УДК 004.62 DOI https://doi.org/10.35546/kntu2078-4481.2025.1.2.22

Л. М. ОЛЕЩЕНКО
кандидат технічних наук,
доцент кафедри програмного забезпечення комп'ютерних систем
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
ORCID: 0000-0001-9908-7422

АЛГОРИТМІЧНО-ПРОГРАМНИЙ МЕТОД ДЛЯ РОЗРАХУНКУ ОПТИМАЛЬНОГО РОЗМІЩЕННЯ УКРИТТІВ З ВИКОРИСТАННЯМ API ТА КАРТОГРАФІЧНИХ ДАНИХ

У сучасних українських містах розміщення укриттів здебільшого управляється за допомогою статичних ГІС-орієнтованих програм, які надають інформаційні карти без реального часу оптимізації чи прогнозного аналізу. Ці інструменти допомагають знаходити укриття, але не враховують динамічні зміни щільності населення, транспортної доступності чи прогалин у покритті. Існуючі рішення не використовують складні математичні моделі, а базуються на заздалегідь визначених критеріях та історичних планах, що може призводити до нерівномірного доступу до укриттів, особливо в районах із високою щільністю населення або обмеженою мобільністю. На відміну від деяких міжнародних рішень, що інтегрують моделювання ГІС та аналіз транспортних мереж, українське програмне забезпечення не повністю адаптується до швидкої урбанізації та змін у міській інфраструктурі, що підкреслює потребу у більш удосконалених підходах з оптимізацією в реальному часі для покращення готовності до надзвичайних ситуацій. Стаття присвячена розробці оптимізованого підходу до розміщення нових укриттів у міських умовах шляхом використання обчислювальних алгоритмів та геопросторових даних. Запропонований алгоритмічно-програмний метод враховує демографічну статистику та просторовий аналіз для визначення найбільш ефективних місць розташування укриттів. У великих містах України, таких як Київ, де спостерігається висока щільність населення, результати дослідження свідчать про необхідність розміщення великих укриттів поблизу основних транспортних вузлів. У передмістях великих міст, таких як Львова та Одеси, укриття доцільно розташовувати в межах 5-кілометрової зони від густонаселених районів, щоб забезпечити зручний доступ через дорожню та залізничну мережу. Для сільських територій передбачається рівномірне розміщення більшої кількості менших укриттів для покриття великих площ.

У дослідженні використано офіційну карту укриттів міста Києва для розробки та реалізації моделі Хаффа в середовищі Python, що дозволяє враховувати поточний розподіл населення та укриттів. Основні етапи запропонованого методу включають розрахунок центру ваги для щільних кластерів населення, генерацію потенційних місць для укриттів, інтерактивну візуалізацію розподілу укриттів та коригування розташування на основі реальних обмежень. Запропонована методика інтегрується з платформами GIS (QGIS, ArcGIS) та дозволяє приймати обґрунтовані рішення щодо розміщення укриттів у режимі реального часу.

Ключові слова: *алгоритмічно-програмний метод, укриття, міське планування, геопросторовий аналіз, модель Хаффа, оптимізація, GIS.*

L. M. OLESHCHENKO
Candidate of Technical Sciences,
Associate Professor at the Computer Systems Software Department
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
ORCID: 0000-0001-9908-7422

ALGORITHMIC-SOFTWARE METHOD FOR CALCULATING OPTIMAL SHELTER PLACEMENT USING API AND MAPPING DATA

In contemporary Ukrainian cities, shelter placement is primarily managed through static, GIS-based software that provides informational maps without real-time optimization or predictive analytics. These tools help residents locate shelters but do not dynamically address coverage gaps, population density shifts, or transportation accessibility. Lacking advanced mathematical models, existing solutions rely on predefined criteria and historical planning rather than data-driven optimization, resulting in potential disparities in shelter accessibility, particularly in high-density or mobility-limited areas. Unlike some international solutions that integrate GIS modeling and transportation analysis, Ukrainian software does not fully adapt to rapid urbanization and infrastructural changes, highlighting the need for a more advanced, real-time optimization approach to improve emergency preparedness. The article focuses on developing an optimized approach for shelter placement in urban environments using computational algorithms and geospatial data. The proposed algorithmic-software method integrates demographic statistics and spatial analysis to determine the most effective shelter *locations. In large Ukrainian cities like Kyiv, where population density is high, the findings suggest that large-capacity shelters should be placed near major transportation hubs. In suburban areas surrounding cities like Lviv and Odesa, shelters should be positioned within a 5 km radius of densely populated regions to ensure accessibility via road and rail networks. For rural areas, a more evenly distributed network of smaller shelters is recommended to maximize coverage across larger territories.*

The research utilizes an official bomb shelter map of Kyiv to develop and implement the Huff model in Python, accounting for existing population distribution and shelter locations. The core steps of the methodology include computing a weighted central point for dense population clusters, generating potential shelter locations, interactive GIS based visualization, and refining placements based on real-world constraints. The proposed method integrates with GIS platforms such as QGIS and ArcGIS, enabling real-time decision-making for optimized shelter distribution.

