the security of every country. It is imperative to have an appropriate methodology that can effectively provide adequate measures to prevent or mitigate potential impacts of hazards that may disrupt the operation of CIs. This paper presents a methodology for the risk assessment of critical infrastructure that addresses three key aspects: (a) suitability for cross-sector systems, (b) capturing dependencies and interdependencies amongst CIs, and (c) ensuring a multi-hazard approach. The proposed methodology focuses on the criticality assessment of CI elements resulting from the loss of their functionality, and the evaluation of the probability of functionality loss for these elements. By combining these assessments, the final results, which portray the risk picture, are presented through a risk matrix in a simple and explicit manner. This approach facilitates better communication with stakeholders by providing a simple and explicit depiction of the risk levels associated with CIs. To illustrate the practical implementation of the proposed methodology, a case study is presented in this paper. The results obtained from the application of the methodology highlight the most critical elements within CIs, which pose the highest level of risk.

1. Introduction

1.1. Background

Critical infrastructures, such as electricity generation, transmission and distribution systems, transportation systems, and water supply systems, play a vital role in modern society. These infrastructures are essential for the functioning of various sectors and ensure the delivery of essential services to consumers. However, their significance also makes them attractive targets for malicious attacks, natural disasters, and other disruptive events [1].

The increasing reliance on critical infrastructures, coupled with the evolving nature of threats, necessitates the implementation of proactive risk assessment strategies. Risk assessment serves as a fundamental tool for identifying vulnerabilities, estimating potential consequences, and developing effective mitigation measures to safeguard critical infrastructures [2].

Understanding the significance of risk assessment of critical infrastructures requires a comprehensive analysis of the existing literature in the field. Therefore, this paper offers an extensive review of the available literature on risk assessment methodologies applied to critical infrastructures.

1.2. Literature review

Over the last decade, there has been a significant increase in research on critical infrastructures and their various aspects, including vulnerability, security, resilience, and protection [3]. This surge in interest can be attributed to the growing recognition of the potential risks and the need to develop effective strategies to mitigate them.

One important area of focus in critical infrastructure research is the development of risk assessment methodologies. Risk assessment serves as a fundamental step in ensuring proper risk management, including risk control and risk reduction, of critical infrastructures. In fact, the new European Commission (EC) Directive aims to enhance the resilience of critical entities providing essential services by emphasizing the

* Corresponding author at: Lithuanian Energy Institute, Kaunas, Lithuania.
E-mail address: inga.saruniene@lei.lt (I. Šarūnienė).

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importance of risk assessment [4]. While classical risk assessment methods exist [5], there is a lack of risk assessment methods that specifically enable the assessment of risk for critical infrastructures or their individual elements. However, in a number of studies, several approaches were developed for CI risk assessment. Some of these studies have focused on developing CI risk assessment approaches tailored to specific types of critical infrastructures, such as electricity infrastructures [6–8], oil and gas network systems [9], drinking water systems [10], and ports [11]. By analysing individual sectors separately, simplifications in the risk assessment process can be achieved, enabling a more targeted and sector-specific analysis.

In addition to single-sector risk assessment, researchers have dedicated efforts to cross-sector analyses that encompass multiple critical infrastructure sectors. These studies have explored risk assessment methodologies for energy systems [12], electricity supply, water supply, transportation (road/rail), and information and communication systems [13]. Meanwhile, Arvidsson et al. [14] detailed review of existing literature on this subject highlights a scarcity of cross-sector studies addressing more than three critical infrastructure sectors simultaneously. By considering the interdependencies between different sectors [15], a more comprehensive understanding of the risks and potential cascading effects can be achieved. This holistic approach enables policymakers and stakeholders to develop integrated risk management strategies that address the vulnerabilities arising from interdependencies.

Some authors have proposed methodologies for risk analysis of interdependent CIs, considering both general and specific hazards such as natural [16] and climate events [17], extreme weather events [18], hurricanes [19,20], terrorist attacks [21], and specific unfavourable scenarios [22]. Equally, Bloomfield et al. [23] highlight the benefits of preliminary interdependency analysis supporting risk assessment of critical infrastructure. By focusing on particular hazards or scenarios [22], researchers aim to assess the vulnerabilities and potential impacts of critical infrastructures in specific contexts. This targeted approach allows for a deeper understanding of the risks associated with specific threats, thereby facilitating the development of tailored risk mitigation strategies.

While numerous studies and scientific papers have addressed the topic of CI risk assessment, it remains a challenging endeavour. This challenge stems from the inherent complexity of critical infrastructure systems, which are characterized by intricate interdependencies and dependencies [24]. Understanding and modelling these interdependencies are crucial for accurate risk assessment. Moreover, the need for a multi-hazard approach further complicates the assessment process. Critical infrastructures are susceptible to various types of hazards, including natural disasters, cyber-attacks, and terrorist activities. Consequently, the risk assessment methodology must consider a wide range of potential threats and their potential cascading effects on interdependent systems [25]. Integrating multiple hazards into the risk assessment process requires the development of sophisticated modelling techniques and the consideration of complex interdependencies.

The reviewed literature reveals that Bayesian networks (BNs) and/or dynamic BNs are widely used as powerful and appropriate techniques for various interdependent infrastructures. Several studies have employed BNs to model and assess system resilience of interdependent electrical infrastructure systems [26], evaluate the resilience of engineering systems [27], model and assess interdependencies between critical infrastructures with a case study of an inland waterway port and its surrounding supply chain network [28], and assess port resilience [29]. BNs have also been utilized for joint resilience assessment of building, transportation, water, and electric power infrastructure systems [30], optimal security management of critical infrastructures [31], modelling of water supply networks [32], scenario analysis for the energy sector [33], evaluation of cascading effects in power grids [34], risk analysis for maritime transport system, by taking into account its different factors (i.e., ship-owner, shipyard, port, and regulator) and their mutual influences [35], operational risk assessment [36], and vulnerability analysis considering cascading effects [37]. Equally, this study shows that BNs are a beneficial technique for a multi-hazard approach.

1.3. Objective and contributions

The reviewed studies in the literature have identified numerous risk assessment methods for various applications, but there is a notable gap when it comes to dedicated methods specifically designed to measure the risk of critical infrastructures using comprehensive measures of consequences as criticality and a proper implementation of a multi-hazard approach. This gap underscores the need for novel approaches to address the unique challenges of assessing risks in critical infrastructures.

In previous studies [38,39], conducted by the authors of this paper, a new method was demonstrated to assess the criticality of energy critical infrastructures. This measure considered the functional connections between infrastructures and their elements, as well as the random operation of all energy systems. Building upon these previous studies, this research expands the methodology presented and introduces a new approach for the risk assessment of critical infrastructures by considering the consequences of functionality loss.

The main objective of this study is to propose a novel approach for measuring the risk of critical infrastructures that incorporates a critically measure to assess consequences and employs BNs to implement a multi-hazard approach, thereby providing a comprehensive and accurate risk assessment framework for critical infrastructures.

The novelty of the study presented in this paper lies in two main aspects. Firstly, the consequences of CI functionality loss are measured using a critically measure that incorporates various characteristics of how critical infrastructures can be influenced by different hazards and assesses their resilience. This approach provides a more comprehensive understanding of the impacts and consequences of disruptions in critical infrastructures.

Secondly, the study addresses the challenge of managing a multi-hazard approach by employing BNs to capture the impact of various factors, including dependencies and cascading effects. The proposed methodology integrates both the probabilities of losing the functionality of critical infrastructure elements and the criticality resulting from the loss of specific elements, contributing to a comprehensive risk assessment of critical infrastructures using risk matrices or other methodologies, as exemplified in a technical report from the EC JRC [40,41].

While the modelling of functionality loss in critical infrastructures is not a novel concept, deterministic risk assessment approaches are commonly used by operators to quantify the loss of functionality due to specific hazards and manage risks through component hardening [42]. However, the proposed criticality measure for CI elements or groups represents an overall estimate of consequences, distinguishing the developed methodology and contributing to the novelty of risk assessment techniques for critical infrastructures.

