УДК 504.064:629.039.58 doi.org/10.31717/2311-8253.25.2.1

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Assessment of Safety Factor Criteria when Selecting Sites for Nuclear Power Plant Construction Based on Fuzzy Expert Evaluation

Keywords:
safety factor,
nuclear power plant sites,
radiation and nuclear facilities,
fuzzy logic mathematical model,
fuzzy importance coefficients,
weights of criteria,
probabilities of criteria influence,
levels of criteria influence,
Wilson Matrix,
optimal decision-making

The article presents further development of the previously developed methodology for strategic analysis of the process of selecting sites for the construction of nuclear power plants using fuzzy logic methods. The development of the research is based on the analysis of the safety factor and its criteria. The object of the study is the process of analyzing potential sites for the construction of radiation and nuclear facilities. The subject of the study is a comparative analysis of potential sites based on a comprehensive assessment of safety factor criteria. The goal is to compare potential sites based on an assessment of the safety factor and its criteria. The assessment is carried out using a model developed in previous studies based on fuzzy logic methods. The objective of the study is achieved through fuzzy expert assessment based on developed expert forms, methodological approaches, and a mathematical model. The selection of input data for the implementation of the model was carried out taking into account practical recommendations and safety documents from the IAEA and national regulators of leading countries in the field of nuclear safety. The consistent use of the fuzzy analytical hierarchy process (AHP), the center of area (CoA) method, and fuzzy simple additive weighting (SAW) allows for a qualitative and reliable expert assessment, minimizing the influence of subjective expert judgments. As a result of implementing the model when comparing sites for the construction of new AP1000 reactors, the following results were obtained: fuzzy importance coefficients and relative weights of safety factor criteria for all sites were determined; the probability of the impact of criteria for each site was assessed; fuzzy estimates of the level of impact of safety criteria for each site were determined. Based on the results obtained and their visualization using the Wilson Matrix, the Khmelnytskyi NPP site was selected as the optimal one in terms of safety. The application of the proposed methodological approach made it possible to draw reasonable conclusions about the impact of safety factor criteria on the preparation and adoption of strategic decisions regarding the selection of the optimal location for the construction of radiation and nuclear facilities.

Introduction

Until today, all NPPs in Ukraine have been constructed using Soviet technologies and designs. However, given Russia's aggression against Ukraine and the impossibility of further cooperation with the aggressor state, the issue has arisen of introducing new technologies in nuclear energy for Ukraine that may be offered by foreign partners. In particular, in 2021, a Memorandum of Understanding was signed between Energoatom and

Westinghouse Electric Company [1]. It implies the participation of Westinghouse Electric Company in completing the construction of Unit 4 of the Khmelnytskyi NPP using AP1000 technology, as well as four additional units at other Ukrainian NPPs. The use of new technical solutions must be accompanied by ensuring a high level of radiation safety, which requires improving approaches to the safety justification of personnel, the public, and the environment. This is due to the fact that radiation impacts may differ as a result of using new construction and operation technologies compared to those previously applied. Moreover, the construction of NPP units in Ukraine with reactor installations produced by Westinghouse Electric Company requires additional substantiation of their environmental impact, taking into account the specific physical–geographical, ecological, and climatic conditions of the areas where the planned NPPs are to be located.

The process of selecting a site suitable for NPP construction is a multifaceted one that includes ensuring safety. From the very beginning, this process should be guided by a clearly defined set of criteria established by regulatory and technical documents. Such criteria are of particular importance for factors that may lead to site exclusion. It is necessary to establish a balance between site characteristics and specific design features, protective measures, and administrative procedures. One of the groups of such criteria is the safety factor criterion. Its analysis is a logical continuation of the implementation of a methodological approach to analyzing the process of selecting optimal NPP construction sites based on fuzzy logic methods [2]. The defined list of safety factor criteria corresponds to both the approaches of the International Atomic Energy Agency (IAEA) [3] to NPP site safety assessment and international practice in this field, as well as to the requirements of national legislation.

The object of the study is the process of system analysis of potential sites for the placement of radiation-nuclear facilities [4]. The subject of the study is the comparative analysis of potential sites based on a comprehensive assessment of safety factor criteria. The aim is to compare sites based on the evaluation of safety factor criteria obtained using the developed model based on fuzzy logic methods [2].

The relevance of the study is determined by the systemic nature of assessing the influence of environmental characteristics on the site selection process, which includes, as one of its key components, the safety factor. This approach enables the decision-maker (DM), in addition to a generalized assessment of environmental influence, to make an optimal choice based on a detailed representation of the safety factor criteria.

The implementation of the research goal is carried out through fuzzy expert evaluation based on developed forms, methodological approaches, and a mathematical model built on the theory of fuzzy sets presented in [2]. The expert evaluation involved a sufficient number of qualified specialists in the fields of nuclear and radiation safety and ecology, determined using mathematical statistics methods [5]. The use of the developed mathematical model, which combines fuzzy logic methods, makes it possible to minimize uncertainties and subjectivity in expert assessments. The results obtained through the implementation of the proposed methodological approach and mathematical model provide DM with the ability to apply various selection strategies and improve the quality of evaluation and decision-making regarding NPP site placement.

Safety Factor in the Analysis of NPP Site Selection Process

When selecting a site for NPP construction, as a radiation-nuclear facility of increased hazard, the fundamental safety objective is the protection of people and the environment against the harmful effects of ionizing radiation [6, 7].

