A Scenario-Based Decision Support System for Enhancing the Resilience of Civil Protection Infrastructure under Aerial Threats

Nataliia Furmanova[1,*,†], Vadim Yakovenko[2,†] and Oleksandr Malyi[1,†]

[1] *Zaporizhzhia Polytechnic National University, Universytetska str., 64, 69011, Zaporizhzhia, Ukraine*
[2] *Odesa National University of Technology, Kanatna Str., 112, 65039, Odesa, Ukraine*

Abstract

This article addresses the challenge of enhancing the resilience of civil protection infrastructure in the face of aerial threats in urbanized areas. The relevance of this research stems from the need to integrate data on shelters, population movement dynamics, threat parameters, and the condition of urban infrastructure into a unified decision support information system. The traditional approach to using shelters as passive protection structures is insufficient in the face of dynamically changing threats, particularly missile attacks, drone attacks, and combined attack scenarios.

A scenario-oriented information and communication model for assessing the suitability of shelters is proposed, based on multi-criteria analysis, adaptive adjustment of weighting coefficients, and consideration of secondary damage factors. The model features a three-tier architecture: data collection, data processing, and decision-making. The data collection tier utilizes information on the technical condition of shelters, geospatial characteristics of the urban environment, accessibility of protective facilities, and population movement dynamics. The data processing level provides multifactorial analysis, scenario modelling, and calculation of a generalized shelter safety index. The decision-making level generates recommendations for the population and civil protection authorities.

The results of preliminary testing of the model demonstrated the ability to rapidly process threat scenarios, the consistency of the decision support system's results with expert assessments, and a reduction in the error of determining shelter accessibility using up-to-date spatial data. The proposed approach can be used as a basis for creating a scalable digital civil protection platform integrated with urban information systems and public warning systems.

Keywords

civil protection infrastructure, critical infrastructure, decision support system, scenario modelling, multicriteria assessment, urban system resilience, civilian shelters, aerial threats, information system, risk management

1. Introduction

Modern cities function as complex socio-technical systems, the resilience of which depends not only on the condition of individual infrastructure facilities but also on the ability to quickly process information about threats, environmental conditions, and population behaviour. In the context of aerial attacks, ensuring the safety of the civilian population becomes particularly critical, specifically through the effective use of existing civil protection infrastructure. Shelters, which have traditionally been viewed primarily as passive protective structures, must be integrated into dynamic information systems capable of adapting to changing threat scenarios in near real-time.

The problem of selecting a safe and accessible shelter [1, 2] is multifaceted. It depends on the technical condition of the protective structure, its capacity, distance from the user, evacuation time,

[1] *RS-2026: Resilient Systems: Secure Digital Technologies and Critical Infrastructure, June 30, 2026, Drohobych, Ukraine*
* Corresponding author.
† These authors contributed equally.
nfurmanova@gmail.com (Nataliia Furmanova); yakob@ukr.net (Vadim Yakovenko); malyi@zp.edu.ua (Oleksandr Malyi)
0000-0002-8670-2948 (Nataliia Furmanova); 0000-0001-8591-6998 (Vadim Yakovenko); 0000-0002-8457-8154 (Oleksandr Malyi)

urban layout, current road and pedestrian accessibility, as well as the nature of the threat itself. An additional complication arises from the need to account not only for direct damage but also for secondary hazards, including fragmentation damage, shock waves, and potential cascading destruction in the urban environment [2].

Existing approaches to informing the public about shelters are primarily focused on providing static reference information: locations, addresses, or general accessibility of the facility. However, in rapidly changing conditions, this approach is insufficient. To improve the effectiveness of civil protection, a system is needed that can integrate geospatial data, information on the condition of shelters, threat parameters, population movement dynamics, and the results of scenario modelling [3, 4]. Such a system must not only display information but also support decision-making at both the individual user level and the level of management bodies.