By integrating the critically measure and BNs, the proposed methodology offers significant advancements in the field of critical infrastructure risk assessment. It enables a more comprehensive and accurate evaluation of risks, facilitates informed decision-making, and enhances the effectiveness of risk management strategies.

This paper is structured as follows. Section 2 presents the methodology framework, which includes a comprehensive list of various hazards, introduces the criticality measure, and describes the construction of the BN for a combination of various CIs. The application of the proposed methodology is demonstrated in Section 3. Section 3.4 presents and analyses the numerical results of a hypothetical energy system. Finally, Section 4 summarizes the conclusions drawn from this study.

2. Methodology framework

The simple classical procedure of risk assessment (as depicted in Fig. 1) is a universal and easily adaptable framework that is considered adequate for assessing risks to CIs as well. While the main steps appear to be general, specific approaches need to be used to effectively perform CI risk assessments in accordance with these steps.

A detailed description of each step is provided in Sections 2.1–2.4 below, highlighting their specific aspects to ensure a comprehensive risk assessment procedure for CI.

2.1. System description

In the first step of conducting a risk assessment for CIs, it is essential to provide a detailed description of the analysed system. This entails specifying its boundaries, i.e., including which CIs and their elements are considered, as well as their respective functions and the relationships between different infrastructures and their elements. In a broader sense, any CI can be characterized as a system-of-systems (SoS), consisting of heterogenous elements that are geographically dispersed and interconnected, forming a multi-graph structure due to numerous dependencies and interdependencies [43]. Such a system can be conveniently described as complex systems (CS) [44], which are defined as "*systems where the collective behaviour of their parts entails emergence of properties that can hardly, if not at all, be inferred from properties of the parts*" [45].

Critical energy infrastructures typically consist of physical facilities (e.g., power plants, refineries, etc.). These facilities are interconnected through a grid of links (e.g., transmission lines, substations, etc.), supervised by different control systems (SCADA, PLC, etc.) and managed by human decision-makers. Each layer within this system exhibits several intra- and inter-dependencies with other layers, as well as with other critical infrastructures such as telecommunication networks, railway systems, gas pipelines, etc. [46]. To effectively address the complexity inherent in managing such interdependencies, a schematic representation of the system can be employed, conceptualizing it as a complex network where components are represented as nodes, and links refer to connections and relationships.

In order to define the operations of critical infrastructures, it is essential to consider the dependencies and interdependencies between them. As indicated in [24], four principal classes of interdependencies are examined: physical, cyber, geographic, and logical. However, in reality, CIs are subject to additional interdependencies, including technological, social, economic, political, organizational, etc. [47]. An example of such interdependency in the energy sector is the physical dependency between the natural gas supply and power plants for electricity generation.

2.2. Hazard identification

Another crucial step in the risk assessment of CIs includes hazard identification. As indicated in [48], a hazard can be defined as "*dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage*". Hazards can be seen as potential threats to CI.

Every CI is susceptible to various hazards, which usually depend on the geographical region and socio-political context in which the CI is located. Hazards affecting CIs can be categorized into different groups, which in more detail are discussed further.

1 **Natural**. These are the most common type of hazards and includes adverse and extreme natural phenomena, such as hazards occurring in the air, on the ground, and under the ground, as well as external fires in close proximity to CI. Natural hazards depend on local seismic, climate, and other geographic conditions.
2 **Technical**. These hazards are caused by the unreliable operation of CI and result from various accidents and failures that occur due to technical reasons, and they can lead to significant disruptions of CI or even a complete termination of CI operation.
3 **Economic**. These hazards encompass various risks related to economic factors. This includes economic crises, the isolation of CI, the dominance of a particular fuel source, producer, or supplier in the energy CI, as well as the presence of monopolies in the case of CI.
4 **Socio-political** and **geopolitical**. These hazards are challenging to identify and evaluate using quantitative measures. However, they are crucial to identify due to their potential for severe consequences. The existence of these hazards significantly influences decision-making processes regarding CI development. This category also includes cyber-attacks and terrorism, which are typically associated with socio-political and geopolitical hazards affecting CI.

The above-described groups of hazards can also be classified as non-malicious and malicious hazards resulting from human activities (refer to Table 1).

2.3. Probability estimation and consequence analysis

In general, any potential hazard can have a negative impact on specific elements of the system and on the system as a whole. In this paper, the following assumption was made: a disruption of functionality in a specific element (or group of elements) is a direct result of the adverse effects of any hazard. Furthermore, the complete or partial

Table 1
Tentative list of human caused hazards for CI [49].

Non-malicious	Malicious
Explosions (explosions of gas, fuel, ammunition, chemical substances, etc.); transport accidents (aircraft crash, accident of automobile and water transport, failure on railways, etc.); failures related to transportation of a dangerous cargo (accidents in transportation of explosive, poisonous, toxic, radioactive, easily inflammable and other cargoes); emergency events on industrial and military objects (explosions, wreck of technical constructions, outflow of toxic and poisonous substances, explosions of the ammunition, the non-authorized shots of rockets, having dug gas and oil pipelines, etc.); loss of CI.	Cyber-attacks, diversions, sabotage, and acts of terrorism.

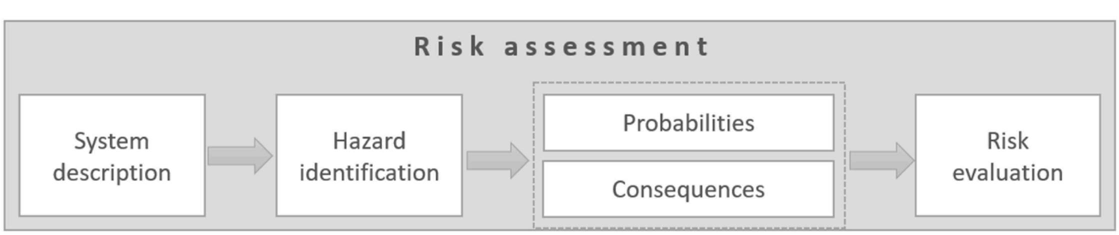


Fig. 1. Scheme of risk assessment procedure adaptable to CI risk assessment.

disruption of the system's overall functionality is a consequence of cascading effects arising from the dependencies and interdependencies between elements within the analysed system.

Based on the previous studies [38,39], this paper proposes simulating the system's operation in scenarios where specific elements or group of elements are not functioning to assess the system's ability to handle the loss of one or several elements, specifically in terms of meeting the demand of final consumers, for consequence analysis. For instance, if there is a disruption in the natural gas supply for heat and electricity generation, fuel diversification can be employed as a solution.

The assessment of consequences is one of the two key pillars of risk assessment. The criticality of CI elements, introduced in previous studies [38,39], serves as a measure to evaluate the impact caused by the loss of one element or group of elements within the system, considering their roles.

The second component involves determining the probability of losing the functionality of one element or group of elements within the system for a specific period due to various hazards. The assessment of consequences is carried out according to $N-1$, $N-2$ and $N-3$ principles. "$N-1$" signifies the scenario where only one element out of N elements does not operate, "$N-2$" refers to two elements in the system that do not operate at the same time, and "$N-3$" represents the scenario where three elements in the system are out of operation at the same time.

2.3.1. Criticality assessment as consequence analysis

The evaluation of consequences resulting from disruptions, either individual or groups of disruptions, is performed using a criticality measure. This measure indicates the level of criticality of elements or groups of elements in relation to these disruptions. The calculation of a system element's criticality, as a measure for quantitative consequence analysis resulting from the loss of the element(s), has been previously proposed in [38]. The criticality of the kth element is defined as the sum of ratios between the supply to each consumer (in the case of the kth element's non-functioning) and the demand of each final consumer, multiplied by the weighted coefficient of each consumer (with values ranging from 0 to 1). For instance, a criticality measure equal to 1 indicates a complete system shutdown if the kth element is not operational. Conversely, a criticality measure equal to 0.15 means that 85% of final consumers demands are met, if the kth element is not operational.