The requirements for site selection are established by legislative and regulatory acts of Ukraine. The procedure for decision-making and the requirements for documents justifying the admissibility of constructing nuclear installations are defined in Article 37 of the Law of Ukraine "On the Use of Nuclear Energy and Radiation Safety" and the Law of Ukraine "On the Procedure for Decision-Making on Siting, Design, and Construction of Nuclear Installations and Facilities Intended for Radioactive Waste Management of National Importance." Furthermore, in 2008, the State Nuclear Regulatory Inspectorate approved the regulatory document *"Safety Requirements for Site Selection of a Nuclear Power Plant"* NP 306.2.144-2008 [8], which establishes safety requirements during NPP site selection and takes into account the IAEA recommendations [9]. It states that *"the fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation."* Principle 8 of SF-1 [9], concerning accident prevention, states that *"all practical efforts shall be made to prevent nuclear or radiological accidents and to mitigate their consequences."* The main means of preventing and mitigating the consequences of accidents is the concept of *defense in depth* (para. 3.31). Defense in depth is ensured through an appropriate combination of specified systems and measures, one of which is *"an adequate site selection and inclusion of appropriate design and engineering solutions providing safety margins, diversity, and redundancy"* (SF-1, para. 3.32). To apply this principle, it is necessary ([9], para. 4) that the suitability of the site for a nuclear installation be assessed considering the following factors:

impact of external events occurring in the region of the specific facility (which may be of natural or human-induced origin);

site and environmental characteristics that may affect the dispersion of radioactive substances in the environment;

population density and distribution, as well as other characteristics of the surrounding area, to the extent that they may affect the feasibility of emergency measures and the need for assessing risks to individuals and the public.

The detailed procedure for analyzing these factors, taking into account their criteria for the purpose of NPP site selection, is presented in [1] as a hierarchical tree, which includes a sequential process of data array formation, generalization, comparison, and decision-making (Table 1).

Table 1. General characteristics of safety criteria selected for comparative analysis of NPP siting

Criterion	General characteristics of criterion
Geology, geotechnics, and seismology (SC1)	The NPP site must be located at a safe distance from fault lines and volcanic activity zones [10, 11]. Locating NPPs in seismically unstable regions can increase construction costs and contamination risks [12, 13]. The permissible distance from an NPP site to an active fault is 8000 m [14]. The geographical characteristics of the land plot are also taken into account, including soil and rock stability [13], soil composition [11], and geological structure [15]. Areas that respond to seismic activity, regions with potential liquefaction, soft soil layers, geological anomalies, high groundwater levels, or subsurface cavities should be avoided [11].
Population density (SC2)	Priority should be given to NPP sites located in areas with low population density. Locations with a population density exceeding 194 persons per 1 km^2 are not suitable for NPP siting [12]. Acceptable NPP locations must be situated at least 8 km away from populated areas [15], while [16] recommends a radius of 30 km.
Impacts on siting territory (SC3)	The criterion considers the ecological conditions surrounding the NPP site due to its potential environmental impact. Water use will influence local vegetation and agriculture. Additionally, pollution and insufficient vegetation cover can negatively affect wildlife [17]. The distance required for the management of radioactive waste disposal should also be taken into account [13]. Siting NPPs near agricultural areas is not recommended due to the potential impact of fallout deposition on farmland [11]. The presence of protected natural areas — national parks, nature reserves, and conservation zones — should also be considered [12]. The acceptable distance from an NPP site to such protected areas is 16 km [14] to avoid unacceptable environmental impacts [18].
Cooling water (SC4)	The distance from the NPP site to a water source should be less than 2 km. If the source is a reservoir or lake, a pipeline system must be constructed to transport water to the future NPP site. Sites located closer to existing water supply lines are preferable [16].
Meteorology (SC5)	Meteorological conditions, such as air temperature, wind speed and direction, humidity, atmospheric stability, and general climate, affect the operational performance of an NPP and must be considered in the design of its cooling systems [17]. Although atmospheric dispersion is generally not a critical factor for determining site suitability, atmospheric characteristics must be assessed to ensure compliance with local requirements for radioactive release dispersion in air [19].
Hydrology (SC6)	The water supply system must remain reliable both under normal operating conditions and during natural events. Sites with abundant water resources and low water quality risks are more favorable [19]. The risk assessment for groundwater contamination is based on potential core-melt accidents in which molten fuel penetrates the containment and reaches subsurface layers. In such cases, most fission products may penetrate up to 30 m below the containment; therefore, groundwater should be located deeper than 30 m [17]. Additionally, regions with low precipitation are preferable to those with heavy rainfall [11]. Potential flood parameters must be evaluated, as flooding could negatively affect safety by allowing water ingress or disrupting transportation and communication networks [12]. Therefore, the elevation of the water supply and drainage systems must be considered [18]. Potential sites for NPP location that are susceptible to flooding are generally preferred [11].

Continuation of Table 1

Proximity to hazardous facilities (SC7)	The IAEA recommends assessing the hazard potential of nearby industrial infrastructure, transportation networks, key infrastructure facilities, and military installations to ensure that these facilities do not pose a threat to the NPP and vice versa [12]. Such facilities include pipelines, industrial and mining operations, and dams. The NPP site must be located at a safe distance from these structures. The IAEA also recommends maintaining an 8 km buffer zone between the NPP and potentially hazardous facilities. Small airports should be at least 10 km away, and large airports at least 16 km.
Topography (SC8)	The terrain structure is important for NPP reactor safety primarily due to slope instability. Sites with steep slopes are unsuitable for NPP construction because of erosion risks [18]. Relatively flat terrain is preferable from a topographical standpoint [11]. Land plots with a slope angle of less than 20° (or 12%) are considered suitable for NPP siting [20]. The elevation of the site may range between 300 and 350 m, with shallow valleys preferred [17].
Land use (SC9)	According to IAEA standards and regulations [14], forests, meadows, and agricultural lands are of low suitability for NPP siting. Moreover, protected or conservation areas are strictly prohibited for such use. Some of these territories may also be unsuitable for future recreational or tourism development.
Sites of wetlands (SC10)	The permissible distance from NPP sites to wetlands such as lakes and rivers is 16 km [14]. Sites with minimal risks to wetlands are considered more favorable [11].
Evacuation routes (SC11)	Evacuation routes must be considered in case of an emergency. These routes should be planned based on monthly, annual, daytime, and nighttime wind directions around the NPP during potential radiological incidents. The population density along evacuation routes must be analyzed, taking into account the proximity to safe infrastructure near the NPP.