This study proposes a scenario-based approach to building a decision support system [3] for assessing the suitability of civilian shelters under aerial threats. The approach is based on an adaptive information and communication model that involves multi-criteria assessment of shelters, adjustment of weighting coefficients depending on the threat scenario, and consideration of secondary damage factors. The model is designed for integration with urban information systems, warning systems [5], and civil protection digital platforms.

The aim of this article is to develop and justify a scenario-based decision support system designed to enhance the resilience of civil protection infrastructure through adaptive assessment of the safety and accessibility of shelters in urban environments.

The main contribution of the study lies in the formalization of a three-level system architecture, which includes a data collection level, a data processing level, and a decision-making level; in the application of a multi-criteria approach to the assessment of shelters; and in the consideration of aerial threat scenarios and secondary risk factors when formulating recommendations for the public and civil protection authorities.

2. Relevance of the Study

Ensuring the resilience of civil protection infrastructure [6] is one of the key tasks for urbanized areas subject to regular aerial threats. Under such conditions, public safety depends not only on the physical availability of shelters but also on the ability of urban systems to rapidly assess their suitability, accessibility, and relevance to a specific hazard scenario. Therefore, civil protection infrastructure should be viewed not as a collection of isolated facilities, but as a component of critical urban infrastructure requiring digital integration, monitoring, and adaptive management [6, 7].

The urgency of the issue is heightened by the fact that most existing information solutions regarding shelters are primarily of a reference nature [8, 9]. They allow for determining the location of a protective structure but do not always account for its current technical condition, actual accessibility, capacity, evacuation time, changes in threat intensity, or the individual characteristics of users. As a result, the population may receive information about the nearest facility, which is not optimal in terms of safety, accessibility, or suitability for a specific type of threat.

A separate factor determining the relevance of this study is the need to account for secondary damage factors. In the event of aerial attacks, the risk to the population arises not only from a direct hit on the target but also from fragmentation damage, shock waves, the destruction of urban infrastructure elements, and potential cascading effects on adjacent infrastructure facilities. Ignoring these factors can lead to an incorrect assessment of the safety level of shelters and ineffective planning of evacuation routes [10].

The urban environment is characterized by high population density, a complex transportation and pedestrian network, varying quality of buildings, uneven distribution of shelters, and inconsistent accessibility of civil protection facilities. Under such conditions, the task of selecting a shelter takes on the characteristics of a multi-criteria optimization problem [8, 9], in which it is necessary to simultaneously consider safety, travel time to the facility, its capacity, technical condition, spatial location, the nature of the threat, and the possibility of safely moving the population.

Solving this problem requires the application of information and communication technology and systems engineering approaches. A civil protection information system must ensure the collection of diverse data, its processing, scenario-based modelling of threat development, and the generation of recommendations for users and management bodies. This is why it is advisable to create a decision support system that combines multi-criteria evaluation [3, 8, 9], adaptive adjustment of model parameters, and the ability to integrate with urban digital platforms.

Thus, the relevance of this study is determined by the need to transition from static information about shelters to an adaptive decision support system capable of assessing the safety and accessibility of civil protection facilities, considering aerial threat scenarios, urban environment characteristics, and secondary damage factors.

3. Problem Statement

The task of ensuring the effective use of civil shelters under aerial threat conditions consists in identifying a civil protection facility that, at a specific moment in time, is the most appropriate for use, taking into account safety level, accessibility, technical condition, capacity, and threat parameters. Unlike the static selection of the nearest shelter [1, 8], the proposed approach involves an adaptive evaluation of the set of available facilities according to the current threat scenario.

Let there be a set of civilian shelters located within a specific urbanized area. For each shelter, a set of parameters can be defined that characterize its technical condition, capacity, spatial location, accessibility, distance to the user, average evacuation time, conditions for approaching the facility, and the potential impact of secondary damage factors. Some of these parameters are relatively constant, such as the structural characteristics of the shelter, while others vary over time, including route accessibility, population density near the facility, or the current threat level.