Key words: *algorithmic-software method, shelters, urban planning, geospatial analysis, Huff model, optimization, GIS.*

Problem statement

In contemporary Ukrainian cities, the strategic placement of shelters and evacuation points is essential for ensuring public safety and effective response. With ongoing urban expansion and increasing population densities, optimizing the distribution of shelters becomes a key priority for urban planners.

Existing Ukrainian software solutions for shelter placement primarily function as static and informational tools rather than dynamic, optimization-driven systems. These applications typically provide users with maps and databases indicating the locations of designated shelters, often relying on manually collected data and predefined criteria. They serve as essential resources for public awareness and emergency preparedness, enabling residents to identify nearby shelters based on their address or GPS location. These tools do not actively optimize shelter distribution or address coverage inefficiencies in real-time.

Most of these software solutions rely on GIS-based mapping without incorporating advanced analytical models. They display shelters' locations but lack predictive capabilities, meaning they do not account for population density changes, transportation accessibility, or potential gaps in coverage. Many existing platforms do not integrate real-time data, making it difficult to adapt shelter placement strategies in response to urban development, population shifts, or infrastructural changes. These applications often do not employ mathematical optimization techniques to minimize accessibility disparities across different city districts. Instead, shelter locations are generally determined based on historical planning or administrative decisions rather than data-driven models. As a result, areas with high population density or limited mobility options may suffer from inadequate shelter accessibility, leaving residents vulnerable in emergency situations.

While some international solutions incorporate GIS modeling and transportation network analysis, they may not fully account for the rapid urbanization and infrastructural challenges specific to Ukrainian cities. The lack of real-time adaptability and optimization in existing software highlights the need for a more advanced approach that actively improves shelter placement through dynamic modeling and scenario-based analysis.

This research focuses on enhancing shelter placement by utilizing computational algorithms and data-driven decision-making processes. By integrating geospatial data with demographic statistics, the research offers a structured methodology to assist city authorities in determining optimal locations for shelters. This approach is particularly relevant for major Ukrainian metropolitan areas, where rapid urbanization and shifting population densities necessitate adaptive planning strategies.

Related research

Traditional approaches to shelter placement often overlook critical factors such as the distribution of residents, transport accessibility, and the varying levels of risk across different areas. The gravity-based Huff model presents itself as a valuable tool for optimizing shelter placement by accounting for these factors [1].

Gravity models are widely utilized in urban planning and spatial economics to assess location attractiveness and movement dynamics. In this context, the attractiveness of a shelter is defined by factors such as its size, capacity, and safety features. The Huff model calculates the probability that individuals will select a particular shelter based on its accessibility and appeal [2]. The article [3] explores site selection models for natural disaster shelters, categorizing them by objectives and hierarchy, analyzing solution methods, and highlighting future research directions for optimizing shelter location and resource efficiency.

The article [4] focuses on the spatial optimization of emergency shelters using urban-scale evacuation simulations. It analyzes short-term fixed shelters, identifying gaps in evacuation efficiency and areas with the highest number of non-evacuated people. The study provides quantitative data on shelter demand, necessary additions, and optimal shelter distribution across different urban areas. The findings offer a data-driven approach to improving emergency shelter planning, enhancing disaster response efficiency, and optimizing urban resource allocation. The urban-scale evacuation simulation allocates evacuees from demand points to nearby shelters, considering multiple objectives. A dataset of demand points, shelters, and road networks was analyzed using network analysis to calculate evacuation distances. Python processed the data to determine evacuee distribution and evacuation times, with spatial statistics and visualization completed in ArcGIS (Fig. 1).

