Application of mathematical optimization in decision making relevant to the resilience of national security: networked society as the basis of interdependence of critical resources

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Abstract:

Introduction/purpose: Destabilization of critical resources (CRs) or critical infrastructure (CI) important for the stability of the state can be dangerous for society, economy, and especially national security. Disruption of one CI object or one of its parts often affects and causes disruption of other dependent CI, because the modern society has become a "networked society". The paper proposes a model for quantifying and defining the interdependence between different CIs and their priorities, based on statements of experts.

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Methods: The proposed methods that combine the Laboratory for Testing and Evaluation of Decision Making (DEMATEL) and the Analytical Network Process (ANP) have been successfully modified by fuzzy logic theory in this work.

Results: Integrating multiple methods into a unique input data analysis model significantly affects the change in ranking.

Conclusion: The work contributes to military science in making strategic decisions related to national security management through increasing the resilience of CRs and the societies that rely on them.

Key words: fuzzy logic, DEMATEL, ANP, MCDM, resources, national security.

Introduction

At the beginning of the 21st century, mankind is more than ever faced with large-scale natural disasters (Our World in Data, 2023) and man-made disasters, pandemics and major cyber attacks (Publications Office of the European Union, 2020). Terrorist acts and violent protests aimed at destroying state foundations and accompanied by human casualties have become an integral attribute of the modern world. Researchers have generally agreed that critical resources comprise critical infrastructure, critical sectors, and critical technologies of vital importance to a society; therefore, destructive impacts on them can pose a danger to a country as a whole and directly to its citizens who often do not even realize their importance. (Berlovsky & Alexandrov, 2022; Tomalska, 2023)

CI security, as an extremely important factor of national security, is only one of the aspects of broader changes in the security discourse since the end of the 20th century. Manuel Castells pointed out the importance of social changes brought about by the information technology revolution, i.e., the connection of the organizational logic of the network and information technologies in his book "The Rise of the Networked Society". (Castells, 2010)

For a better understanding of global processes and social changes, he offers an analytical tool in which the main functions and processes are viewed as networks (e.g. financial, political, military and security networks, etc.) where the actors are therefore not individuals but organizations, states and nations. (Starčević & Milenković, 2023)

Exposure to a wide range of security challenges, risks and threats (SCRTs) that are not necessarily of a military nature, and which threaten the security of a state and its citizens, requires a balance between reactive and proactive activities of decision makers. (Ninković, 2021; Milenković & Subotić, 2022)

Progressive increase and the unpredictability of modern SCRTs originating from the turbulent geopolitical environment, as well as those immanent to the structures of the internal system, have brought numerous changes regarding the national security of modern states. SCRTs are identified "as part of the national security planning process and are reflected in the basic strategic and doctrinal documents (National Security Strategy, Defense Strategy and Doctrine of the Serbian Army) of the Republic of Serbia" (Bojanić, 2022). The SCRTs identified in these documents (Golubović & Saković, 2023) often reflect the political inclinations and preferences of policy makers, who suffer from the same cognitive biases as anyone else, which can only be overcome with a scientific approach. As a result, these documents and decisions routinely overestimate the relative importance of some threats while underestimating others, or they are simply presented as a phrase "challenge, risk and threat" without prioritization or ranking. In support of this, there is an observation that in the past national security strategies of the Republic of Serbia (2009 and 2019), the term CI was not mentioned at all. (Milosavljević & Vučinić, 2021) The Republic of Serbia adopted the Law on Critical Infrastructure for the normative regulation of CI, in order to harmonize it with European legislation. In order to protect "European critical infrastructure" (Publications Office of the European Union, 2020), its interdependence and importance, the EU regulated this area in order primarily to protect the energy network and gas pipelines that cross the territory of several countries.

Therefore, the importance of safe and resilient CI is imposed not only as a response to SCRTs (whether caused by climate change, political or economic phenomena), but also because of the networking and so-called interdependence between CIs at the national level. According to the Law on Critical Infrastructure: "CI is systems, networks, facilities or their parts, interruption of functioning or interruption of delivery of goods or services can have serious consequences for national security, health and lives of people, property, environment, safety of citizens, economic stability, that is, disrupting the functioning of the Republic of Serbia (Službeni glasnik Republike Srbije, 87/2018). CI is essential for the production and distribution of a continuous flow of basic goods and services (Huang et al, 2014). CI systems are highly interdependent and interact at different levels, which makes them vulnerable to disasters and failures, and ultimately leads to losses. Modeling of hybrid methods for the analysis of interdependence and significance of CI is very important for social and economic security. Such methods provide important input data that is the basis for the management of the CI system and related decision making. CI enables society to carry out day-to-day activities that support the production and transmission of electricity, natural gas and oil and includes telecommunications (information and communications), transportation, water supply systems, banking, and finance (Serre & Heinzlef, 2018). Providing CI makes the society and the state safe and resilient. Currently, a large number of quantitative methods have been developed to help solve problems in all areas of life and work. These are first of all mathematical optimization methods, especially multi-criteria methods, suitable for solving problems when viewed from multiple aspects - criteria based on which decisions are made (Jamwal et al, 2021).

The aim of this work is to determine the interdependence of CIs and to improve the strategic framework for evaluating the overall challenges, risks, and threats in Strategic National Security Management (SNSM). The paper proposes an integrated method that combines DEMATEL, ANP, and fuzzy logic – the method evaluates the perspective of experts in evaluating interdependence and determining the potential importance of CI.