The system's input data includes: information about shelters and their characteristics; geospatial data on the urban environment; data on route accessibility; parameters of the current or projected aerial threat scenario; information on the location of a user or group of users; and additional constraints related to age, mobility, and the individual needs of the population. Such data may come from urban information systems, sensor networks, mapping services, warning systems [5], and other authorized sources of operational information.

The main criteria for evaluating shelters [1, 2, 8, 9] are: the facility's level of physical security; time to reach the shelter; the technical condition of the protective structure; accessibility for different population groups; capacity; risk of secondary damage; suitability of the shelter for a specific type of threat; and the reliability of information about the facility. Depending on the threat scenario, the weight of individual criteria may vary. For example, for a fleeting threat, the minimum time to reach the shelter may be a priority, whereas for a scenario with a high risk of fragmentation damage, the structural characteristics of the facility and its location relative to open areas and dense development take on greater importance.

The system's output is a ranked list of shelters or a recommendation regarding the most appropriate civil protection facility for a specific user, group of users, or management body. For the public, such a recommendation may include the nearest safe shelter, alternative options, and an approximate route [10]. For management bodies, the system can generate an overview of shelter occupancy, high-risk zones, accessibility issues, and potential evacuation routes.

Thus, the research objective can be formulated as the development of a scenario-oriented decision support system that, based on diverse data regarding shelters, the urban environment, users, and threats, performs a multi-criteria assessment of civil protection facilities and generates adaptive recommendations for their use. The main requirement for such a system is the ability to rapidly adjust assessment results in response to changes in the threat scenario, the state of infrastructure, and the spatio-temporal characteristics of the urban environment.

4. Research Results

4.1. General Architecture of the Decision Support System

The proposed decision support system is designed for the adaptive assessment of the suitability of civil shelters under aerial threat conditions. It is based on an information and communication model that combines data on civil protection facilities, characteristics of the urban environment, parameters of the current threat scenario, and individual user parameters. Unlike static shelter maps, such a system must not only display information but also generate recommendations that account for changes in the situation.

The system architecture consists of three interconnected levels: the data collection level, the data processing level, and the decision-making level. The general architecture of the proposed decision support system is shown in Figure 1.