*Compiled from [https://www.sciencedirect.com/science/article/pii/S2666546823000356]

Analysis of Methods for Evaluating the Safety Factor in the Design of Nuclear Power Plant Siting

Considering that NPPs are radiation-nuclear facilities of increased hazard, the IAEA has developed specific standards and guidelines for selecting sites for such facilities. Publication [21] summarizes the practical experience of various IAEA member states in addressing the requirements of SSR-2/1 (Rev. 1) [22] regarding the design and safety confirmation of new NPPs. The general practices of member states include approaches to implementing enhanced requirements when assessing new NPP sites, taking into account both external hazards considered during design and natural hazards that exceed those accounted for in design. The recommended methods for addressing external hazards are presented in the following IAEA Safety Standards Series:

IAEA Safety Standards Series No. SSG-68, *Design of Nuclear Installations against External Events except Earthquakes* [23];

IAEA Safety Standards Series No. SSG-67, *Seismic Design of Nuclear Installations* [24].

Consideration of external hazards during NPP design generally involves the following steps:

identification of all external events and their combinations that need to be considered in design as part of site assessment tasks (as required by IAEA Safety Standards Series No. SSR-1);

site evaluation for nuclear installations.

External hazards depend on the specific site, and various IAEA Safety Standards [9, 23, 24] define typical hazards that should be considered as design basis external hazards applicable to a specific site and installation. Thus, requirement 1 of SSR-1 [9] emphasizes that *"the safety objective in the evaluation of sites for nuclear installations shall be to characterize the natural and human-induced external hazards that could affect the safety of the nuclear installation, in order to provide adequate information to demonstrate the protection of people and the environment against harmful effects of ionizing radiation."*

In accordance with requirement 1 of SSR-1 [9], site evaluation involves determining a list of external events of:

natural origin (e.g., earthquakes, floods, extreme meteorological conditions, extreme winds, dust and sand storms, lightning, volcanic activity);

human-induced origin (e.g., accidental aircraft crashes, explosions, fires, vehicle impacts, releases of hazardous gases or liquids that may cause corrosion).

Depending on the site characteristics, external events from the above list, as well as appropriate combinations of events where relevant, are considered design basis external events. For example, in Kyiv, the determination of relevant combinations takes into account:

1) combinations of hazards resulting from a common initiating phenomenon (e.g., precipitation and flood / extreme wind / lightning; extreme wind and flood);

2) combinations between an external event and its consequences, such as:

earthquake and internal fire / flood / pipe rupture / heavy load drop;

earthquake and external flood / explosion;

loss of off-site power due to earthquake, flood, strong wind, tornado, lightning, explosion, or aircraft crash;

aircraft crash and subsequent explosion;

3) combinations between an external event and an independent external event or a postulated initiating event identified either through probabilistic analysis or considered for assessing design margins based on engineering judgment (e.g., earthquake and design-basis accident).

However, external hazards and anthropogenic events that may occur independently (external hazards caused by human activity and equipment failures or operator errors) are not considered relevant combinations unless it can be shown that such combinations have a sufficiently high probability of occurrence. Similar types of combinations are considered in other countries, including France and Japan (Hitachi GE).

Based on the relevant data collected during site evaluation, the magnitude level for each considered external event (or combination of events) is determined according to regulatory requirements, guidelines, and/or designer's rules and instructions.

In China, the application of the national regulatory guide [25] and additional safety guides on external hazards [26, 27] combines deterministic and probabilistic methods applied to site data to determine the appropriate magnitude levels of the considered events.

In the Republic of Korea [28, 29], the approach involves determining, based on site data analysis, the magnitude level that bounds the most probable maximum event that could occur during the plant's lifetime.

In Japan, under the NRA Ordinance on Installation Permit Standards [30], regulatory requirements for external events (both natural and human-induced) have been significantly strengthened, taking into account the lessons learned from the Fukushima Daiichi-1 accident.

In some countries (France, the United Kingdom), regulatory guidance such as the Western European Nuclear Regulators Association (WENRA) safety reference levels for existing reactors [31] and target values in terms of annual exceedance frequency are applied. These are used to characterize the magnitude levels of natural external events.

In addition to the regulatory guidelines mentioned above, general approaches are also used to determine the magnitude levels of various external hazards. The determination of magnitude levels considers all available data, including historical records of past events at and near the site, as well as hazard assessment data. The processing of available data may include deterministic and probabilistic considerations with proper treatment of uncertainties.

Where necessary, projected increases in hazard levels are accounted for from the early stages of design to reduce risks in future periodic safety reviews. This is particularly relevant to hazards associated with geological and meteorological conditions. Ultimately, when the calculated frequency of occurrence of an external hazard (or combination of hazards) is sufficiently low, the hazard may either be excluded from further consideration or treated with special assessment, as practiced in China, France, Japan (Hitachi GE), and the Republic of Korea.

In some countries (e.g., France, Japan (Hitachi GE), the Republic of Korea), a specific plant design may be developed or selected for several different sites. In such cases, a "reference" or "generic" design is defined for the main structural components of the plant (e.g., reactor vessels, safety system buildings). Therefore, the list of hazards to be considered and their magnitude levels are defined so as to ensure a bounding case — meaning that the reference plant design can be implemented at any of the considered sites with only limited adaptation to account for site-specific features.

Thus, analysis of the sources shows that adopting a safety-based approach in NPP site selection is essential for determining the radiological risk to the public and the environment from internal and external events or possible failures caused by human or equipment errors. The principle of nuclear safety is to ensure the protection of NPP personnel, the public, and the environment. It can be concluded that existing requirements for site selection and regulatory documents are consistent with the objectives of protecting public health, safety, and the environment.

Algorithm for Safety Factor Analysis

The algorithm for studying the safety factor is based on the methodology for NPP site selection analysis using the theory of fuzzy sets, presented in [2]. A specific feature of the proposed model, in relation to the factors and their criteria presented for evaluation and comparison, is that the model factors and their components are formalized in accordance with linguistic expert assessments obtained through the sequential application of fuzzy logic methods — Fuzzy AHP [32], CoA [33], and Fuzzy SAW [34].

This approach allows for higher-quality and more reliable expert evaluation, accounting for and minimizing the influence of subjectivity in expert opinions and judgments. The research algorithm developed on the basis of [2] is shown in Fig. 1.

