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Dynamic Risk-Aware Shelter Planning for Nuclear Emergencies: A Conceptual TOPSIS-Based Framework

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1. Introduction

General emergency evacuation plans for nuclear power plants (NPPs) have been developed based on static infrastructure and population data. However, in an actual emergency, both population movement and radioactive dispersion are highly dynamic. Diverse factors like time of day, seasonal changes, and special events significantly influence the risk landscape and the number of people requiring shelter. Existing shelter designation methods often fail to reflect these dynamic conditions, which could impact evacuation plans or shelter capacity, potentially increasing exposure risks.

Recent advancements in data availability and improvements in computational power for processing that data present new opportunities for developing more effective evacuation plans, such as enabling the more efficient designation of shelter locations [1]. This study proposes a conceptual decision framework that integrates dynamic population estimates and meteorological risk factors into a multi-criteria evaluation of shelter suitability. To achieve this, the framework employs the Technique for Order Preference by Similarity to Ideal Solution(TOPSIS), a multi-criteria decision-making method that evaluates alternatives by ranking them according to their relative closeness to an ideal solution.

TOPSIS has been widely applied in diverse decision-making contexts, including the selection of emergency shelters in earthquake-prone regions, optimization of disaster response resources, and site selection in energy and infrastructure planning. Its strength lies in balancing multiple, and often conflicting, criteria within a structured and transparent process [2, 3]. In the context of nuclear emergencies, this makes TOPSIS particularly suitable for integrating spatial, demographic, and meteorological variables into a unified evaluation framework.

Instead of presenting an empirical case study, this paper focuses on the theoretical foundation of such an approach. By outlining how real-time data can be structurally incorporated into shelter planning, this study provides a basis for adaptive, scenario-based evacuation strategies that are responsive to evolving risk conditions.

2. Method

2.1. Overview of the TOPSIS Method

This study proposes a framework for designating nuclear emergency shelters based on the TOPSIS. TOPSIS is a MCDM method that finds the optimal alternative by considering several conflicting criteria. The core principle is as follows:

- Positive-Ideal Solution: A hypothetical solution that has the best value for every single evaluation criterion.
- Negative-Ideal Solution: A hypothetical solution that has the worst value for every single evaluation criterion.

The best alternative is the one that is closest to the positive-ideal solution and farthest from the negative-ideal solution.

2.2. Framework Structure and Criteria

The proposed framework evaluates each alternative (i.e., candidate shelter or administrative district) based on four primary criteria, each reflecting a critical aspect of nuclear emergency planning. These criteria are designed to incorporate both static and dynamic data inputs, enabling a flexible and real-time evaluation process.

1) Risk Exposure Factors (C_1) : This criterion captures direct hazard exposure, primarily measured as the distance from the nearest nuclear power plant (NPP). Greater distance generally implies lower radiation risk in the event of an accident.

2) Capacity and Resource Availability (C_2) : This criterion assesses the shelter's ability to accommodate evacuees and provide essential resources such as medical supplies, food, and water. Capacity indicators may include absolute shelter capacity and capacity-to-population ratio.

3) Population Vulnerability (C_3) : This criterion captures the spatiotemporal variability of population density and distribution, considering fluctuations that arise due to hourly, seasonal, and event-based factors. It quantifies the estimated number of individuals present in a given area who would require evacuation under specific real-time conditions.

4) Meteorological Hazards (C_4) : This criterion accounts for atmospheric conditions—particularly wind direction, speed, and stability—which significantly influence the dispersion of radioactive materials.

Importantly, the relative importance of each criterion may vary depending on the specific scenario. For instance, during high-wind conditions, greater emphasis may be placed on meteorological factors. The framework supports this flexibility by allowing the adjustment of criterion weights, thereby enabling decision-makers to adapt the shelter selection process to evolving threat conditions.

3. Application of the TOPSIS Framework

Building upon the conceptual framework outlined in the previous chapter, this section details the specific steps for applying the TOPSIS methodology to identify optimal emergency shelter locations in a dynamic environment. The procedure for applying this conceptual framework is as follows:

1) Construct a Decision Matrix: Create a table with candidate shelters as rows and the four criteria as columns. Each cell contains the performance value for a specific shelter based on a given criterion.

2) Normalize and Weight the Data: Normalize all criterion values to a common scale. Then, multiply the normalized values by the weights that reflect their relative importance in the given scenario.

3) Determine Ideal Solutions: From the normalized and weighted matrix, derive the ideal (optimal) and negative-ideal (worst) values for each criterion.

4) Calculate Distances: Compute the Euclidean distance of each shelter from both the ideal and negative-ideal solutions.

5) Final Ranking: Calculate the relative closeness(CC_i^*) of each shelter to the ideal solution. The shelter with the highest CC_i^* value is considered the optimal choice for the given conditions.

These steps are summarized in a conceptual flowchart in Figure 1, which systematically visualizes the decision-making process during an emergency.

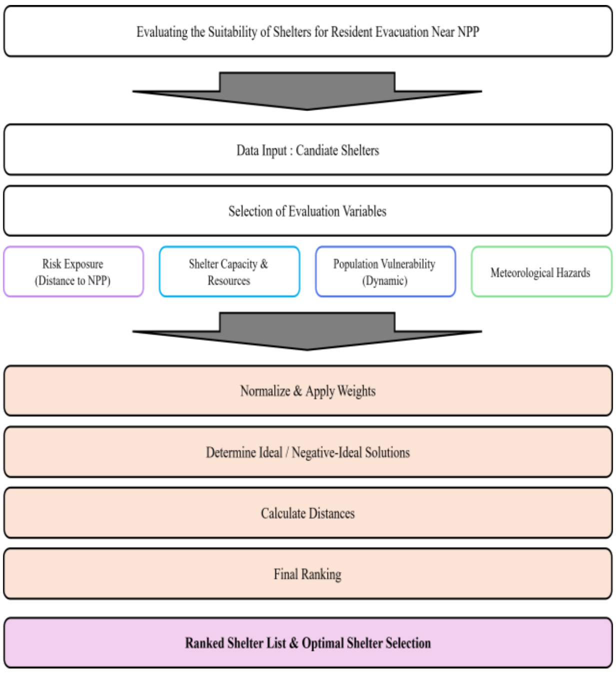

Figure 1. Conceptual Flowchart

4. Conclusion

This study proposes a conceptual framework for selecting emergency shelters during a nuclear accident, presenting a new approach that integrates dynamic factors beyond static planning. This framework utilizes the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method to provide a structured, multi-criteria decision-making process.

For future research, it's necessary to systematically derive the weights for each factor by using a structured decision-making method like the Analytic Hierarchy Process (AHP). Additionally, there is a need to develop a more precise model for estimating population density that accounts for fluctuations based on time of day and facility type. Integrating non-physical factors like the structural integrity and radiation shielding performance of shelters as evaluation criteria is also essential to broaden the basis for selecting the optimal shelter.

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