This assessment of the criticality, which was introduced in [38], captures the specific characteristics of CIs and their interdependencies, as well as the functional relationships between infrastructures and their elements. For instance, when considering power plants in the energy system, parameters such as installed electricity and heat capacities, efficiencies, fuel types used, connections with natural gas pipelines, availability of alternative fuels in case the primary fuel is unavailable, connections with power grids and district heating networks, and others are taken into account. Similarly, for the natural gas transmission system, factors such as the connection of pipeline segments, possible flow directions, connections with other CIs, and others are considered. The demands of final consumers are typically conservatively fixed by selecting values associated with unfavourable conditions. For instance, the demands for heat and electricity may be determined based on the coldest period of the year, and statistical data may be used for this purpose.

2.3.2. Multi-hazard approach for probability estimation to lose element's functionality

The methodology accounts for disruptions occurring across multiple systems and considers the potential for cascading effects. This is important because a disruption in one system can trigger disruptions in other interconnected systems. The criticality measure, discussed in Section 2.3.1, takes into account these possibilities. For instance, if there is a disruption in the natural gas supply system, it could lead to disruptions in heat or electricity generation technologies, resulting in an unsupplied energy amount. However, if there are alternative fuel sources available for energy generation, the impacts of the disruption on all the systems would be mitigated, and no significant consequences would occur.

Various factors, such as internal and external hazards, the technical reliability of each element, the operation of other elements, etc., influence the functionality of the system's elements. Therefore, it is necessary to employ an approach that considers these aspects in order to estimate the probability of element functionality, i.e., a multi-hazard approach is required for this purpose. Bayesian networks, as a powerful and effective tool in implementing a multi-hazard approach, have been chosen to estimate the probability of element functionality in the system.

The probability of functionality for each element is estimated using a specific BN model. This BN model consists of the analysed ith element (node-child) and nodes-parents, which represent internal, external (natural and human-made) hazards, and connected elements of the referred system. The schematic representation of this model is presented in Fig. 2. The topological scheme of the referred system serves as a basis for setting up the BN of the system, enabling the estimation of the probability of losing functionality for each element.

The probability of losing functionality of the jth element y_j is calculated as the joint probability of its corresponding random variable Y_j to have the value "False" (F):

$$P(Y_j = F) = \sum_{H_{(h)1},\cdots,H_{(i)l},Y_{k_1},\cdots,Y_{k_r}\in\{T,F\}} P(Y_j = F,\ H_{(h)1},\cdots,H_{(i)l},Y_{k_1},\cdots,Y_{k_r}), \quad (1)$$

here $H_{(h)1}, \ldots, H_{(h)s}$ – random variables representing external "human-made" hazards, $H_{(n)1}, \ldots, H_{(n)m}$ – random variables representing external "natural" hazards, $H_{(i)1}, \ldots, H_{(i)l}$ – random variables representing internal hazards, and random variables Y_i, $i\in\{k_1, \ldots, k_r\}$, $1 \le k_1 \le \ldots \le k_r \le N$, correspond to the functionality of connected elements of the system.

The probabilities obtained from formula (1) contribute to $N-1$ analysis as the second component to evaluate the risk of each element.

$N-2$ analysis, which considers the scenario where two elements in the system do not operate simultaneously, is not straightforward, especially when analysing the loss of functionality of non-independent elements. In general, three different cases are possible and need to be considered in $N-2$ analysis:

a) Independent elements. When elements y_i and y_j are independent, meaning their loss of functionality follows the same rule, the probability that both elements y_i and y_j lose their functionality can be calculated as:

$$P(Y_i = F, Y_j = F) = P(Y_i = F)P(Y_j = F), \quad (3)$$

here both probabilities $P(Y_i = F)$ and $P(Y_j = F)$ can be obtained by constructing separate BNs for elements y_i and y_j, or by using a single BN for the entire system (if only it has no cycle).

b) One-way dependant elements. When element y_j depends on element y_i (either directly or through other elements of the system: y_i – …→y_j), there are multiple ways in which both elements can lose their functionality. These include: y_i fails causing a cascading effect on y_j, or y_j fails while y_i is still operating, but y_i fails right after that. In this case, the probability is calculated as:

$$P(Y_i = F, Y_j = F) = P(Y_i = F)P(Y_j = F|Y_i = F) + P(Y_j = F|Y_i = T)P(Y_i = F), \quad (4)$$

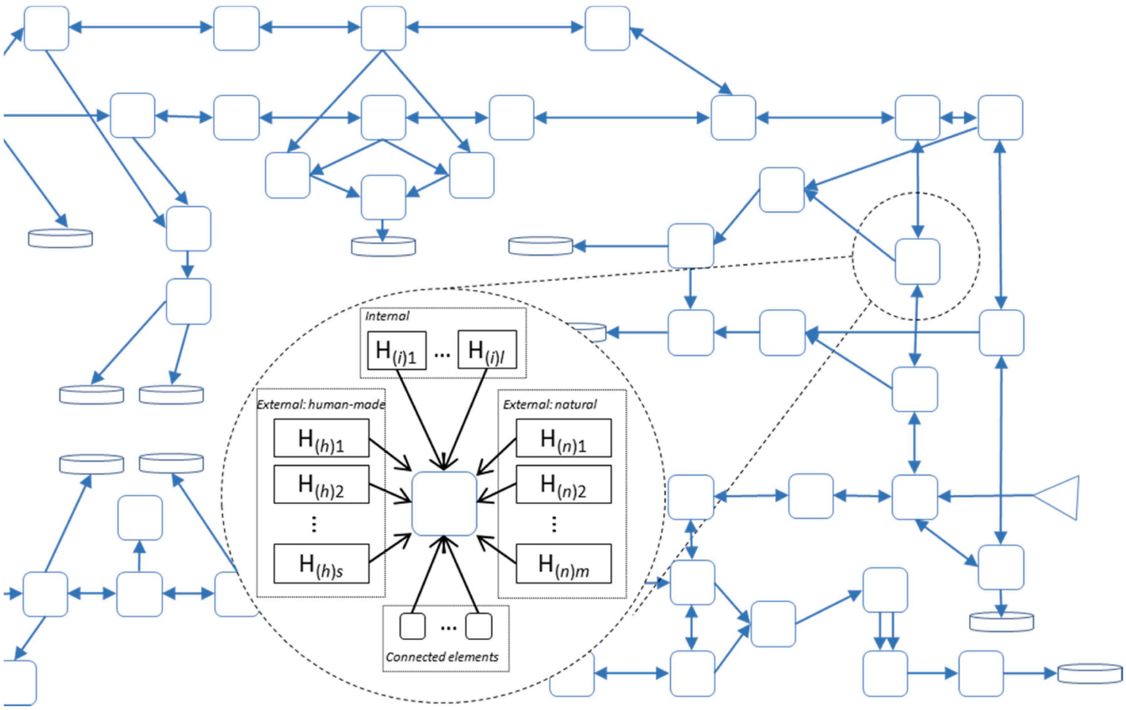


Fig. 2. Fragment of the topological scheme of the reference system and the Bayesian network for one of its elements.

here the probability $P(Y_i = F)$ is obtained from the BN constructed for element y_i; the probability $P(Y_j = F|Y_i = F)$ is obtained from the BN constructed for element y_j while considering the scenario where element y_i is not operating (lost its functionality); the probability $P(Y_j = F|Y_i = T)$ is obtained from the BN constructed for element y_j while considering the scenario where element y_i is operating. Alternatively, a single BN for the entire system can be used as well (if only it has no cycle).