Identification of the safety factor criteria influencing NPP site selection was carried out in accordance with [2] and Table 1.

Fuzzy expert pairwise comparison of the i-th criterion with the j-th within the evaluation of a specific site is performed by each of the $k = (1, \overline{K})$ experts using the term set T_1 = {E, M, S, VS, ES}, which defines the degree of criterion comparison as: Equal (E), Moderate (M), Strong (S), Very Strong (VS), and Extremely Strong (ES). The result of such expert comparisons is a set of linguistic pairwise comparison matrices for all considered sites. In the next step, their contents are transformed into matrices of fuzzy triangular numbers using the term set T1* (see Fig. 1).

$$\tilde{A} = (\tilde{a}_{ij})_{n\times n} = \begin{bmatrix} (1,1,1) & (\alpha_{12},\beta_{12},\gamma_{12}) & \dots & (\alpha_{1n},\beta_{1n},\gamma_{1n}) \\ (\gamma_{21},\beta_{21},\alpha_{21}) & (1,1,1) & \dots & (\alpha_{2n},\beta_{2n},\gamma_{2n}) \\ \dots & \dots & \dots & \dots \\ (\gamma_{n1},\beta_{n1},\gamma_{n1}) & (\gamma_{n2},\beta_{n2},\alpha_{n2}) & \dots & (1,1,1) \end{bmatrix} \quad (1)$$

where $\tilde{a}_{ij} = (\alpha_{ij},\beta_{ij},\gamma_{ij})$, $\tilde{a}_{ji} = \tilde{a}_{ij}^{-1} = (\frac{1}{\gamma_{ij}},\frac{1}{\beta_{ij}},\frac{1}{\alpha_{ij}})$, $i,j = \overline{1,n}$; n is number of criteria.

By determining the fuzzy geometric means for the components of the matrix and the inverse fuzzy vector of the sum of geometric mean values

$$\begin{cases} \tilde{S}_i = (\sqrt[n]{\alpha_{i1}\times\dots\times\alpha_{in}}; \sqrt[n]{\beta_{i1}\times\dots\times\beta_{in}}; \sqrt[n]{\gamma_{i1}\times\dots\times\gamma_{in}}) = (\alpha_i,\beta_i,\gamma_i) \\ \tilde{r} = \tilde{S}_1 \oplus \dots \oplus + \tilde{S}_n = \begin{Bmatrix} \alpha_i + \dots \times \alpha_n \\ \beta_i + \dots + \beta_n \\ \gamma_i + \dots + \gamma_n \end{Bmatrix} = (r_\alpha, r_\beta, r_\gamma) \\ (\tilde{r})^{-1} = \left(\frac{1}{r_\alpha},\frac{1}{r_\beta},\frac{1}{r_\gamma}\right) \end{cases} \quad (2)$$

the fuzzy coefficients of importance and the relative weights of the safety factor criteria for all sites included in the analysis are calculated:

$$\begin{cases} \tilde{v}_i = (\alpha_i,\beta_i,\gamma_i)\otimes(\tilde{r})^{-1} = (v_{1i}; v_{2i}; v_{3i}) \\ \widetilde{w}_i = \left(\frac{v_{1i}}{\sum_{i=1}^{n}(\widetilde{v_{1i}})}; \frac{v_{2i}}{\sum_{i=1}^{n}(\widetilde{v_1})}; \frac{v_{3i}}{\sum_{i=1}^{n}(\widetilde{v_{3i}})}\right) = (w_{1i}; w_{2i}; w_{3i}) \end{cases} \quad (3)$$

Using a similar but simplified algorithm that excludes pairwise comparison of criteria, the probabilities of impact realization ("Very Low", "Low", "Medium", "High", "Very High") of the safety criteria are determined based on the linguistic terms T2 = {VL, L, M, H, VH} and T* (see Fig. 1) as well as fuzzy estimates of the level of impact ("No Significant", "Very Low", "Low", "Medium", "High", "Very High", "Extremely High") of the safety criteria according to terms T3 = {NS, VL, L, M, H, VH, EH} and T3*, taking into account the direction of influence ("t" — Threats, "o" — Opportunities).

The results obtained in Stages 2, 3, and 4 of the algorithm of assessment of fuzzy triangular importance coefficients and relative weights, probabilities of influence realization, and fuzzy estimates of the level of influence — are used for visualization by means of the Wilson Matrix of positive and negative factor influence (advantages and disadvantages) (Fig. 2). This matrix defines influence zones ranging from A (maximum) to D (minimum), describing their impact on the process of NPP site selection.

Implementation of the Safety Factor Analysis Algorithm for the Selection of Potential NPP Construction Sites

The safety factor criteria identified in Stage 1 for strategic analysis during the selection of potential NPP construction sites form the set SC = {SC_1, …, SC_{11}}.

Following the approach presented in [5], 12 qualified experts were involved in the expert evaluation process. The minimum required number of experts, determined using mathematical statistics, was m = 11. The linguistic confidence level of experts was defined as High (H). As a result, 12 experts × 3 sites = 36 matrices were obtained, the structure of which for the different algorithm stages is shown in Fig. 3.

A fragment of expert evaluation results according to the algorithm presented in Fig. 1 for the Khmelnytskyi NPP site, in triangular form, is shown in Fig. 4.

Sequential implementation of Stage 2 of the algorithm made it possible to obtain the fuzzy importance coefficients and their relative weights. The results are presented in Tables 2 and 3.

At Stage 3, the fuzzy values of the probabilities of influence realization of the safety factor criteria on the NPP site selection process were determined using the proposed algorithm (Table 4).