Description of the problem and the contribution

In the previous two decades, in the academic and practical discourse, there was a greater focus on the concept of CI resistance, rather than on the concept of protection. According to the above, the analysis focuses on the shortcomings of classic risk management based on quantitative assessments and crisis management principles. The disaster in Fukushima in 2011 focused analysis on the phenomena of interdependence, cascading effects and simultaneous crises. The interdependence of CIs is defined by the impact of failure or destabilization of one CI (sector) on other infrastructures. (Keković & Ninković, 2021)

Figure 1 shows an example of interdependence, the importance of CIs and the cascading effect of addictive disorders (Luiijf, et al, 2016). The interdependence of CIs can be more closely described by the impact of disruption or damage of one CI (sector, sub-sector) on other infrastructures. Therefore, CI systems necessary to meet the needs of society represent another challenge for evaluating the interdependence and potential importance of CIs. It can be stated that this complexity and infrastructural interdependencies bring increasing uncertainty, and this implies a shift in security trends from an approach focused on individual risk factors, through an all-hazards approach, all the way to an approach oriented towards system resistance, i.e. strategy for confronting and managing systemic challenges, risks and threats. Therefore, the aim of the paper is to find an adequate strategy to minimize the challenges, risks and threats to CIs, in order to propose a method for their evaluation with the participation of experts. In this paper, we seek answers to the following questions: (1) Do the preferences of experts affect the ranking of sectors and sub-sectors? (2) What would be the result of applying the fuzzy DEMATEL-ANP method for the analysis of interrelationships in sectors and sub-sectors of CIs?

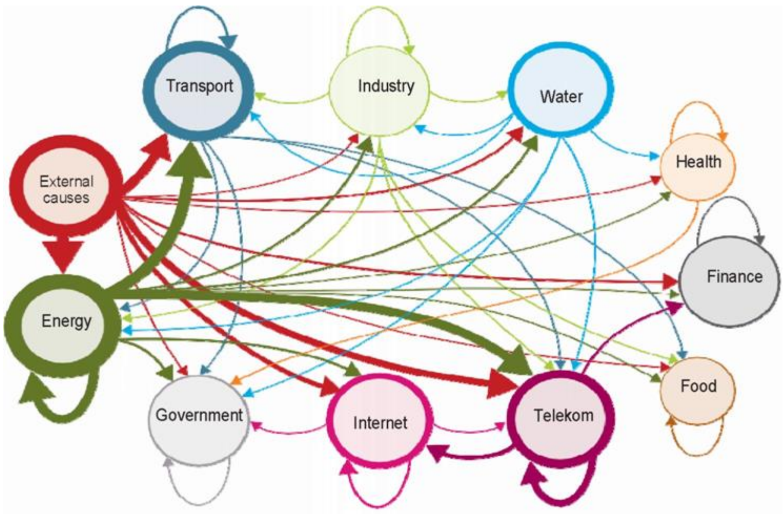


Figure 1 – An example of the interdependence and the cascading effect of addictive disorders

The contribution of this study is two-fold. Firstly, in conventional methods for interdependence and significance analysis where expert opinions are missing as input data. Some authors have noted that numerous analytical methods developed in earlier studies mainly focus on decision making by a single decision maker (Laugé et al, 2015). Individual evaluation and ranking of alternatives are the key aspects of decision making; therefore, they must be considered as part of a group decision-making process in order to generate objective and reliable multi-expert decisions (Deng & Jiang, 2019). Experts' subjectivity significantly affects the order of alternatives, i.e., the decision-making process, and therefore needs to be taken into account (Trivedi, 2018). Accordingly, the purpose of our research is to propose a procedure for interdependence and significance analysis that is suitable for CIs. Secondly, this study explores the prioritization of the interdependencies of critical sectors and sub-sectors necessary in the SNSM process. In this sense, DEMATEL is used to construct the interrelationships between influencing factors in an integrated model. This method tests the relative strength between influencing factors. The ANP technique used to define the relative importance of influencing factors is also presented. This method is used to weight and prioritize critical impact factors between sectors and sub-sectors.

Literature review

The complexity and uncertainty of infrastructural interdependence causes a shift in protection trends from an approach focused on individual threats, through an all-hazards approach, to an approach oriented toward system resilience, i.e., strategies for dealing with and managing systemic risks and uncertainties. (Tomalska, 2023)

In her study, this author emphasizes the need to understand the concept of CI vulnerability in terms of system attributes, not deficiencies. Ninkovic (Ninković Vladimir) states in his hypothesis that: "...the sources of strategic risks can be identified in natural disasters caused by climate change, challenges of global networks (primarily in the digital sphere) and interdependencies of CIs, and not in isolated attacks of terrorist or criminal groups". (Ninković, 2021, p.1206)

It is precisely this uncertainty, carried by the interdependence of CIs, which is the imperative of our research for the application of mathematical optimization.

Various models and methods have been used to evaluate and analyze the interdependence of CIs. In their paper, Lin and Pan presented a CI interdependence model based on Leontief's (Wassily Leontief) input-output model for the simulation and analysis of CI interdependence, which can input real data from real public open source data (Lin & Pan, 2022). Rinaldi proposed a model for characterizing and evaluating the interdependencies of CI systems that includes the use of sector-specific designs, for example, gas pipelines, electricity networks or ICT. (Rinaldi, 2004)

To analyze infrastructure interdependence in the Netherlands which is relevant due to its high rate of urbanization and innovative development, the group of authors used a multi-mode relationship framework to identify the interrelationships between infrastructure systems. (Gürsan et al, 2023)

They recognized seven types of interdependence of socio-technical infrastructure which can influence change in urban sustainability: functional, evolutionary, spatial, life cycle interdependence, policy/procedural, market, and culture/norm. The authors Huang et al.