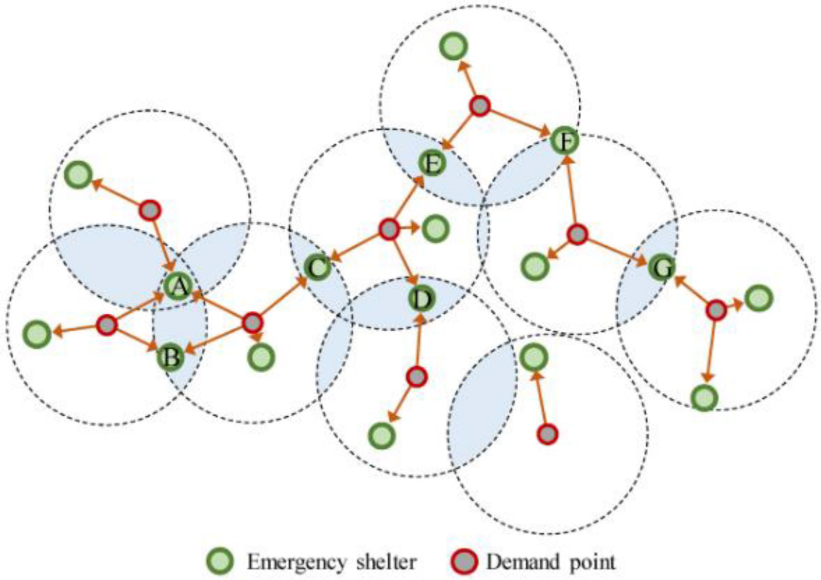

Fig. 1. A simplified conceptual diagram of the evacuation simulation [4]

For non-evacuated individuals, spatial optimization redistributed them to plots without shelters or available resources. Priority was given to plots with over 1000 non-evacuated people, ensuring shelter areas exceeded 2000 m² and met relevant standards. Overlapping and concentrated target plots were optimized for resource efficiency and feasibility. Fig. 2 illustrates the spatial optimization of emergency shelters, where black points represent demand locations that require evacuation. The red areas indicate plots with existing shelter resources, while the green areas mark potential locations for new shelters. The black lines and arrows show evacuation routes connecting demand points to shelters. Overlapping circles suggest areas where multiple shelters serve the same demand points, highlighting the need for efficient resource distribution. Letters (A–I) denote key optimization target plots, where additional shelters can be strategically placed to maximize coverage and improve evacuation efficiency. Black points represent unserved demand areas, red plots indicate existing shelter resources, and green plots are potential new shelter sites. To ensure efficiency, priority is given to plots with over 1000 non-evacuated people, shelters must exceed 2000 m², and target plots should be concentrated rather than scattered. The final shelter size and type are determined based on standards, supply, and demand analysis.

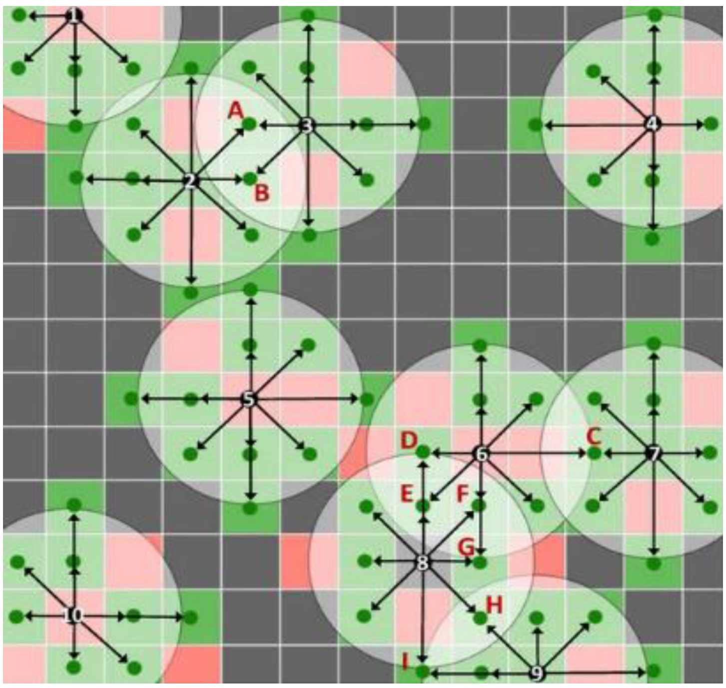

Fig. 2. The concept of optimizing shelter locations [4]

The research [5] focuses on optimizing shelter locations and evacuation routes while considering uncertainties in disaster scenarios. It proposes a two-stage stochastic evacuation model using Benders decomposition to minimize total evacuation time by efficiently assigning evacuees to shelters and routes. The model incorporates second-order cone programming and employs advanced techniques like multicuts, Pareto-optimal cuts, and a cutting plane algorithm to improve computational efficiency. Practical tests with up to 1,000 scenarios demonstrate the effectiveness of the approach in solving large-scale evacuation problems within reasonable time limits.