At Stage 4, the levels of impact of safety factor criteria on the decision-making strategy for NPP siting were

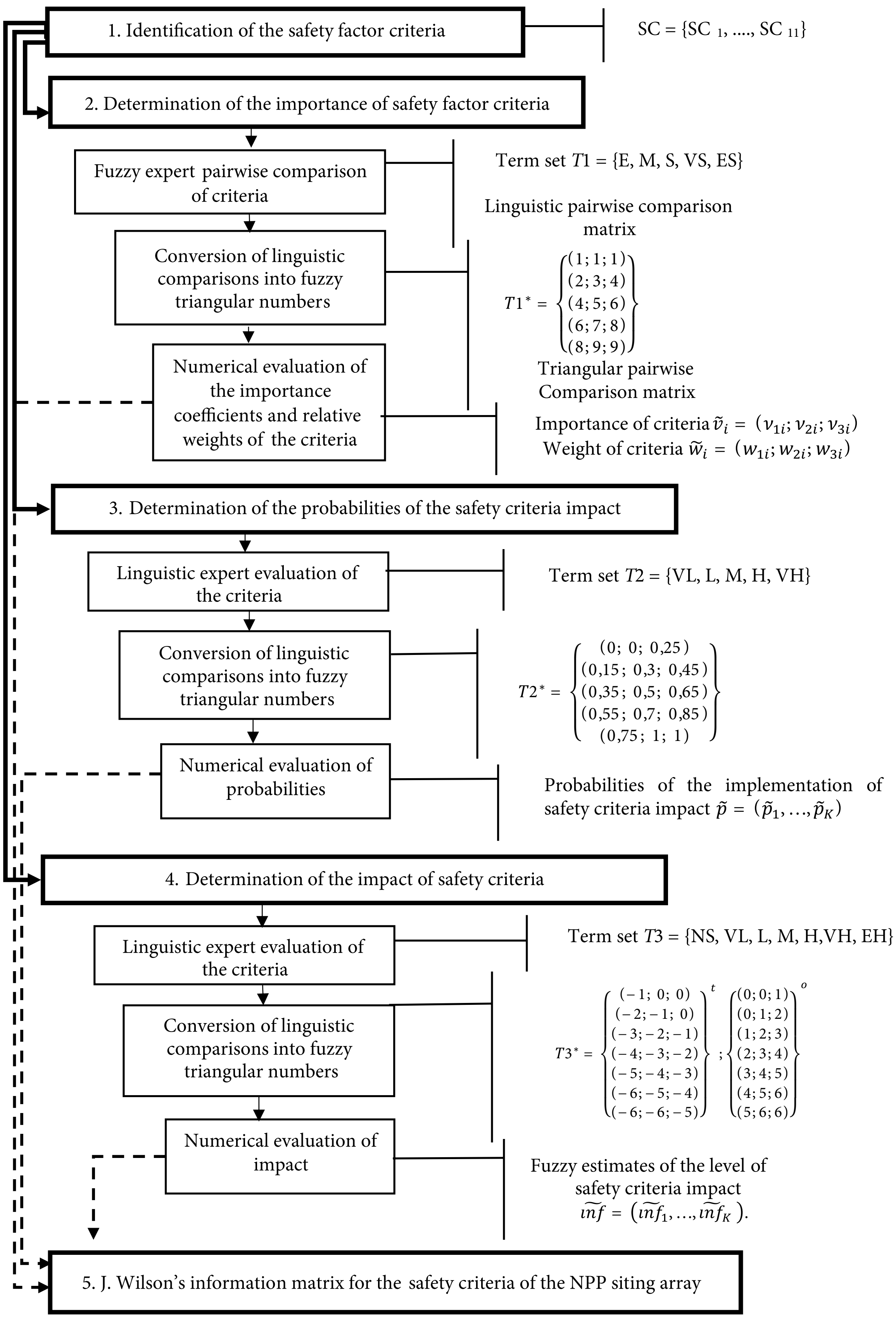


Fig. 1. Algorithm for the safety factor analysis in selecting NPP siting location

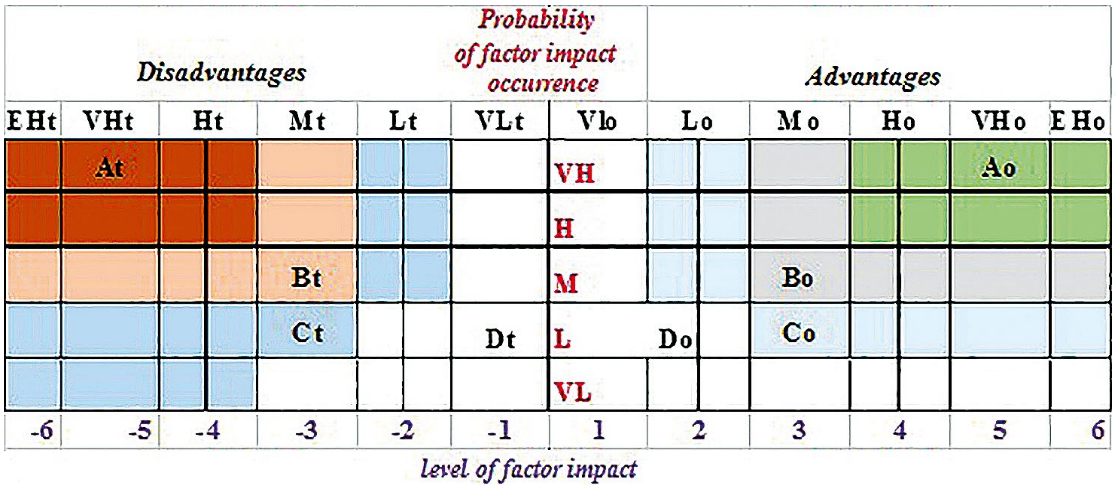


Fig. 2. Fuzzy evaluation matrix of advantages and disadvantages of safety criteria influence on NPP site assessment [1]