(2014) proposed an integrated method consisting of: Decision Making Testing and Evaluation Laboratory (DEMATEL) and Analytical Network Process (ANP) for the analysis of CI interdependencies that takes into account the feedback effects between different CIs (Trivedi, 2018). The study Kasmi et al. (2021) presents the fuzzy logic-based clustering algorithm to better identify and analyze the overall interdependencies between entities in CIs. ANP and DEMATEL were used to find interdependencies between components in an urban area. (Sarmadia & Aghababaei, 2023)

Modeling hybrid methods for evaluating the interdependence and significance of CIs is of essential importance in order to respond to the challenges in creating a strategy for the CI management. Therefore, a quantitative model is necessary for determining interdependence and identifying the priority CI system based on the perception of each expert. The neutralization of subjectivity in expert statements in (Pamučar et al, 2019) was performed by applying interval rough numbers using only internal knowledge from the data. In the study, they showed that the limits of the interval do not depend on subjective assessment, but are defined based on the imprecision of the data. According to (Fazli et al, 2015), the combination of DEMATEL and ANP is the best model for risk reduction due to the fact that DEMATEL can display complex interrelationships between criteria. Therefore, we can say that DEMATEL-ANP is an effective method that helps managers to choose the best strategies in order to effectively respond to overall challenges, risks and threats.

General model description

A hybrid method that integrates fuzzy logic, DEMATEL and ANP is called FDEMANP, Figure 2. Fuzzy set theory is usually combined with other theories to derive new theories. (Deng & Jiang, 2019; Pribićević et al, 2020)

Another important contribution of fuzzy set theory is that it provides a systematic procedure for transforming a knowledge base into a non-linear mapping. In contrast to conventional logic, in fuzzy logic the belonging of one element to a specific set is not precisely defined, which is why it is very close to human perception. It uses the experience of a human expert in the form of linguistic "If-Then" rules, and the mechanism of approximate reasoning calculates the degree of direct influence. In this paper, the algorithm of approximate reasoning will be used to show the degree of direct influence of each criterion (sub-sector) in order to obtain the interdependence and importance of sectors and sub-sectors.

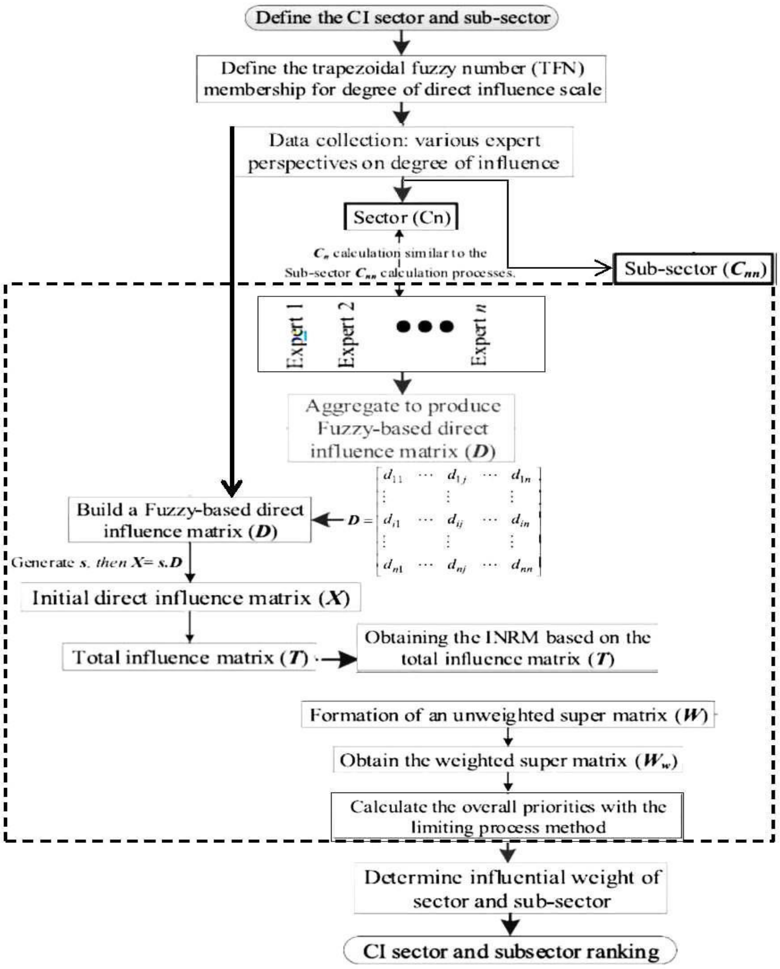


Figure 2 – Hybrid method FDEMANP

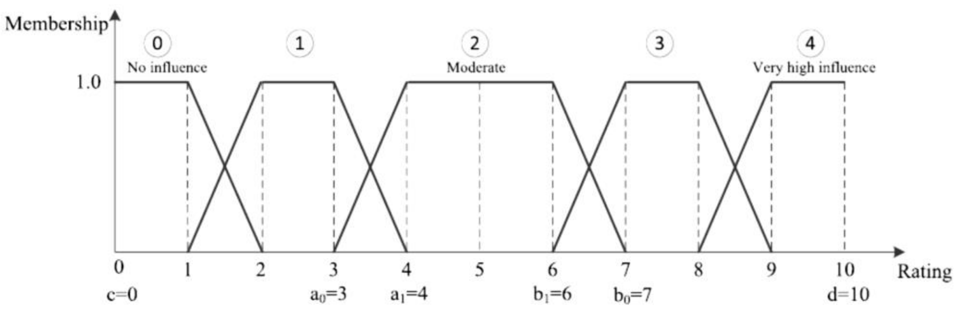


Figure 3 – Five-point Likert scale

Therefore, the arguments for the application of fuzzy logic are: 1. It considers the subjectivity of perception and uncertainty, allowing the use of expert ratings and fuzzy indicators, respectively. 2. It processes and generates qualitative and quantitative evaluations with immediate and easy transitions between them. To this end, it introduces/uses linguistic and quantitative variables, scales and logical rules. 3. It enables thinking about processes, connections and interactions between its sub-sectors. 4. There are no strict methodological requirements for its implementation. 5. The simplicity in its use enables quick and easy change of logical rules and scales.