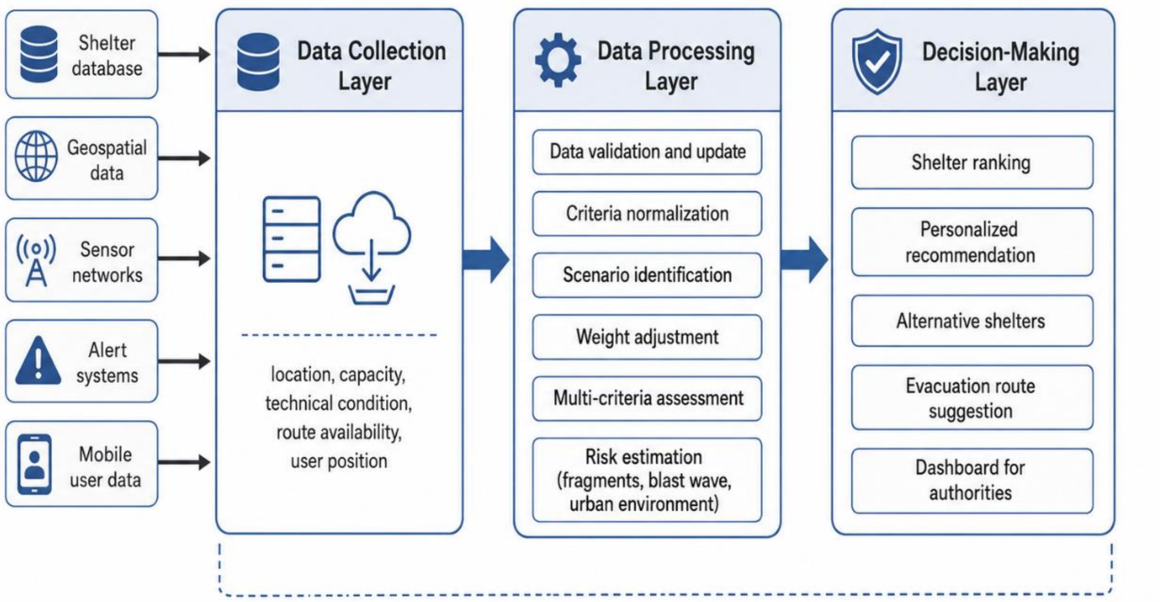

Figure 1: Architecture of the scenario-based decision support system

The data collection level ensures the acquisition of primary information from diverse sources. Such sources may include shelter databases, geoinformation services, sensor networks, facility condition monitoring systems [7], public alert systems [5], as well as users' mobile devices. At this level, an initial set of parameters necessary for further assessment is formed: shelter coordinates, their technical condition, capacity, accessibility, route characteristics, the user's current location, and existing movement restrictions.

The data processing level converts the received information into a form suitable for decision-making. At this level, parameters are normalized, data validity is verified, local criteria are calculated, weighting coefficients are adjusted based on scenarios, and a generalized shelter suitability index is determined. Additionally, this level can account for secondary damage factors [2], including the risks of fragmentation impact, shock wave effects, and difficulties in accessing shelters due to the characteristics of urban development.

The decision-making level generates the practical output of the system. For an individual user, this output is a recommendation regarding the most appropriate shelter and possible alternatives. For civil protection authorities, the system can generate a ranked list of shelters, a map of high-risk zones, an assessment of facility occupancy, and recommendations for organizing evacuation flows [7, 10].

The proposed three-tier architecture allows for the separation of data acquisition, analytical processing, and management decision-making. This ensures the system's scalability, the ability to connect new information sources, and the adaptation of the model to various threat scenarios.

4.2. A Multi-Criteria Model for Assessing the Suitability of Shelters

Assessing the suitability of a shelter under an aerial threat is a multi-criteria task [1, 2, 8, 9], since the safety of a facility cannot be determined by a single parameter, such as distance from the user or capacity. To obtain a well-founded recommendation, it is necessary to consider a set of local criteria that characterize both the shelter itself and the conditions of its use at a specific point in time.

Let a set of local criteria be defined for each shelter, where K is the number of evaluation criteria. Such criteria may include [1, 2, 8, 9]:

- the technical condition of the shelter;
- capacity and current occupancy;
- distance to the user;
- average or predicted evacuation time;
- accessibility of the route;
- suitability of the shelter for people with limited mobility;
- protection against fragmentation damage;
- resistance to shock waves;
- location relative to open terrain, dense development, or potentially hazardous facilities;
- relevance and reliability of information about the shelter.

A summary indicator of a shelter's suitability can be presented as a weighted combination of local criteria [1, 2]:

$$F(s_j) = \sum_{i=1}^{K} a_i f_i(s_j) \tag{1}$$

where $F(s_j)$ is the generalized suitability index of shelter s_j; $f_i(s_j)$ is the value of the i-th local criterion for shelter s_j; a_i is the weighting coefficient of the i-th criterion; K is the number of evaluation criteria.

The weight coefficients a_i determine the relative importance of each criterion in a specific threat scenario. To ensure the correctness of the evaluation, they must satisfy the following conditions:

$$a_i \geq 0, \quad \sum_{i=1}^{K} a_i = 1 \tag{2}$$

Before calculating the generalized indicator, local criteria must be normalized, as they may have different physical natures and different units of measurement. For example, evacuation time is measured in minutes, capacity in the number of people, technical condition can be determined using an expert scale, and the risk of secondary damage as a probabilistic or interval estimate. Normalization allows all criteria to be brought into a comparable form and used in a single assessment model [8, 9].

For criteria whose values need to be maximized, such as technical condition or level of protection, normalization based on the principle of utility maximization can be used. For criteria whose values need to be minimized, such as evacuation time, distance, or the risk of secondary damage, it is advisable to apply inverse normalization. This allows higher values of normalized criteria to be interpreted as better in terms of the shelter's suitability.