Criterion	Expert evaluation					Linguistic evaluation				
	SC_1	SC_2	…	SC_{10}	SC_{11}	SC_1	SC_2	…	SC_{10}	SC_{11}
SC_1	1, 1, 1	2, 3, 4	…	4, 5, 6	6, 7, 8	E	M	…	S	VS
SC_2	1/4, 1/3, 1/2	1, 1, 1	…	2, 3, 4	8, 9, 9	1/M	E	…	M	ES
…	…	…	1, 1, 1	…	…	…	…	E	…	…
SC_{10}	1/6, 1/5, 1/4	1/4, 1/3, 1/2	…	1, 1, 1	4, 5, 6	1/S	1/M	…	E	S
SC_{11}	1/8, 1/7, 1/6	1/9, 1/9, 1/9	…	1/6, 1/5, 1/4	1, 1, 1	1/VS	1/ES	…	1/S	E

a

Criterion	Expert evaluation					Linguistic evaluation				
	SC_1	SC_2	…	SC_{10}	SC_{11}	SC_1	SC_2	…	SC_{10}	SC_{11}
SC_1	1, 1, 1	0.55, 0.7, 0.85	…	0.15, 0.3, 0.45	6, 7, 8	E	H	…	L	M
SC_2	1/(0.85, 0.7, 0.55)	1, 1, 1	…	0.55, 0.7, 0.85	8, 9, 9	1/H	E	…	H	VH
…	…	…	1, 1, 1	…	…	…	…	E	…	…
SC_{10}	1/(0.45, 0.3, 0.15)	1/(0.85, 0.7, 0.55)	…	1, 1, 1	4, 5, 6	1/S	1/H	…	E	L
SC_{11}	1/(0.65, 0.5, 0.35)	1(1, 1, 0.75)	…	1/(0.45, 0.3, 0.15)	1, 1, 1	1/M	1/VH	…	1/L	E

b

Criterion	Expert evaluation					Linguistic evaluation				
	SC_1	SC_2	…	SC_{10}	SC_{11}	SC_1	SC_2	…	SC_{10}	SC_{11}
SC_1	1, 1, 1	1, 2, 2	…	2, 3, 4	3, 4, 5	E	L	…	M	H
SC_2	1/2, 1/2, 1	1, 1, 1	…	4, 5, 6	5, 6, 6	1/L	E	…	VH	EH
…	…	…	1, 1, 1	…	…	…	…	E	…	…
SC_{10}	1/4, 1,/3, 1/2	1/6, 1/5, 1/4	…	1, 1, 1	1, 2, 3	1/M	1/M	…	E	L
SC_{11}	1/5, 1/4, 1/3	1/6, 1/6, 1/5	…	1/3, 1/2, 1	1, 1, 1	1/H	1/EH	…	1/L	E

c

Fig. 3. Structure of expert and linguistic evaluation of safety factor criteria according to the stages of the algorithm: (a) Stage 2 (pairwise comparison of criteria); (b) Stage 3 (probability of influence realization); (c) Stage 4 (level of influence of criteria)

Khmelnytskyi NPP					Expert 1						
	SC_1	SC_2	SC_3	SC_4	SC_5	SC_6	SC_7	SC_8	9	SC_{10}	SC_{11}
SC_1	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*
SC_2	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*
SC_3	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*
SC_4	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*
SC_5	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*
SC_6	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*
SC_7	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*
SC_8	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*
SC_9	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(0,17;0,2;0,25)*	*(0,25; 0,33;0,5)*
SC_{10}	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*	*(4; 5; 6)*	*(1; 1; 1)*	*(2; 3; 4)*
SC_{11}	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*	*(2; 3; 4)*	*(0,25; 0,33;0,5)*	*(1; 1; 1)*

a

Khmelnytskyi NPP							
Expert 1		Expert 2		Expert 3		Expert 4	
SC_1	***(0.35, 0.5, 0.65)***	SC_1	***(0.35, 0.5, 0.65)***	SC_1	***(0.1, 0.1, 0.25)***	SC_1	***(0.35, 0.5, 0.65)***
SC_2	***(0.35, 0.5, 0.65)***	SC_2	***(0.35, 0.5, 0.65)***	SC_2	***(0.35, 0.5, 0.65)***	SC_2	***(0.35, 0.5, 0.65)***
SC_3	***(0.75, 1, 1)***	SC_3	***(0.55, 0.7, 0.85)***	SC_3	***(0.15, 0.3, 0.45)***	SC_3	***(0.35, 0.5, 0.65)***
SC_4	***(0.35, 0.5, 0.65)***	SC_4	***(0.75, 1, 1)***	SC_4	***(0.55, 0.7, 0.85)***	SC_4	***(0.55, 0.7, 0.85)***
SC_5	***(0.15, 0.3, 0.45)***	SC_5	***(0.15, 0.3, 0.45)***	SC_5	***(0.35, 0.5, 0.65)***	SC_5	***(0.35, 0.5, 0.65)***
SC_6	***(0.1, 0., 0.25)***	SC_6	***(0.35, 0.5, 0.65)***	SC_6	***(0.75, 1, 1)***	SC_6	***(0.35, 0.5, 0.65)***
SC_7	***(0.15, 0.3, 0.45)***	SC_7	***(0.15, 0.3, 0.45)***	SC_7	***(0.35, 0.5, 0.65)***	SC_7	***(0.15, 0.3, 0.45)***
SC_8	***(0.15, 0.3, 0.45)***	SC_8	***(0.35, 0.5, 0.65)***	SC_8	***(0.1, 0.1, 0.25)***	SC_8	***(0.35, 0.5, 0.65)***
SC_9	***(0.15, 0.3, 0.45)***	SC_9	***(0.15, 0.3, 0.45)***	SC_9	***(0.35, 0.5, 0.65)***	SC_9	***(0.15, 0.3, 0.45)***
SC_{10}	***(0.35, 0.5, 0.65)***	SC_{10}	***(0.55, 0.7, 0.85)***	SC_{10}	***(0.1, 0.1, 0.25)***	SC_{10}	***(0.15, 0.3, 0.45)***
SC_{11}	***(0.35, 0.5, 0.65)***	SC_{11}	***(0.35, 0.5, 0.65)***	SC_{11}	***(0.15, 0.3, 0.45)***	SC_{11}	***(0.35, 0.5, 0.65)***