The goal of this article is to optimize shelter placement using proposed computational algorithm and geospatial data, providing a structured methodology for city authorities to adapt to urbanization and population shifts, ensuring strategic shelter distribution, improved accessibility, and enhanced public safety in large Ukrainian metropolitan areas.

Proposed method for calculating optimal shelter placement

This research finds that in high-density urban areas such as Kyiv, large-capacity shelters should be situated near major transportation hubs. In suburban areas surrounding cities like Lviv and Odesa, shelters should be positioned within a 5 km radius of densely populated regions to ensure accessibility via road and rail networks. Rural areas, on the other hand, require a greater number of smaller shelters distributed over larger areas to maximize coverage.

The research utilizes data from an official bomb shelter map of Kyiv to develop and apply the Huff model in Python, taking into account population density and the current distribution of shelters. While shelter maps help residents locate the nearest safe place, challenges arise in densely populated areas where high demand may exceed the available shelter capacity. This issue becomes particularly critical when shelters have limited space, potentially leading to overcrowding and access difficulties during emergencies (Fig. 3). The research aims to address these concerns by optimizing shelter distribution and accessibility for residents.

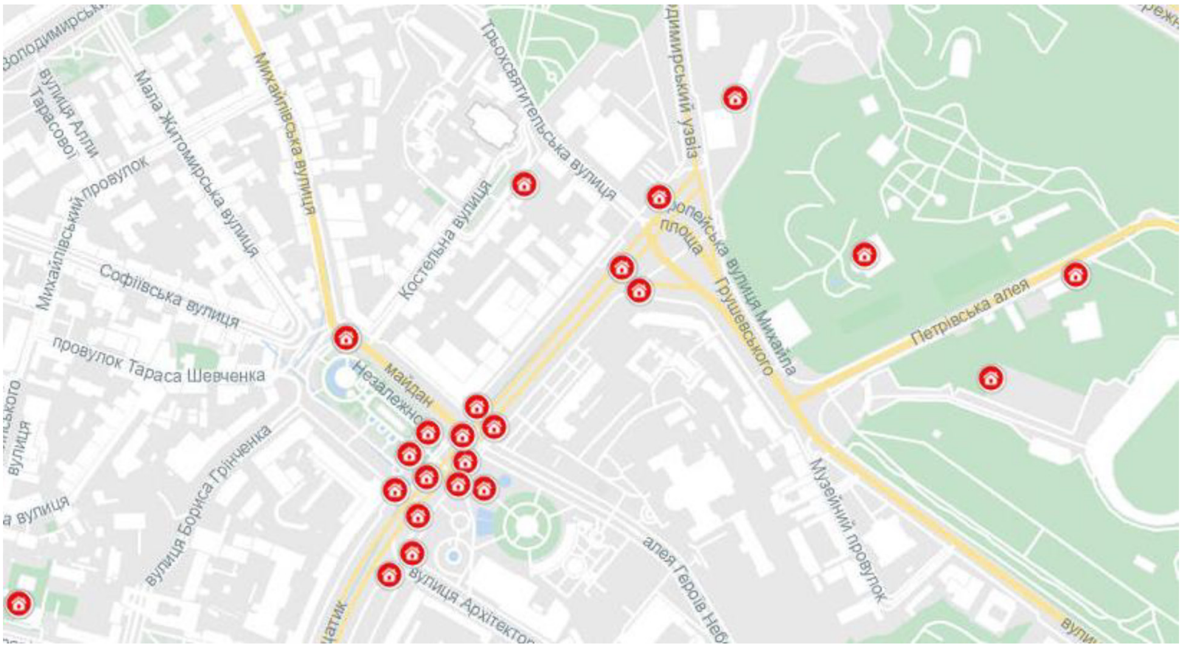

Fig. 3. Fragment of the shelter map in Kyiv [6]

The proposed method ensures that shelters are optimally positioned to enhance accessibility while addressing variations in population density. The probabilistic Huff model supports this optimization process (Fig. 4).

The proposed methodology follows core steps.

1. *Computing a weighted central location for population clusters based on density analysis*. This process examines the spatial distribution of residents and determines a centroid that reflects population density. The latitude and longitude of each cluster are weighted according to the number of residents at that location. By summing these weighted values and dividing by the total population, the model identifies an optimal reference point for new shelters.