The result of the calculation is a ranked list of shelters based on the value of the generalized indicator $F(s_j)$. The most appropriate shelter to recommend is the one with the maximum value of this indicator for the current threat scenario and taking into account the user's individual constraints.

4.3. Scenario-Based Adjustment of Weighting Coefficients

A distinctive feature of the proposed model is that the weighting coefficients of local criteria [1, 2] are not constant across all situations. Their values must vary depending on the aerial threat scenario, the characteristics of the urban environment, and the user group for which the recommendation is being generated. This allows for the adaptation of shelter evaluations to real-world conditions and avoids situations where a single universal set of criteria is applied to fundamentally different types of hazards.

Within the scope of the study, it is advisable to consider several basic threat scenarios: a missile attack, a drone attack [11], a combined or cascading attack, as well as a scenario of increased risk of secondary damage. Each of these scenarios affects the priority of evaluation criteria differently. For example, for a fleeting threat, evacuation time and distance to the shelter become particularly important. For a scenario with a high risk of fragmentation damage, the role of the shelter's structural protection, its location relative to open areas, dense development, and potentially hazardous objects increases. For combined attacks, a comprehensive assessment of the facility's resilience and the possibility of safely relocating the population [10] becomes crucial.

Let the set of possible aerial threat scenarios be defined as:

$$C = \{c_1, c_2, \ldots, c_m\} \tag{3}$$

where C is the set of possible threat scenarios, c_p is a specific threat scenario, and m is the total number of scenarios considered in the model.

For each scenario $c_p \in C$ a corresponding vector of weighting coefficients is formed:

$$A^{(p)} = \{a_1^{(p)}, a_2^{(p)}, \ldots, a_K^{(p)}\} \tag{4}$$

where $a_i^{(p)}$ is the weight coefficient of the i-th criterion for scenario c_p, and K is the number of local evaluation criteria.

Then, the generalized shelter suitability index for a given scenario can be expressed as:

$$F^{(p)}(s_j) = \sum_{i=1}^{K} a_i^{(p)} f_i(s_j) \tag{5}$$

where $F^{(p)}(s_j)$ is the generalized suitability index of shelter s_j for scenario c_p.

Therefore, the recommended shelter can be determined as:

$$s^* = \arg\max_{s_j \in S} F^{(p)}(s_j) \tag{6}$$

where s^* is the recommended shelter, S is the set of available shelters, and $F^{(p)}(s_j)$ is the generalized suitability index of shelter s_j for the current threat scenario c_p.

Weight coefficients may be adjusted based on expert assessment [9], statistical data, results of preliminary modelling, or regression analysis methods. Once a sufficient amount of data has been accumulated, it is advisable to use adaptive models that refine the weight coefficients in accordance with actual assessment results and changes in threat parameters.

For the practical application of the system, it is important that scenario adjustments do not complicate the user's work. The selection of a threat scenario can be performed automatically based on available input data or semi-automatically — with the involvement of a civil protection system operator. In any case, the result should be not only the calculated value of the aggregate indicator but also a clear explanation of why a specific shelter is recommended in a particular situation.

The proposed approach allows for the dynamic nature of aerial threats to be considered and enhances the validity of recommendations. Thanks to scenario-based adjustment of weighting coefficients, the system can change evaluation priorities without restructuring the entire model, which is an important condition for its scalability and practical use in urban civil protection information systems.

4.4. Recommendation Generation Algorithm

The generation of recommendations regarding shelter selection [8, 9, 10] is carried out as a sequence of stages, including the acquisition of input data, the determination of a threat scenario, the calculation of local criteria, the computation of a generalized suitability index, and the ranking of available shelters. This approach ensures the transparency of the system's operation [3] and the possibility of further improving its individual components.

In the first stage, the system receives data on the current location of the user or group of users, a list of available shelters within a specified radius, the characteristics of these shelters, the condition of routes to them, and the parameters of the current threat scenario. If certain data is incomplete or outdated, the system may reduce the weight of the corresponding criterion or mark the recommendation as requiring further verification.