b

Khmelnytskyi NPP							
Expert 1		Expert 2		Expert 3		Expert 4	
$SC1$	***(-4,-3,-2)***	$SC1$	***(2,3,4)***	$SC1$	***(4,5,6)***	$SC1$	***(2,3,4)***
$SC2$	***(-5,-4,-3)***	$SC2$	***(2,3,4)***	$SC2$	***(3,4,5)***	$SC2$	***(3,4,5)***
$SC3$	***(-4,-3,-2)***	$SC3$	***(2,3,4)***	$SC3$	***(2,3,4)***	$SC3$	***(3,4,5)***
$SC4$	***(-6,-5,-4)***	$SC4$	***(5,6,6)***	$SC4$	***(5,6,6)***	$SC4$	***(5,6,6)***
$SC5$	***(-4,-3,-2)***	$SC5$	***(1,2,3)***	$SC5$	***(1,2,3)***	$SC5$	***(3,4,5)***
$SC6$	***(-3,-2,-1)***	$SC6$	***(2,3,4)***	$SC6$	***(5,6,6)***	$SC6$	***(4,5,6)***
$SC7$	***(-3,-2,-1)***	$SC7$	***(1,2,3)***	$SC7$	***(1,2,3)***	$SC7$	***(1,2,3)***
$SC8$	***(-3,-2,-1)***	$SC8$	***(2,3,4)***	$SC8$	***(1,2,3)***	$SC8$	***(2,3,4)***
$SC9$	***(-3,-2,-1)***	$SC9$	***(1,2,3)***	$SC9$	***(4,5,6)***	$SC9$	***(1,1,2)***
$SC10$	***(-3,-2,-1)***	$SC10$	***(2,3,4)***	$SC10$	***(2,3,4)***	$SC10$	***(1,1,2)***
$SC11$	***(-3,-2,-1)***	$SC11$	***(2,3,4)***	$SC11$	***(1,1,1)***	$SC11$	***(2,3,4)***

c

Fig. 4. Fragment of expert evaluation results represented as triangular fuzzy numbers:
a — pairwise comparison of criteria; b — probability of influence realization;
c — impact level of criteria

Table 2. Fuzzy averaged importance coefficients of safety factor criteria

Criterion	Importance coefficient of criterion		
	Khmelnytskyi NPP	Rivne NPP	South Ukraine NPP
SC_1	0.198	0.177	0.189
SC_2	0.177	0.188	0.168
SC_3	0.193	0.197	0.188
SC_4	0.167	0.180	0.181
SC_5	0.215	0.214	0.212
SC_6	0.200	0.208	0.204
SC_7	0.176	0.170	0.166
SC_8	0.191	0.194	0.191
SC_9	0.171	0.173	0.162
SC_{10}	0.185	0.178	0.203
SC_{11}	0.211	0.209	0.207

Table 3. Fuzzy averaged relative weights of safety factor criteria

Criterion	Importance coefficient of criterion		
	Khmelnytskyi NPP	Rivne NPP	South Ukraine NPP
SC_1	0.079	0.070	0.075
SC_2	0.070	0.075	0.067
SC_3	0.077	0.078	0.075
SC_4	0.066	0.072	0.072
SC_5	0.085	0.085	0.084
SC_6	0.080	0.083	0.081
SC_7	0.070	0.068	0.066
SC_8	0.076	0.077	0.076
SC_9	0.068	0.069	0.064
SC_{10}	0.073	0.071	0.081
SC_{11}	0.084	0.083	0.082

determined. The fuzzy triangular expert evaluations, aggregated into generalized influence parameters, are presented in Table 5.

Thus, the results of the expert evaluation of the safety factor criteria make it possible to assess the impact of the components of the safety factor in the "Threats — Opportunities" coordinate system.

The obtained results serve as the basis for constructing the Wilson Information Matrix to visualize threats and opportunities in NPP site selection and to support the formation of optimal management decisions (Fig. 5).

Table 4. Probabilities of realization of safety factor criteria impact on the NPP site selection process

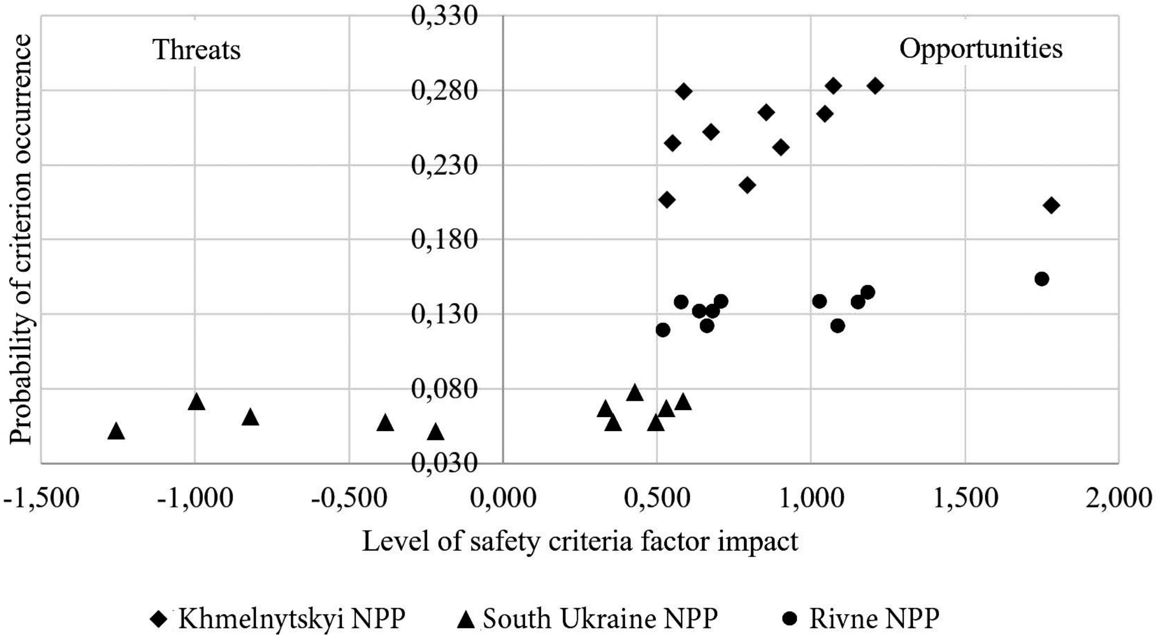
Criterion	Probabilities of impact realization of criteria		
	Khmelnytskyi NPP	Rivne NPP	South Ukraine NPP
SC_1	0.072	0.078	0.072
SC_2	0.094	0.097	0.092
SC_3	0.088	0.091	0.082
SC_4	0.103	0.097	0.087
SC_5	0.088	0.087	0.092
SC_6	0.087	0.091	0.077
SC_7	0.082	0.084	0.087
SC_8	0.069	0.071	0.071
SC_9	0.082	0.083	0.077
SC_{10}	0.072	0.074	0.077
SC_{11}	0.087	0.096	0.098