c) Interdependent elements. When elements y_i and y_j are interdependent (either directly or through several other elements: $y_i \leftarrow \ldots \rightarrow y_j$), the cascading effect can spread in both directions, similar to the previous case. In this case, the probability that both elements y_i and y_j lose their functionality is calculated as:

$$\begin{aligned} P(Y_i = F, Y_j = F) &= P(Y_i = F)P(Y_j = F|Y_i = F) \\ &+ P(Y_j = F|Y_i = T)P(Y_i = F) \\ &+ P(Y_j = F)P(Y_i = F|Y_j = F) \\ &+ P(Y_i = F|Y_j = T)P(Y_j = F), \end{aligned} \tag{5}$$

here the probabilities $P(Y_i = F)$ and $P(Y_j = F)$ are obtained from the BNs constructed for elements z_i and y_j separately; the probability $P(Y_j = F|Y_i = F)$ is obtained from the BN constructed for element z_j while considering the scenario where element y_i is not operating (lost its functionality); the probability $P(Y_j = F|Y_i = T)$ is obtained from the BN constructed for element y_j while considering the scenario where element y_i is operating; the probability $P(Y_i = F|Y_j = F)$ is obtained from the BN constructed for element y_i while considering the scenario that element y_j does not operate (lost its functionality); the probability $P(Y_i = F|Y_j = T)$ is obtained from the BN constructed for element y_i while considering the scenario that element y_j is operating.

For other $N - k$ ($k = 3, 4, \ldots$) cases (k elements in the system do not operate simultaneously), each case should be considered individually as they cover combinations of the previously described cases.

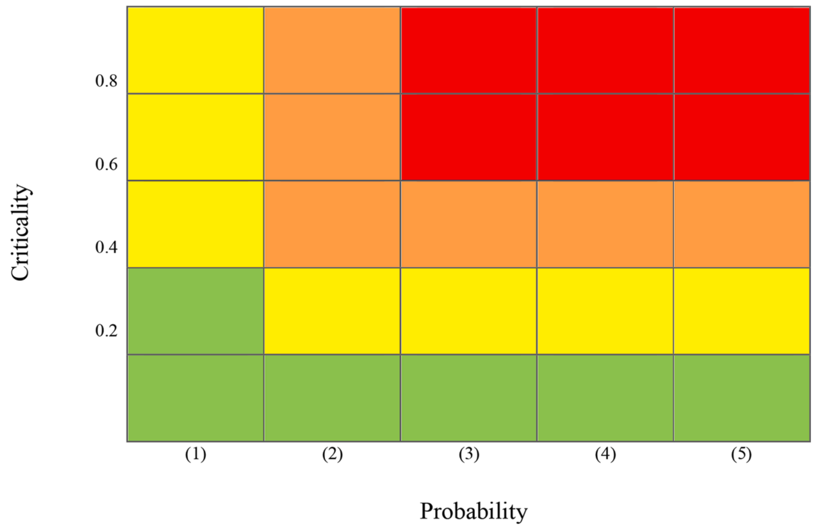
Furthermore, more complex BN structures are also possible. In such cases, the current node-parent(s) depend(s) on additional factors. For instance, the reliability of an element, which is one of the main internal factors influencing its functionality, can also be assessed using a BN [50].

2.4. Risk evaluation

Appropriate risk evaluation relies on purposefully and accurately selecting the right risk metric. The risk metric serves two crucial purposes: (1) it enables for discussing and communicating the results of risk analysis and important risk aspects, and (2) it facilitates decision-making by providing a quantitative measure for evaluating risk. The selection of the correct risk metric is of vital importance as it determines the type of information obtained from the risk analysis and determines whether the results are valid and informative to decision-makers and stakeholders [51]. These criteria have been summarized in a comprehensive discussion on value-related, informative, and analytical issues that affect the interpretation and selection of risk metrics by [51].

Indicators such as importance measures [52] and risk matrices [13, 41,53] have been identified as appropriate, applicable, and beneficial for CI risk analysis. Specific risk matrixes have been introduced to provide an overall risk profile and additionally, the authors [5,22] propose expanding this approach by including the third dimension – the source of risk. In previous authors' work [38], Fussell-Vesely and Birnbaum's importance measures were utilized to identify the most important CI elements and groups of elements. The importance measures approach aids in identifying the most critical elements within the referred system. However, it only provides a partial view of the risk associated with the loss of functionality of one or more elements in the referred system.

Therefore, the risk matrix, as one of the risk metrics, distinguishes for its capability to capture both essential components: the severity of consequences and the probability of their occurrence [41]. In this paper, the risk matrix is proposed that is adapted for CI risk analysis (it is presented in Fig. 3): here, the severity of consequences is expressed as the criticality of an element or a group of elements.



Classification of probability:
(1) – very unlikely: expected to occur less than once in 10000 years
(2) – unlikely: expected to occur at least once in 1000 – 10000 years
(3) – possible: expected to occur at least once in 100 – 1000 years
(4) – likely: expected to occur at least once in 10 – 100 years
(5) – very likely: expected to occur at least once in 10 years

■ – very high, ■ – high, ■ – medium, ■ – low (tolerable) risk.

Fig. 3. An example of adapted risk matrix for CI.

The classification of risk into low, medium, high, and very high risk areas may vary depending on the specific type of a particular CI, as well as the legal framework established by the government of a particular country, directives or, for instance, industry-specific standards that may exist.

3. Case study

3.1. Energy system description

A case study was conducted on the Lithuanian energy system to illustrate the practical application of the proposed methodology. The risk assessment in this study considered the criticality of various elements within the energy infrastructure. The analysed energy system might be seen as a system-of-systems while it includes the power system, district heating systems, fuel supply system for electricity and heat generation, and other related systems. Different connections between these systems exist in the analysed case. For instance, physical connections in the power system include the transmission network that connects generation sources and the distribution network. Functional connections, for example, include the interconnection of thermal power plants with natural gas pipelines, district heating and electricity supply networks. Additionally, reversible connections between different systems also exist, for example, natural gas is supplied to power plants for electricity generation, which is also used to facilitate the operation of the natural gas transmission system. In this particular paper, the case study focuses on the electricity system, which is represented as a graph consisting of various nodes that correspond to different infrastructure elements within the analysed system.

In the case study, elements of different infrastructures of the energy system are represented as nodes, denoted as: $y_1, y_2, \ldots, y_N$, where N is the total number of elements (in the analysed case, $N = 157$). Elements within the natural gas supply system – from y_1 to y_{90}, heat generation technologies – from y_{91} to y_{126}, power plants generating electricity – from y_{127} to y_{133}, technologies of renewable energy sources – from y_{134} to y_{157}.

The main data sources and assumptions used for the modelling in this case study were derived from previous authors studies [38,39], where the criticality of system elements was evaluated for the analysed system. The main assumptions of the study include the description of generation and supply technologies (e.g., electricity, heat, and natural gas) and various parameters used to characterize these technologies (elements), such as installed capacity, efficiency, capacity and availability factors, pipeline flow rates and directions, and many other. Some of the data used was briefly described without disclosing actual data due to security and confidentiality reasons. Other assumptions, including energy system's structure, technologies, fuels used, and modelling aspects, were also introduced in these studies [38,39], and are used in this current study as well.

3.2. Criticality assessment of the reference system

In this study, the criticality is determined by considering the energy supplied to consumers per unit of time in the system after turning off the element at a given time, taking into account consumer energy demand and the number of consumers. Data for the energy demand was externally input into the model based on the statistical data. The optimization of energy supply amounts was carried out using the optimization techniques, aiming to maximize energy generation in the analysed system. For example, the gas supply system was simulated using a mathematical optimization model known as the optimization of maximum flow with goal programming. The criticality assessment of elements, considering the assumptions discussed above, was performed according to $N-1$, $N-2$, and $N-3$ principles based on the previous study [38].

The results of the $N-1$ analysis revealed that the loss of functionality of element y_{89} results in the highest criticality value. This element represents the pipeline that connects the natural gas supply system with the electricity generation technology of the highest capacity. In the $N-1$ case, the criticality values of other system elements did not exceed 0.1. The $N-2$ analysis showed that the pair consisting of y_{89} and y_{131}

exhibited exceptionally high criticality compared to other pairs. Element y_{131} represents one of the power plant units with the highest capacity, which can generate electricity using alternative fuels.