In the second stage, preliminary filtering of shelters is performed. Objects that do not meet the minimum requirements may be excluded from further consideration: those in critically poor technical condition, overloaded, lacking an accessible route, or unavailable to a specific population group. This prevents the recommendation of a shelter that is formally the closest but is actually unsuitable.

In the third stage, the values of local criteria are calculated for each shelter. Criteria related to distance, evacuation time, capacity, accessibility, and risk level are normalized. Afterward, a corresponding vector of weighting coefficients is determined for the current threat scenario.

In the fourth stage, a generalized suitability index for each shelter is calculated. The resulting values are used to generate a ranked list of civil protection facilities [8, 9]. The shelter with the highest value of the generalized suitability index is considered a priority for recommendation, if it meets the user's individual constraints and current accessibility conditions.

In the fifth stage, the system generates a result for the user or operator. For the public, the recommendation may include the primary shelter, alternative options, an approximate route [10], and an explanation of the main reasons for the selection. For civil protection authorities, the result can be presented as a dashboard displaying the status of shelters, facility occupancy, high-risk zones, and potential evacuation issues.

The general algorithm of the system's operation can be presented in the following sequence:

1. Obtaining data on users, shelters, the urban environment, and the threat scenario.
2. Verifying the relevance and completeness of the input data.
3. Preliminary filtering of unsuitable or inaccessible shelters.
4. Calculating and normalizing local criteria.
5. Determining weighting coefficients according to the threat scenario.
6. Calculating a generalized suitability index for shelters.
7. Ranking of available shelters.
8. Generation of recommendations for the user or management authority.

The overall structure of the recommendation generation algorithm is presented in Figure 2.

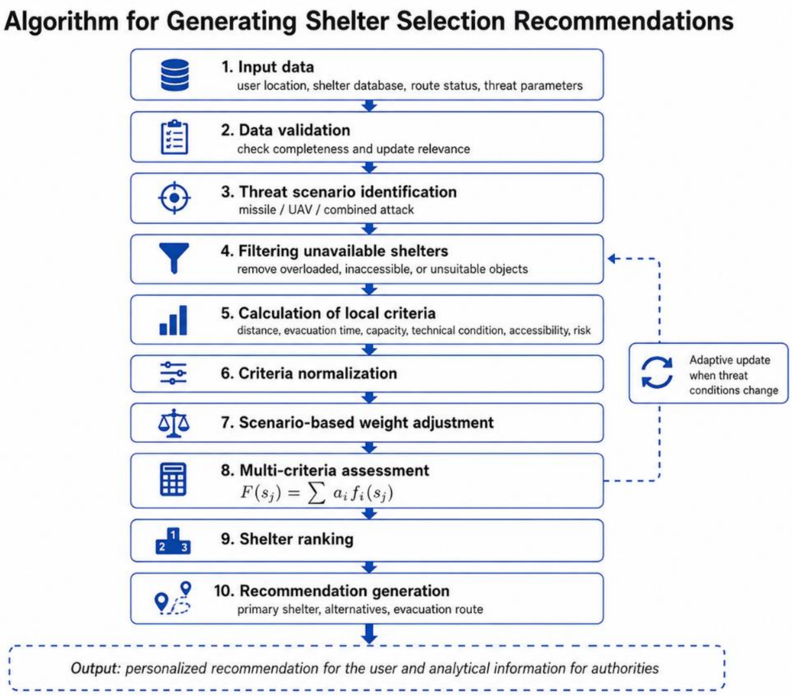

Figure 2: Algorithm for generating shelter selection recommendations

The proposed algorithm can be implemented as part of a mobile application, a city information system, or a specialized decision support platform [3] for civil protection agencies. Its advantage lies in the ability to combine personalized recommendations for the public with generalized analytics for management structures.