Table 1 – TFN determined for the degree of influence

Influence rating	**Likert scale**	**TFN**
Very high influence	4	(8,9,10,10)
High influence	3	(6,7,8,9)
Moderate	2	(3,4,6,7)
Low influence	1	(1,2,3,4)
No influence	0	(0,0,1,2)

In the decision-making process, the fuzzy technique is used to transform rational (crisp) numbers into fuzzy numbers that, with the help of the membership function, show the degree of belonging of the elements to a given set. According to (Zadeh, 1965), linguistic expressions (linguistic variables) can be very successfully used for quantification of uncertainty in complex and uncertain situations (Božanić et al, 2015). According to this, before the first step, the Likert scale and the membership functions of the Trapezoidal Fuzzy Number (TFN) should be defined for the degree of direct influence, Figure 3. For this study, we took the Likert scale from 0 to 4, which means "no impact" to "very big impact", i.e., five TFNs, Table 1. The reason why we took a five-point scale is that the ANP analysis is based on the DEMATEL technique, which usually uses a scale of 0–4 (Pamučar et al, 2017). The contribution of this fuzzy Likert approach is in the precision of the measurement, as it allows the points of the scale to be stacked, thus regulating the imprecise information in the statements given by experts.

After the preliminary steps, the collected data can be imported to obtain expert observations on the degree of impact. In his research, Hu (Hu et al, 2009) determined that for the DEMATEL technique, the optimal number of respondents is in the range of three to nine.

A concise mathematical representation of the FDEMANP method is presented in Figure 4:

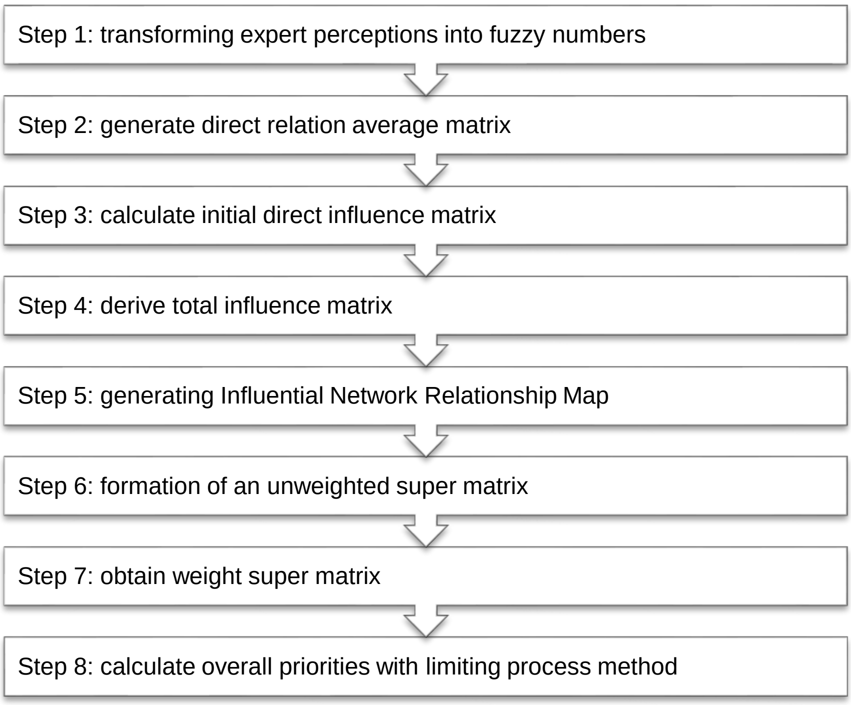


Figure 4 – Presentation of the steps of applying the FDEMANP method

The proposed method

The limitation of prediction and prevention of the occurrence of all BIRPs - the CI protection strategy requires adaptation based on the identification of the root causes of vulnerability related to the functioning of CIs. (Tomalska, 2023)

Confirmation and justification of the application of the hybrid method of FDEMANP - this section shows its application on the example of critical resources of the Republic of Serbia. Before applying the hybrid method, it is necessary to define the CI sectors and sub-sectors, which will be the boundary of the problem analysis, shown in Table 2 (Službeni glasnik Republike Srbije, 87/2018).

In the work, we limited ourselves to 4 sectors due to a simple presentation of the model, compared to 8 identified in the Official Gazette. For each sector, there are identified sub-sectors that are of vital importance for the sustainability of the economy and society as a whole.

Table 2 – Defined sectors and sub-sectors of critical infrastructure

Sector	Sub-sector	Description of the criteria
Energy (C1)	Electricity (C_{11})	Electricity infrastructure (power plants, transmission systems, control stations)
	Oil (C_{12})	Oil infrastructure (storage, processing systems, control stations, pumps, and pipelines)
	Natural gas (C_{13})	Gas infrastructure (storage, control stations, pumps and pipelines)
Water (C2)	Watersheds (C_{21})	Watersheds and upstream areas of major rivers
	Dams (C_{22})	Reservoirs, pipelines and pumping stations
	Water treatment (C_{23})	Water treatment plants, pipelines and pumping stations
	Water supply (C_{24})	Service piping systems and control centers
IKT (C3)	Information (C_{31})	Software, hardware, cyber-security and Internet
	Telecommunication (C_{32})	Infrastructure for telecommunications (stations and broadcasting equipment)
Transportation (C4)	Ground (C_{41})	Road and rail infrastructure used for transport, tunnels and bridges
	River (C_{42})	Infrastructure for ship traffic (ports and facilities)
	Aviation (C_{43})	Airports, air traffic control centers, control towers
	Postal services and logistics (C_{44})	Major distribution centers and related facilities

Nine experts from different areas were interviewed: three experts from the transport sector, two experts from the energy sector, one expert from the water sector, and three experts from the telecommunications sector. These experts have a minimum of 10 years of experience in infrastructure planning and management in the mentioned areas.