The $N-3$ analysis revealed that there are 30 triplets with the same exceptionally high criticality level and in most cases it consisted of elements of y_{89} and y_{131}.

3.3. Probability of element(s) functionality

Not always the highest risk is achieved by the high criticality, if only the probability of a particular case is negligible. To address this, the probability of functionality loss was estimated for each element using the proposed multi-hazard approach based on BN (see Section 2.3.2).

A Bayesian network was constructed for the analysed energy system in the case study (description is given in Section 3.2), capturing dependencies amongst system elements and potential hazards. In the paper, a detailed fragment of the BN for elements y_{89}, y_{131} and y_{133} (where element y_{133} represents one of the power plant units with the highest capacity, which can generate electricity using alternative fuel) is presented in Fig. 5. This presentation aims to demonstrate the application of the proposed approach, as the loss of functionality of these three elements (and their combinations) leads to the highest criticality value.

Elements y_{131} and y_{133} depend on element y_{89} in a one-directional manner: $y_{89} \to y_{131}$ and $y_{89} \to y_{133}$. Table 2 provides a list of the main hazards or factors that may affect the functionality of elements y_{89}, y_{131} and y_{133}. In this particular case, three types of hazards (natural, technical, socio-political and geopolitical) have been identified for analysed elements (y_{89}, y_{131} and y_{133}) regarding the geographical location, climatic conditions, seismic conditions, and socio-political/geopolitical context. The hazard identification process involves classifying the hazards according to their specific categories, described in Section 2.2.

Plant's safety report, external-event probabilistic risk assessment report other such kind report may properly serve for initial probabilities used in a particular Bayesian network. It should be noted that probabilistic fragility curves for individual assets in the system and stress-testing would enhance this probabilistic analysis. However, this study does not incorporate probabilistic fragility curves for individual assets and does not focus on stress-testing in its current stage. It may be accepted as one of the limitations to be improved in the future.

A Bayesian network was created, and probability calculations were performed using the GeNIe Modeler [55,56]. As the software is not open-source, code is not available in this methodology. The approach of calculations and the numerical implications of the analysis are provided further.

$N-1$ *analysis*: the probabilities of losing the functionality of the analysed elements are obtained from the BN constructed to the entire system, a fragment of which is provided in Fig. 5.

$N-2$ *analysis*: if y_{89} fails, it causes a cascading effect on y_{131} (or y_{133}), or if y_{131} (or y_{133}) fails while y_{89} operates, but y_{89} fails right after that. The probability of this combination is calculated as follows:

$$\begin{aligned} &P(Y_{89}=F, Y_{131}=F\ ) \\ &\quad = P(Y_{89}=F)P(Y_{131}=F|Y_{89}=F) \\ &\qquad + P(Y_{131}=F|Y_{89}=T)P(Y_{89}=F). \end{aligned} \tag{6}$$

Conditional probabilities can be calculated using the BN with the "set evidence" option (*true* or *false*).

$N-3$ *analysis*: if element y_{89} fails (loses its functionality), it causes a cascading effect on y_{131} and y_{133}, or if elements y_{131} and y_{133} fail while element y_{89} is still functioning, but after that the failure of element y_{89} occurs as well. The probability of this combination is calculated as follows:

$$\begin{aligned} &P(Y_{89}=F, Y_{131}=F, Y_{133}=F\ ) \\ &\quad = P\ (Y_{89}=F)P(Y_{131}=F|Y_{89}=F) \\ &\qquad \times P(Y_{133}=F|Y_{89}=F) \\ &\qquad + P(Y_{131}=F|Y_{89}=T) \\ &\qquad \times P(Y_{133}=F|Y_{89}=T)P(Y_{89}=F). \end{aligned} \tag{7}$$

The same approach was used to estimate the remaining probabilities of losing functionalities of any two or three elements, focusing on the most critical combinations based on their criticality value, i.e., higher than 0.3.

Additionally, sensitivity analysis has been conducted to investigate the effects of small changes in numerical parameters (i.e., probabilities) on the output parameters (e.g., posterior probabilities) when analysing the constructed BN. The BN calculations were performed using the GeNIe Modeler [55,56], which implements an algorithm proposed by [57] to perform sensitivity analysis in the BN.

The results of the sensitivity analysis for elements y_{89} (Fig. 6) and y_{131} (Fig. 7) reveal that technical reliability is the most important factor in the probability of losing functionality for both elements. The presence of sabotage (or terrorism) also shows a significant impact on the results, considering the calculations were conducted assuming "efficient" sabotage or terrorism. It is important to note that while the estimation of technical reliability was based on a substantial amount of data extracted from the power plant's safety reports, and therefore can be considered sufficiently accurate, the estimation of sabotage or terrorism relied largely on expert opinions, making it less precise.

Table 2
Identification of hazards and other factors for elements y_{89}, y_{131} and y_{133}.

Type of hazard or factor	Identified hazards or factors Element y_{89}	 Element y_{131}	 Element y_{133}
Natural	earthquake[(1)]	earthquake[(1)] flooding[(1)] extreme wind[(1)]	earthquake[(1)] flooding[(1)] extreme wind[(1)]
Technical	rupture probability[(2)]	failure probability[(3)]	failure probability[(3)]
Socio-political and geopolitical	sabotage or terrorist attack	alternative fuel sabotage or terrorist attack	alternative fuel sabotage or terrorist attack
Related elements in the system	y_{87}[(4)] and y_{88}[(4)]	y_{89}[(5)]	y_{89}[(5)]

[(1)] the power plant's external-event probabilistic risk assessment report can serve for quantitative evaluation;.

[(2)] rupture probability can be estimated using an approach that captures results from non-destructive inspections and failure data ([54]);

[(3)] the power plant's safety report can serve for quantitative evaluation;

[(4)] element y_{89} has a direct connection with neighbouring elements y_{87} and y_{88} of the natural gas transmission system;

[(5)] elements y_{131} and y_{133} rely on the functionality of element y_{89}, which should ensure the supply of primary fuel (natural gas).

3.4. Risk evaluation using risk matrix

The risk matrix as proposed in Section 2.4, provides a concise representation of both the probabilities of functionality loss of elements and their associated criticalities.

In the analysis presented, a total of 645,113 different scenarios were considered, involving the examination of $N-1$, $N-2$ and $N-3$ events. These scenarios encompass instances where a single element, as well as combinations of two and three elements, are faulted. Out of these scenarios, only 55 resulted in a criticality value exceeding 0.3. These selected scenarios were included in the risk matrix (Fig. 8) and subjected to a more detailed analysis.

It is important to note that in the context of real CI risk assessment, the determination of risk levels (i.e., areas of low, medium, high, and very high risk) within the risk matrix should be aligned with the applicable legal framework. In this paper, a hypothetical CI was examined, and the classification of risk areas is established using the risk matrix proposed in Section 2.4 to illustrate the application of the proposed methodology.

The results demonstrate that out of 55 analysed scenarios, 21 scenarios (38.2%) are classified as high risk, while the remaining 34 scenarios (61.8%) are categorized as the medium risk. However, as depicted in Fig. 4, only one $N-1$ scenario shows medium risk (shown by the dashed circle in Fig. 8), and only one $N-2$ scenario is classified as high risk (indicated by the round dotted circle in Fig. 8). The high-risk area in the risk matrix is mostly covered by $N-3$ scenarios, which exhibit a significant impact but have a low probability of occurrence, because at least three elements in the hypothetical CI simultaneously have to not operate.

Based on this analysis, it can be concluded that the hypothetical energy system, in the case of disruptions, ensures high resilience and low risk to critical energy infrastructure. Some of the selected scenarios from each group ($N-1$, $N-2$ and $N-3$) that have a significant impact on the results are analysed in more detail further.