Table 5. Quantitative estimates of the influence levels of safety factor criteria on NPP site selection

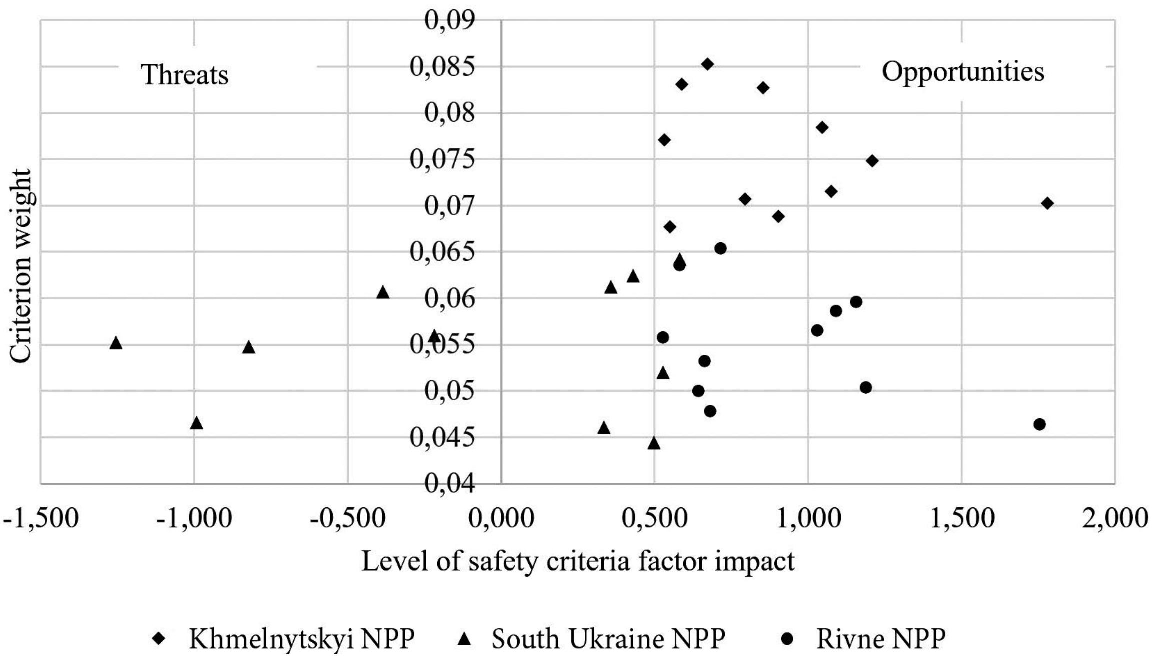
Criterion	Influence levels of safety factor criteria		
	Khmelnytskyi NPP	Rivne NPP	South Ukraine NPP
SC_1	1.781	1.087	–1.255
SC_2	1.207	1.187	–0.995
SC_3	1.045	1.028	–0.821
SC_4	1.073	1.752	0.527
SC_5	0.673	0.712	0.582
SC_6	0.854	1.152	0.358
SC_7	0.550	0.638	0.334
SC_8	0.531	0.523	–0.219
SC_9	0.903	0.680	0.497
SC_{10}	0.794	0.662	–0.384
SC_{11}	0.588	0.578	0.428

The structure of Wilson Matrix for the specified research objects and their criteria clearly shows the advantages of the Khmelnytskyi and Rivne NPP sites compared to the South Ukraine NPP site. Thus, according to the indicator "probability of safety criteria implementation" (Fig. 5, a), the safety criteria assessments for the Khmelnytskyi NPP site are clearly formed within the A0-B0 zone (see Fig. 2). The localization of the probability of safety criteria implementation assessments indicates a significant advantage of the Khmelnytskyi NPP site compared to others.

The Wilson matrix for the "criterion weight" indicator (Fig. 5, b) is somewhat less structured. All es-



a



b

Fig. 5. Modified Wilson matrix for safety factor criteria in NPP site assessment:
a — probability of realization of criteria; b — relative weights of criteria

timates of the weights of safety criteria are grouped in the B0-C0 advantage area for the Khmelnytskyi and Rivne NPP sites. However, the center of the indicator cluster for the Khmelnytskyi NPP has a higher absolute value and better localization in terms of threats and opportunities.

Conclusions

The analysis of safety factor criteria represents a logical continuation of the methodological approach to strategic analysis of optimal siting for radiation-nuclear facilities based on fuzzy logic methods. The defined list of safety factor criteria corresponds to IAEA approaches to NPP site safety assessment, international practices in this field, and the requirements of Ukrainian national legislation. The safety assessment of the analyzed sites was carried out using expert evaluation of criteria and the developed fuzzy set-based model. As an example, the process of comparing three proposed sites for the construction of new AP1000 reactors was demonstrated. Based on the obtained results and their visualization using the Wilson matrix, it can be concluded that the optimal alternative is A1 — the Khmelnytskyi NPP site. The proposed methodological approach provides well-substantiated conclusions regarding the influence of safety factor criteria, supporting strategic decision-making for selecting optimal sites for radiation-nuclear facility construction.

The results obtained using the proposed methodology — as demonstrated in the safety factor analysis — justify further research aimed at developing a comprehensive analysis algorithm, determining integral indicators, and integrating the developed model into a decision support system for NPP siting analysis.

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Надійшла / Received 06.08.2025
Рекомендована до друку / Accepted 15.09.2025