Step 1. The function of linguistic affiliation, which will be used to quantify the direct influence of the criteria of critical resources, is formed based on the statement of experts, by which they proposed the degree of direct influence of each criterion (sub-sector) *i* on each criterion *j*, marked as d_{ij}.

After the collected expert statements, the base of fuzzy rules for DEMANP is formed by quantification through the five-point Likert scale (Figure 3) using a linguistic term (Table 1). Defuzzification of attachment functions is performed in order to obtain a crisp numerical form of the fuzzy set based on the formula:

$$F(d_{ij}) = \frac{[b_0 - c] + [b_1 - c]}{\{[b_0 - c] + [b_1 - c]\} - \{[a_0 - d] + [a_1 - d]\}} \quad (1)$$

In defuzzification, c has the same value for all linguistic concepts. The membership function has a value of zero for the values a_0 and b_0 at the extreme limits of each linguistic term, while it has a maximum value when the membership function is one for the values a_1 and b_1. In the second step, in order to generate a matrix of direct relations for each expert's statement, the mean value of expert statements D is calculated (Table 3):

$$D = \begin{bmatrix} d_{11} & \cdots & d_{1j} & \cdots & d_{1n} \\ \vdots & & \vdots & & \vdots \\ d_{i1} & \cdots & d_{ij} & \cdots & d_{in} \\ \vdots & & \vdots & & \vdots \\ d_{n1} & \cdots & d_{nj} & \cdots & d_{nn} \end{bmatrix} \quad (2)$$

Using equations (3) and (4), the initial direct influence matrix (Table 4) is obtained by normalizing the average matrix D.

$$X = s * D \quad (3)$$

$$s = min\left[1/\max_i \sum_{j=1}^{n} \left| d_{ij} \right|, 1/\max_j \sum_{i=1}^{n} \left| d_{ij} \right| \right] \quad (4)$$

By carrying out the listed steps in order, the weight value of the impact of each CI sector is obtained from the total impact matrix, followed by the unweighted supermatrix. Applying mathematical expressions, a weighted supermatrix is obtained, generated from FDEMANP, which includes different degrees of influence among infrastructure sectors.

Finally, the value of each sector or sub-sector is obtained by calculating the boundary matrix of the supermatrix through the use of the ANP procedure. According to the final results, "traffic" has the highest impact weight value among sectors, while "information" within the sub-sector has the highest weight value.

Table 3 – Initial decision matrix

	E1										
	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}		C_{32}	C_{41}	C_{42}	C_{43}	C_{44}
C_{11}	(0;0)	(3;4)	(3;3)	(2;3)	(2;3)	...	(2;3)	(2;5)	(1;1)	(4;4)	(4;4)
C_{12}	(3;4)	(0;0)	(3;5)	(1;5)	(2;3)		(3;3)	(3;5)	(2;3)	(4;4)	(4;4)
C_{13}	(3;4)	(3;5)	(0;0)	(4;5)	(3;4)		(3;3)	(3;5)	(2;5)	(4;5)	(4;4)
C_{21}	(3;4)	(4;4)	(4;4)	(0;0)	(2;3)		(3;4)	(4;5)	(3;4)	(3;4)	(5;5)
……											
C_{41}	(3;3)	(2;3)	(4;5)	(1;5)	(2;2)		(2;3)	(0;0)	(2;2)	(3;5)	(3;3)
C_{42}	(4;4)	(2;3)	(2;5)	(5;5)	(1;1)		(2;3)	(2;3)	(0;0)	(3;4)	(3;4)
C_{43}	(2;2)	(1;5)	(2;3)	(2;5)	(1;1)		(3;5)	(2;5)	(1;2)	(0;0)	(5;5)
C_{44}	(3;3)	(2;5)	(1;3)	(2;3)	(4;5)		(3;3)	(3;5)	(4;5)	(4;4)	(0;0)
...											
	E9										
	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}		C_{32}	C_{41}	C_{42}	C_{43}	C_{44}
C_{11}	(0;0)	(2;5)	(2;5)	(1;5)	(1;5)	...	(1;5)	(1;4)	(2;2)	(3;4)	(3;3)
C_{12}	(2;4)	(0;0)	(3;4)	(1;4)	(1;5)		(2;4)	(2;4)	(2;2)	(3;5)	(3;5)
C_{13}	(1;4)	(3;3)	(0;0)	(3;4)	(3;5)		(2;4)	(2;3)	(3;4)	(4;4)	(3;5)
C_{21}	(2;4)	(4;4)	(4;4)	(0;0)	(2;5)		(4;4)	(4;4)	(2;5)	(2;5)	(4;5)
……											
C_{41}	(1;3)	(1;2)	(4;4)	(1;4)	(2;4)		(1;4)	(0;0)	(3;3)	(2;3)	(4;5)
C_{42}	(3;5)	(1;2)	(1;4)	(4;4)	(1;3)		(1;5)	(1;4)	(0;0)	(4;4)	(4;4)
C_{43}	(1;2)	(1;3)	(1;4)	(1;4)	(1;3)		(4;5)	(1;4)	(2;2)	(0;0)	(3;3)
C_{44}	(1;2)	(2;4)	(1;4)	(1;4)	(4;4)		(5;5)	(4;5)	(3;4)	(4;5)	(0;0)