***N* – 1 scenario**. This scenario is characterized by the loss of functionality of a single element in the system, which poses medium risk primarily due to a relatively high probability of failure (2.29E-2) and criticality (0.326). In the analysed energy system, this element refers to the gas pipeline segment that connects the largest gas-fired power plant. The loss of natural gas supply to this power plant results in medium risk rather than high risk, mainly because there is sufficient diversification of electricity production technologies used by other power plants. It is worth noting that this power plant also has the option to use an alternative fuel. However, the risk is not entirely eliminated since the majority of electricity production in the analysed system relies on natural gas-fired power plants.

***N* – 2 scenarios**. The majority of these scenarios pose medium risk to the CI. However, there is one scenario that results in high risk when both the functionality of the largest gas-fired power plant and the gas pipeline connecting to this plant are simultaneously lost. The failure of these two critical elements simultaneously is associated with a relatively high critically (0.557) but has a low probability of occurrence (4.40E-4). High dependency on natural gas supply and reliance on electricity production from gas-fired power plants demonstrate high risk to the CI. The remaining $N-2$ scenarios have lower criticality and pose medium risk.

***N* – 3 scenarios**. The majority of these scenarios include the same two elements as in the high-risk $N-2$ scenarios, along with an additional element that does not operate at the same time. This third element is primarily associated with the gas pipeline responsible for supplying natural gas to gas-fired heat generation technologies. The loss of functionality of all three elements in the CI poses high risk to the system, primarily due to high criticality (>0.5). However, some of these scenarios have a very low probability of occurrence (<*E*-5) and fall into the medium risk area.

The results obtained from the real case application of the proposed methodology for CI risk assessment in this study can provide valuable insights for decision-makers involved in planning strategic energy infrastructure projects. The methodology, serving as a tool, can aid in the development of national or regional energy strategies, determining the directions of energy supply and generation technologies, as well as making other energy-related improvements. These findings offer practical guidance and support for informed decision-making in the planning and implementation of energy infrastructure initiatives.

Summarizing the results, the risk analysis conducted on the hypothetical energy system using the risk matrix approach revealed valuable insights into the resilience and risk levels of critical energy infrastructure. One notable finding is that the majority of high-risk scenarios are from the $N-3$ category, where at least three elements of the system simultaneously fail. These scenarios exhibit high criticality but have a low probability of occurrence. This highlights the importance of considering the potential cascading effects and interdependencies within the infrastructure when assessing risk. It is crucial to understand the factors that contribute to the low probability of $N-3$ scenarios, such as redundancy measures or system robustness, to further enhance the resilience of critical energy systems.

Another significant observation is the dependency on natural gas supply and the reliance on gas-fired power plants, as indicated by the high-risk $N-2$ scenarios. Simultaneous failure of the largest gas-fired power plant and the connecting gas pipeline poses a high risk to the system. This finding underscores the vulnerability of energy systems with a heavy reliance on a single energy source and highlights the need for diversification and alternative energy options. To mitigate such risks, future energy infrastructure planning could explore strategies for integrating renewable energy sources, energy storage systems, and interconnectivity with other power generation technologies.

Overall, these results emphasize the importance of comprehensive risk assessments in energy infrastructure planning. By identifying critical scenarios and assessing their risk levels, decision-makers can prioritize investments and develop strategies that enhance the resilience of critical energy systems. Integrating risk assessment methodologies, such as the risk matrix approach employed in this study, into the decision-making process will provide valuable insights for planning and implementing energy infrastructure initiatives in a way that ensures long-term sustainability and security of energy supply.

The primary limitation of applying this methodology is the absence

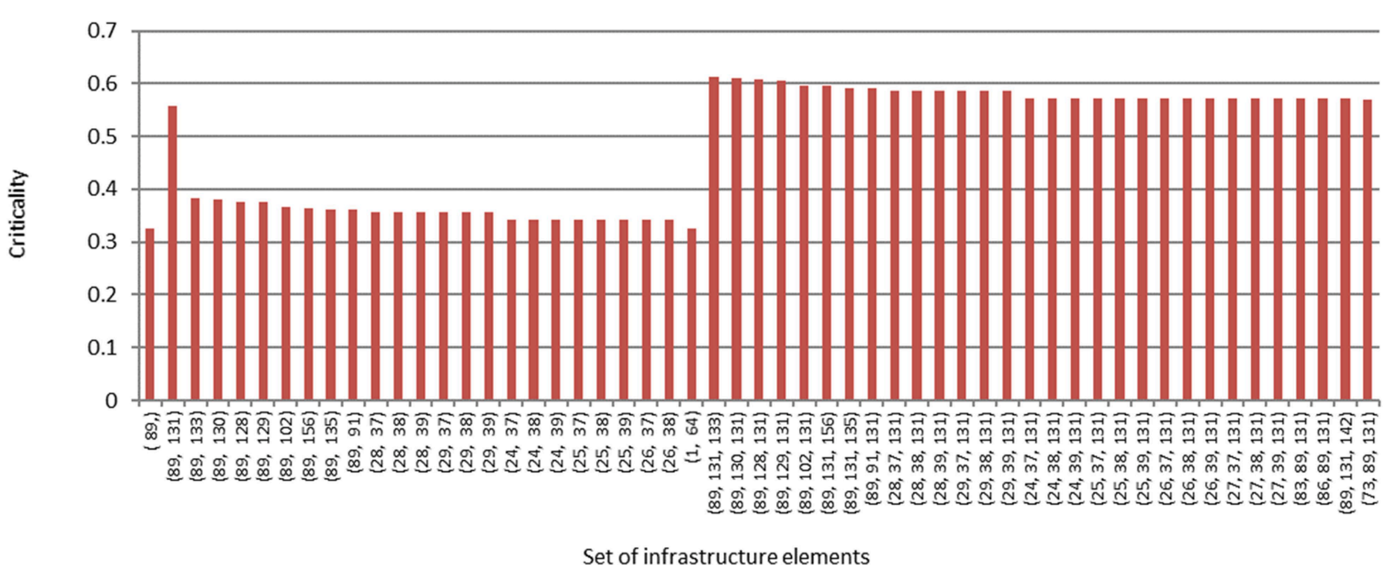


Fig. 4. Estimates of criticality for $N-1$, $N-2$ and $N-3$ analyses.