4.5. Results of Preliminary Model Testing

To verify the proposed model's performance, preliminary testing was conducted on a training dataset containing a set of hypothetical aerial threat scenarios [1, 2], shelter parameters, urban environment characteristics, and route accessibility data. The purpose of the testing was to evaluate the system's ability to quickly process input data, generate a ranked list of shelters, and ensure that the results align with expert assessments.

The testing considered scenarios that differed in threat type, secondary damage risk level, spatial distribution of users, and characteristics of available shelters. For each scenario, the system performed preliminary filtering of objects, calculation of local criteria, scenario-based adjustment of weighting coefficients, determination of a generalized suitability index, and generation of recommendations for shelter selection.

Preliminary testing results showed that the proposed model ensures rapid scenario processing with an average time of up to 0.8 seconds. This performance metric is crucial for decision support systems that must operate in rapidly changing environments and require timely updates to recommendations.

A comparison of the system's results with expert assessments demonstrated agreement in 92% of cases. This indicates that the multi-criteria model with scenario-based adjustment of weighting coefficients is capable of replicating the logic of expert shelter selection while providing a formalized and scalable approach to evaluation.

The impact of using updated spatial data on the accuracy of determining shelter availability was assessed separately. Incorporating data on user locations and route parameters [4, 10] made it possible to reduce the error in assessing shelter availability to 6%. This confirms the feasibility of integrating geospatial data and mobile services into the civil protection decision support system.

The model also demonstrated flexibility when the threat scenario changed. Specifically, when transitioning from a missile attack scenario to a drone attack scenario or a combined attack, the system adjusted the priority of local criteria without requiring a complete model overhaul. This is an important advantage for practical application in urban information systems, where hazard parameters can change rapidly.

However, the test results should be considered preliminary, as they were obtained from a training sample. Further validation of the model requires expanding the set of scenarios, using real or near-real geospatial data, refining the technical condition parameters of shelters, and involving civil protection experts for an independent verification of the ranking results.

5. Conclusions

This article proposes a scenario-based decision support system for assessing the suitability of civil shelters in the face of aerial threats. Unlike approaches based primarily on static information about the location of shelters [8, 9], the proposed model takes into account the technical condition of civil protection facilities, their accessibility, spatial location, urban environment parameters, user characteristics, and the current threat scenario.

The developed information and communication model has a three-tier architecture, comprising a data collection layer, a data processing layer, and a decision-making layer. This approach ensures a logical separation of the processes of information acquisition, analytical processing, and the formulation of recommendations for the public or civil protection authorities. The system architecture is scalable and allows for the integration of new data sources, including geospatial services, sensor networks, urban information platforms, and warning systems.

A multi-criteria approach [1, 2, 8, 9] is used to evaluate shelters, which involves calculating a composite suitability index based on local criteria and weighting factors. An important feature of the model is the scenario-based adjustment of weighting coefficients depending on the type of aerial threat. This allows for changing the priority of evaluation criteria without rebuilding the entire model and adapting recommendations to different hazard conditions.

The proposed approach allows for the consideration not only of direct hazard factors but also of secondary effects of aerial attacks, including fragmentation damage, shock wave effects, and potential cascade failures in an urban environment. Taking these factors into account increases the validity of shelter safety assessments and can contribute to more effective planning of evacuation routes.

Preliminary testing of the model on a training sample demonstrated the ability to rapidly process threat scenarios, the consistency of the system's results with expert assessments, and a reduction in the error of determining shelter accessibility using updated spatial data. The results confirm the potential of the proposed approach for building digital civil protection platforms integrated with urban information systems.

Further research should focus on expanding the set of threat scenarios, utilizing real geospatial and sensor data, refining methods for determining weighting coefficients, and applying machine learning methods [12] to forecast threat dynamics and generate risk profiles for urban areas. A separate area of development is the practical implementation of the system in the form of a mobile application and an analytical dashboard for civil protection authorities.

Declaration on Generative AI

During the preparation of this work, the author(s) used ChatGPT (GPT-5.5 Thinking) in order to: perform grammar and spelling checks, support language editing, and prepare Figures 1 and 2. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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