Table 4 – Initial matrix of direct influence

D	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{41}	C_{42}	C_{43}	C_{44}
C_{11}	0.000	2.283	2.513	1.744	1.831	3.056	2.556	3.722	3.889	3.611	3.556	3.056	2.667
C_{12}	3.999	0.000	1.828	0.621	0.536	0.536	0.687	0.839	0.839	3.854	3.988	3.856	4.111
C_{13}	3.344	1.234	0.000	0.317	0.456	0.415	0.489	0.687	0.741	1.729	1.811	1.815	1.358
C_{21}	2.281	0.833	0.556	0.000	3.722	3.056	3.000	1.231	1.231	0.844	0.628	1.231	0.727
C_{22}	2.737	0.511	0.454	3.238	0.000	2.299	2.632	0.833	0.833	0.388	0.443	0.434	0.332
C_{23}	1.443	0.668	0.566	2.168	2.112	0.000	3.000	0.834	0.763	0.387	0.622	0.342	0.546
C_{24}	1.510	0.933	0.888	2.334	2.055	2.622	0.000	0.953	0.722	0.613	0.386	0.386	0.613
C_{31}	2.415	1.456	1.434	0.911	1.232	1.787	1.567	0.000	3.388	1.776	1.944	1.777	1.723
C_{32}	2.334	1.445	1.168	0.776	1.168	1.277	1.223	3.343	0.000	2.712	3.268	3.165	2.502
C_{41}	1.389	2.333	2.111	0.500	0.444	0.667	0.833	0.722	0.889	0.000	2.056	2.278	3.343
C_{42}	1.000	1.722	1.333	0.325	0.556	0.611	0.389	1.212	1.056	2.056	0.000	2.345	3.389
C_{43}	1.135	3.664	3.132	0.634	0.543	0.778	0.556	0.889	0.889	2.056	2.000	0.000	3.121
C_{44}	0.650	0.989	0.528	0.671	0.646	0.430	0.341	0.978	0.936	1.576	1.549	1.569	0.000

Discussion of the obtained results

Table 5 shows the values obtained using the DEMANP method and FDEMANP with multiple experts for decision making. Tables 5 a) and b) show the effect of the interdependence values of CI sectors, where small changes in values can be seen, and the most significant thing is that all CI sectors have negative values (di-ri). The negative (di-ri) values of the CI sector in both cases indicate that all four sectors mutually influence each other and are mutually dependent on each other.

According to the results using the FDEMANP method, two sub-sectors (Water supply C_{21} and road transport C_{41}) have different impact values. Regarding the analysis of the CI sub-sector, both analytical methods have similar values (di-ri). Interestingly, the two sub-sectors (C_{21} and C_{41}) have different patterns of (di-ri) outcomes. According to the DEMANP methodology, the C_{21} sub-sector has a negative (di-ri) value, which shows that it is influenced by other sub-sectors.

Table 5 – Sums of influences on, and exerted by, CI sector and sub-sectors
a) Conventional method (DEMANP)

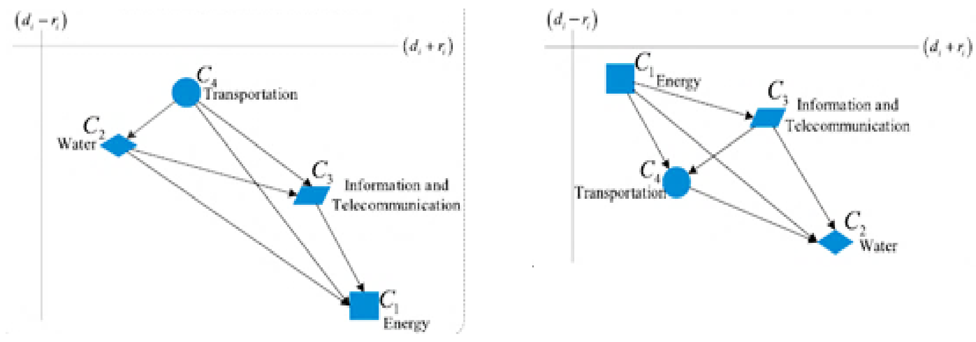
Sect.	r_i	d_i	d_i+r_i	d_i-r_i	Sub-sec.	r_i	d_i	d_i+r_i	d_i-r_i
C1	21.640	9.361	30.971	-12.288	(C_{11})	6.272	6.176	12.438	-0.126
					(C_{12})	5.853	7.485	13.358	1.653
					(C_{13})	6.988	6.689	13.687	-0.270
C2	19.083	9.078	28.171	-10.015	(C_{21})	6.633	6.516	13.129	-0.126
					(C_{22})	6.342	6.272	12.573	-0.037
					(C_{23})	7.314	6.785	14.108	-0.528
					(C_{24})	6.963	6.986	13.948	0.037
C3	20.963	9.644	30.587	-11.368	(C_{31})	6.923	7.474	14.387	0.562
					(C_{32})	7.141	6.872	13.983	-0.259
C4	18.680	10.147	28.827	-8.553	(C_{41})	5.508	5.625	11.143	0.148
					(C_{42})	5.743	5.793	11.526	0.059
					(C_{43})	6.664	5.910	12.574	-0.755
					(C_{44})	6.265	5.916	12.180	-0.349

b) Proposed method (FDEMANP)