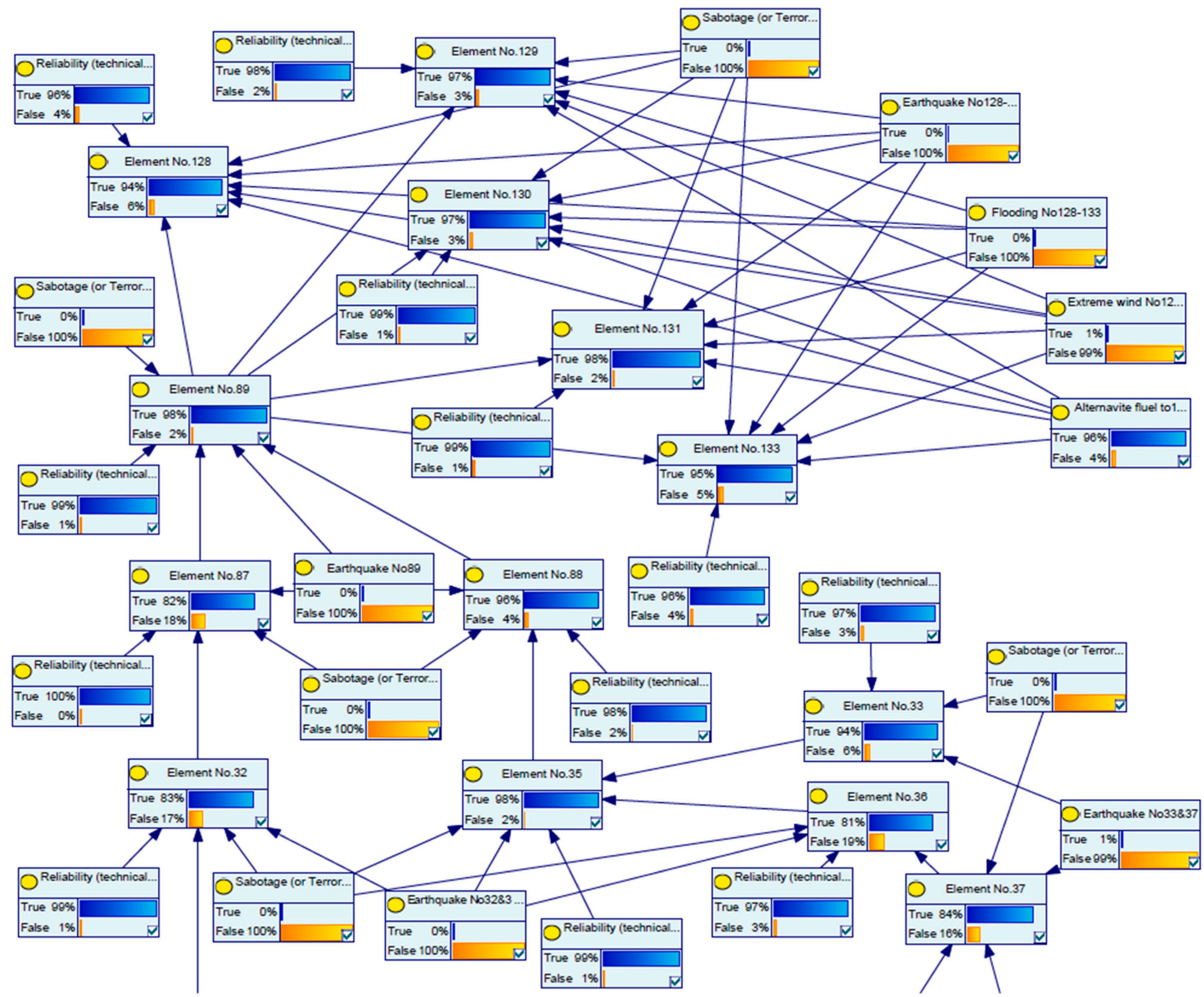


Fig. 5. Fragment (related to elements y_{89}, y_{131} and y_{133}) of the BN of the referred system.

of result validation. The decision to forego result validation in this research was a deliberate one based on the specific nature of the research objectives. There are several key reasons for this approach. This study primarily focused on developing and implementing a methodology for risk assessment of critical infrastructures. Given the exploratory or developmental nature of this work, the primary goal was to establish and evaluate the methodology itself rather than validating specific results. Also, obtaining real data for result validation can be extremely challenging or even unfeasible. Without a reliable reference point for validation, it can be misleading to attempt result validation. Additionally, the application of the methodology might be seen as preliminary, and it is acknowledged that extensive result validation could be considered in subsequent studies as the methodology matures and more data becomes available. While it is acknowledged the importance of result validation in many scientific studies, it is believed that in this specific context, the focus on methodological development and early-stage exploration aligns with the objectives of this research.

4. Conclusions

Ongoing activities and recent studies in the field of CI risk assessment highlight the ongoing challenges associated with analysing cross-sector systems affected by various threats. One possible reason for these challenges is the absence of universally accepted methodology for comprehensively assessing the risk of CI while considering the aforementioned factors.

This study presents a cross-sector and multi-hazard approach for the risk assessment of critical infrastructures, capturing dependencies and interdependencies between different infrastructures. The study focuses on analysing and numerically evaluating the capacity of CIs to withstand various emergency scenarios, where one element or group of elements lose functionality due to multifarious causes. This is accomplished by introducing an integral measure "the criticality of the CI's element (or group of elements)". The use of a single integral measure for evaluating consequences allows for the application of the obtained results using a risk matrix in a straightforward and explicit manner, facilitating better communication with stakeholders. The proposed methodology effectively identifies high-risk CI elements and their groups. The factors that exert the greatest influence can also be identified through BN sensitivity analysis. However, it is important to note that the proposed integral characteristic "the criticality of the CI's element (or group of elements)" does not include financial loss. Nevertheless, this factor can be easily integrated into the design of the risk matrix. Additionally, representing the system as a BN can be challenging, particularly for non-experts in BN

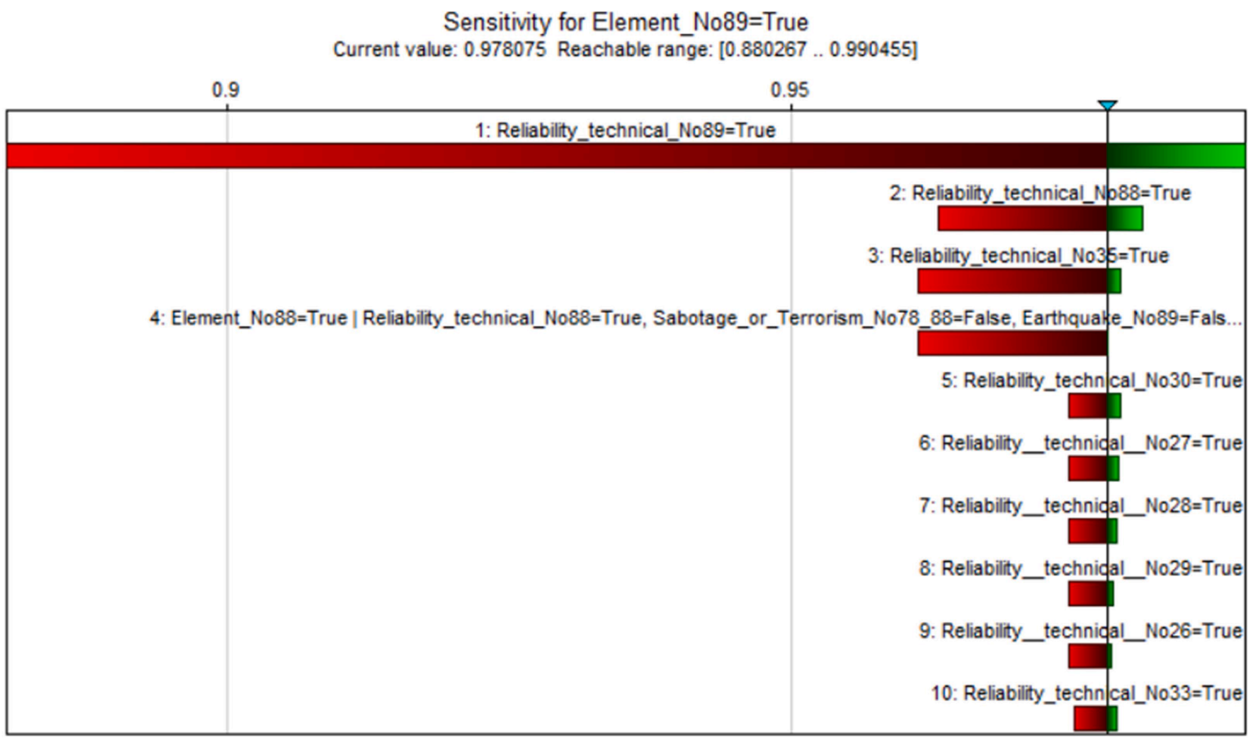


Fig. 6. Sensitivity analysis of element y_{89} functionality and its contributing factors.