Sect.	r_i	d_i	d_i+r_i	d_i-r_i	Sub-sect.	ri	di	di+ri	di-ri
C1	12.345	6.903	19.248	-5.442	(C_{11})	6.972	6.862	13.854	-0.080
					(C_{12})	6.331	7.728	14.029	1.387
					(C_{13})	7.534	7.163	14.687	-0.381
C2	16.255	7.335	23.580	-8.930	(C_{21})	7.167	7.389	14.516	0.243
					(C_{22})	6.823	6.662	13.426	-0.152
					(C_{23})	7.615	7.197	14.783	-0.427
					(C_{24})	7.467	7.477	14.943	0.043
C3	15.339	7.254	22.524	-8.145	(C_{31})	7.377	7.973	15.339	0.653
					(C_{32})	7.445	7.053	14.466	-0.323
C4	15.057	6.052	21.148	-9.032	(C_{41})	6.155	6.115	12.242	-0.035
					(C_{42})	6.529	6.738	13.228	0.189
					(C_{43})	7.264	6.530	13.784	-0.764
					(C_{44})	6.958	6.639	13.627	-0.289

However, the FDEMANP methodology gives a positive value (di-ri) for C_{21}, indicating that the sub-sector influences the others. Thus, both methods exhibit distinct differences (di-ri) C_{41}. Also, according to the DEMANP calculation, C_{41} has an impact on other CI sub-sectors, while according to FDEMANP, C_{41} is a sub-sector that is affected by other CI sub-sectors. The relations between sectors and sub-sectors, i.e., the network of influence can be visually displayed by data mapping (di+ri, di-ri). Mapping is done to create a cause and effect relationship diagram (CERD) of four sectors, as presented in Figures 5 (a) and (b), respectively. A diagram is created to visually represent complex relationships in order to conclude which sectors/sub-sectors are most important and how they influence each other.

The arrows show the directions of influence. In Figures 5 (a) and (b), sectors with positive net impacts are grouped as causes while those with negative net impacts are grouped as effects. Using the FDEMANP method, the obtained calculation and display results on the CERD show different mutual influence values compared to those generated by the conventional DEMANP method. Accordingly, it can be concluded that C_{21} is a sub-sector of CI that affects other sub-sectors while C_{41} is a sub-sector that is influenced by other sub-sectors (negative value (di-ri)).



(a) *(b)*

Figure 5 – CERD generated using DEMANP and FDEMANP

Table 6 – Influential weights of sectors and sub-sectors - comparision between DEMANP (DA) and FDEMANP (FDA)

Sector	Local weight		Ranking		Order	Sub-sector	Local weight		Ranking		Order
	DA	FDA	DA	FDA			DA	FDA	DA	FDA	
Energy (C1)	0.247	0.207	3	4	▼	(C_{11})	0.076	0.062	8	12	▼
						(C_{12})	0.067	0.059	11	13	▼
						(C_{13})	0.083	0.067	7	9	▼
Water (C2)	0.281	0.277	1	1	●	(C_{21})	0.066	0.065	12	10	▲
						(C_{22})	0.062	0.062	13	11	▲
						(C_{23})	0.071	0.070	9	7	▲
						(C_{24})	0.069	0.068	10	8	▲
IKT (C3)	0.256	0.262	2	2	●	(C_{31})	0.118	0.120	2	2	●
						(C_{32})	0.120	0.123	1	1	●
Transport. (C4)	0.218	0.256	4	3	▲	(C_{41})	0.083	0.104	6	6	●
						(C_{42})	0.089	0.106	5	5	●
						(C_{43})	0.106	0.119	3	3	●
						(C_{44})	0.095	0.115	4	4	●

▲ *and* ▼ *indicate a change in rank order (increasing and decreasing, respectively);*
● *indicates no change in rank order.*

The limit matrix of the supermatrix is calculated in the same way as for the ANP procedure to obtain the final priorities of each sector/sub-sector of CI. Table 6 presents the absolute local weight and ranking of individual CI sectors and sub-sectors based on their influential weight values, obtained using both DEMANP and FDEMANP. Using the

DEMANP method, we obtained that the sector C2 is "water" CI which has the highest weight value; this result can be understood according to the display on CERD; based on the weight coefficient, information and telecommunications – C3 follow, then energy – C1 and transport - C4 which has the least weight. According to the FDEMANP hybrid method, the ranking of CI sector weight values is as follows: water - C2, information-telecommunications - C3, transport - C4 and energy - C1. The FDEMANP analysis at the CI sub-sector level revealed that ICT telecommunications C_{32} and information C_{31} have the highest impact weights. This result is expected, accordingly Information and telecommunications play a key role in critical infrastructures, as almost every sector or sub-sector is controlled by ICT and network systems in today's "networked society". The failure of the ICT system could not only affect banking, finance, and transport, but also energy and water distribution systems. This is then followed by aviation C_{43}, postal services and logistics C_{44}, river C_{42}, land C_{41}, etc. From Table 6, we can conclude that the ranking of all sub-sectors of the CI infrastructure sectors C1 and C2 has changed significantly compared to the results obtained by the DEMANP method. Accordingly, this would be the answer to the first question, that the change in rank is influenced by the input data which includes the preferences of experts and which is processed using various quantitative methods integrated into our analysis model.

The answer to the second question (What is the result of the application of the proposed method?) would be that, compared to other methodologies (for example, Monte Carlo simulation or network theory), the proposed hybrid method FDEMATEL provides an easy and fast way to evaluate the interdependence and importance of CIs with expert preferences. The advantage of this method is that it gives the possibility of CERD display of complex interdependencies between sectors and sub-sectors without the use of software tools and time-consuming data collection.

Conclusions

The term "Networked Society" points out the vulnerability of modern society and the fact that the interdependence of critical resources brings increasing uncertainty. This kind of society requires a change in the protection process, from one aimed at individual challenges, risks and threats, to a process aimed at the resilience of the state, i.e. strategies for dealing with and managing systemic risks and uncertainties.