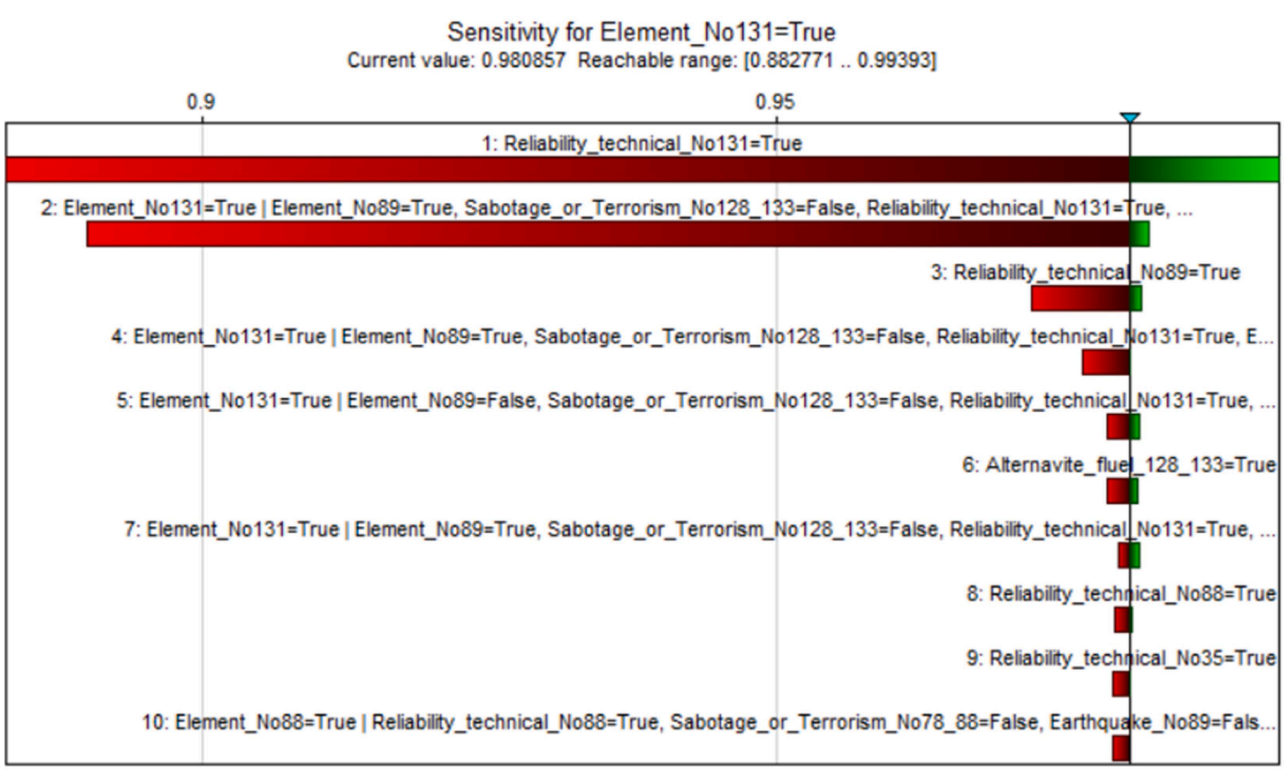
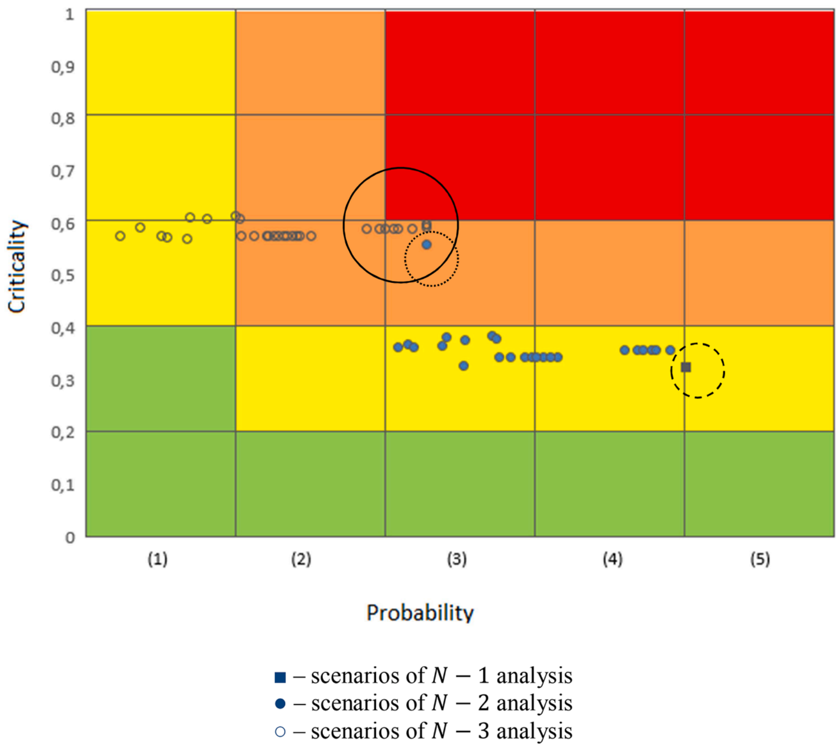


Fig. 7. Sensitivity analysis of element y_{131} functionality and its contributing factors.

applications, especially when dealing with complex CIs.

An illustrative case study was conducted for the Lithuanian energy system, which includes electricity, district heating, and fuel supply, to demonstrate the applicability and capabilities of the proposed methodology. Simulation of the analysed system within different scenarios enabled to identify the most critical elements of CIs which lead to the highest level of risk. In real case applications, this would serve as a significant basis for decision-makers when planning strategic infrastructure projects, including modifications, reconstructions, and new initiatives. Furthermore, it has the potential to assist in shaping key strategic directions of policy development by selecting a system configuration that poses low (or acceptable) risk to critical



■ – **very high,** ■ – **high,** ■ – **medium,** ■ – **low (tolerable) risk**

Fig. 8. Risk matrix for analysed CI scenarios.

infrastructure.

Overall, this study contributes to the ongoing efforts in CI risk assessment and provides a comprehensive approach for analysing and evaluating the risk of critical infrastructures. The findings have practical implications for infrastructure planning, risk management, and policy development, offering a valuable tool for decision-makers in ensuring the resilience and security of critical infrastructures.

While the methodology has its strengths, it is acknowledged that it also has certain limitations. The study primarily focuses on a hypothetical system based on the Lithuanian energy system, which may limit the generalizability of the findings to other regions or countries. The effectiveness of the proposed methodology heavily relies on the availability and quality of data related to critical infrastructures. Obtaining accurate and comprehensive data can be challenging, particularly when dealing with intricate systems and interdependencies. It should be noted that the proposed risk measure does not account for financial loss. Integrating financial considerations into the risk assessment would provide a more comprehensive understanding of the overall impact of disruptions on critical infrastructures. Another limitation of the study is the absence of result validation. The primary aim was the development and implementation of a robust risk assessment methodology for critical infrastructures. As such, the focus was on establishing and evaluating the methodology itself, rather than validating specific results. Additionally, securing real-world data for result validation proved to be a formidable challenge, often rendering such validation unfeasible or misleading in the absence of a reliable reference point.

Further research can focus on refining the proposed methodology by addressing the limitations mentioned above. This includes developing strategies to generalize the approach to different cross-sector systems, improving data collection and quality assurance processes, incorporating financial loss considerations, and simplifying the representation of complex systems. To enhance the robustness and applicability of the methodology, another direction of future research should focus on result validation, efforts to access diverse datasets, case-specific validations, and comparative assessments against established methods, ultimately ensuring the methodology's reliability and real-world applicability. Future research can also explore the inclusion of probabilistic fragility curves to provide a more detailed understanding of asset vulnerability and system resilience. Future work can also focus on stress-testing the system with multiple realizations of spatially and temporally correlated multi-hazard events. This will help capture a wider range of failure combinations and improve the robustness of the proposed risk assessment methodology for critical infrastructures.

CRediT authorship contribution statement

Inga Šarūnienė: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Linas Martišauskas:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ričardas Krikštolaitis:** Writing – original draft, Methodology, Investigation, Conceptualization. **Juozas Augutis:** Supervision, Methodology, Conceptualization. **Roberto Setola:** Writing – review & editing, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2023.109797.

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