Appreciation of uncertainty at the strategic level of management is a very important aspect for objective and unbiased multi-criteria decision making. Difficulties often arise in presenting data on decision attributes through exact (precise) numerical values. The aforementioned aggravating circumstances are caused by doubts when making decisions, as well as by the complexity and vagueness of numerous realistic indicators. This paper presents a successful modification of the DEMANP method with the theory of fuzzy sets, on the example of the evaluation of interdependence and CI priorities within the process of Strategic National Security Management.

The result of the applied hybrid FDEMANP method is a confirmation that, in terms of the complex interdependence of CIs, all CI sectors are simultaneously affected by other CI sectors and sub-sectors. By introducing the statements of numerous experts into the calculation in the decision-making process, the FDEMANP method represents a very suitable tool for considering uncertainty when making key decisions. The presented hybrid method showed superiority in dealing with uncertainty in the sense of ambiguity, subjectivity, imprecision and vagueness, when the input data relies exclusively on the statements of experts.

The paper confirmed that connecting different quantitative methods into a unique model of evaluation of input data processed in order to process different statements of experts significantly affects the change in rank. The analyzes also showed that the hybrid method of FDEMANP can be used to evaluate the causes and consequences of interdependence and importance of CI sectors and sub-sectors.

Therefore, by applying the hybrid method of FDEMANP, the Strategic Management of National Security can be improved by making development planners and CI operators understand how the disruption of one part of the CI system prevents the delivery of gas, water, electricity, information, etc., which has an impact on the stability of other CI systems.

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Aplicación de la optimización matemática en la toma de decisiones relevantes para la resiliencia de la seguridad nacional: la sociedad en red como base de la interdependencia de recursos críticos

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CAMPO: matemáticas aplicadas, ciencias militares
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: La desestabilización de recursos críticos (RC) o infraestructura crítica (IC) importantes para la estabilidad del estado puede ser peligrosa para la sociedad, la economía y especialmente la seguridad nacional. La interrupción de un objeto de IC o de una de sus partes a menudo afecta y causa la interrupción de otros IC dependientes, porque la sociedad moderna se ha convertido en una "sociedad en red". El artículo propone un modelo para cuantificar y definir la interdependencia entre diferentes IC y sus prioridades, basado en declaraciones de expertos.

Métodos: Los métodos propuestos que combinan el Laboratorio de Ensayo y Evaluación de la Toma de Decisiones (DEMATEL-por sus siglas en inglés) y el Proceso Analítico de Redes (ANP- por sus siglas en inglés) han sido modificados exitosamente mediante la teoría de la lógica difusa en este trabajo.

Resultados: La integración de múltiples métodos en un modelo único de análisis de datos de entrada afecta significativamente el cambio en la clasificación.

Conclusión: El trabajo contribuye a la ciencia militar en la toma de decisiones estratégicas relacionadas con la gestión de la seguridad nacional mediante el aumento de la resiliencia de los RC y las sociedades que dependen de ellos.

Palabras claves: lógica difusa, DEMATEL, ANP, MCDM, recursos, seguridad nacional.

Применение математической оптимизации при принятии решений об устойчивости национальной безопасности: сетевое общество как основа взаимозависимости критических ресурсов

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РУБРИКА ГРНТИ: 27.47.19 Исследование операций,
28.17.31 Моделирование процессов управления,
78.21.49 Военная электроника и кибернетика

ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Дестабилизация таких важных факторов стабильности государства, как критические ресурсы (КР) и критическая инфраструктура (КИ) представляет опасность для общества, экономики и особенно для национальной безопасности. Разрушение одного объекта КИ или одной из его частей зачастую влияет на другие зависимые КИ и вызывает их разрушение, поскольку современное общество стало «сетевым обществом». В данной статье представлена модель для количественной оценки и определения взаимозависимости между различными КИ и их приоритетами, основанная на мнении экспертов.

Методы: В данном исследовании применялось сочетание метода пробно-оценочной лаборатории для принятия решений (DEMATEL) с методом аналитического сетевого процесса (ANP), которые были успешно модифицированы теорией нечеткой логики.

Результаты: Интеграция нескольких методов в единую модель анализа входных данных существенно влияет на изменение ранжирования.

Выводы: Данное исследование вносит вклад в военную науку, в частности, в области принятия стратегических решений, связанных с управлением национальной безопасностью, за счет повышения устойчивости КР и обществ, которые на них полагаются.

Ключевые слова: нечеткая логика, DEMATEL, ANP, MCDM, ресурсы, национальная безопасность.

Примена математичке оптимизације у одлучивању значајна за отпорност националне безбедности: умрежено друштво као основ међузависности критичних ресурса

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ОБЛАСТ: математика, војне науке
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Дестабилизација критичних ресурса (КР) или критичне инфраструктуре (КИ) важне за стабилност државе може бити опасна по друштво, економију, а посебно националну безбедност. Поремећај једног објекта КИ, или једног његовог дела, често утиче и изазива поремећај других зависних КИ, јер смо постали „умрежено друштво". У раду је предложен модел за квантификовање и дефинисање међузависности између различитих КИ и њихових приоритета, на основу исказа стручњака.

Методе: Предложене методе које комбинују Лабораторију за тестирање и евалуацију одлучивања (DEMATEL) и аналитички мрежни процес (ANP) успешно су модификоване теоријом fuzzy логике.

Резултати: Интегрисање више метода у јединствени модел анализе улазних података значајно утиче на промену рангирања.

Закључак: Рад доприноси војној науци у доношењу стратешких одлука у вези са управљањем националном безбедношћу, кроз повећање отпорности КР и друштва које се на њих ослања.

Кључне речи: fuzzy логика, DEMATEL, ANP, MCDM, ресурси, национална безбедност.

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