2. *Generating potential shelter locations in proximity to the computed central point*. Using the weighted center as a reference, new shelter sites are strategically distributed in a radial or grid-based layout to enhance accessibility. Factors such as distance, population coverage, and transportation infrastructure influence the placement strategy.

3. *Mapping and visualizing existing shelters, population density, and proposed locations through an interactive GIS platform*. The generated map offers an intuitive representation of shelter distribution, highlighting underserved regions and assessing the effectiveness of the proposed locations. Tools like Folium and GIS software enhance the visual analysis.

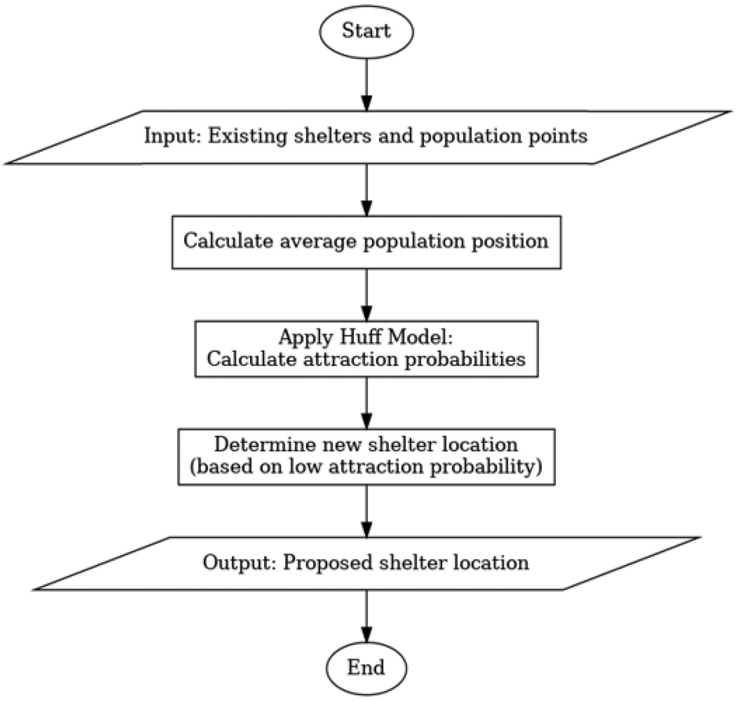

Fig. 4. Algorithm workflow of the proposed method

4. *Refining the shelter distribution iteratively based on real-world constraints and expert feedback*. The preliminary locations are adjusted to account for land use regulations, infrastructure feasibility, and accessibility requirements. Input from urban planners and emergency management authorities ensures that the final shelter placements meet safety standards and community needs.

Algorithmic implementation steps

The process of optimizing shelter locations involves several computational steps to ensure that the shelters are strategically positioned to maximize accessibility and serve the most densely populated areas. Below is a detailed breakdown of the methodology used for this implementation.

Step 1. Compute the weighted average position of population points.

To accurately determine a central reference point based on population distribution, a weighted average of the geographical coordinates (latitude and longitude) is computed. The weight assigned to each coordinate is proportional to the population at that specific location. This ensures that locations with higher populations exert a greater influence on the computed center.

By using this weighted approach, the calculated central point better reflects the distribution of the population rather than just the arithmetic mean of coordinates.

Software implementation:

```
# Function to calculate weighted average position
def calculate_average_population_position(points):
    total_population = sum(point['population'] for point in points)
    avg_lat = sum(point['lat'] * point['population'] for point in points) / total_population
    avg_lon = sum(point['lon'] * point['population'] for point in points) / total_population
    return avg_lat, avg_lon
# Sample population data
population_points = [
    {'name': 'Point 1', 'lat': 50.4515, 'lon': 30.5250, 'population': 1000},
    {'name': 'Point 2', 'lat': 50.4535, 'lon': 30.5265, 'population': 800},
    {'name': 'Point 3', 'lat': 50.4520, 'lon': 30.5220, 'population': 1200},
]
# Calculate central population-weighted point
avg_lat, avg_lon = calculate_average_population_position(population_points)
```

Step 2. Generate potential shelter locations.

Once the weighted central point is determined, it serves as a reference for placing new shelters. The shelter locations are generated using a systematic approach, ensuring they are placed in a way that optimizes coverage of highly populated areas. The shelters are arranged in a radial pattern around the central point to improve accessibility and distribution. Software implementation:

```
# Function to generate new shelter locations
def generate_new_shelters(base_lat, base_lon, count):
    return [
        {'name': f'New Shelter {i+1}', 'lat': base_lat + 0.001 * i, 'lon': base_lon + 0.001 * i}
        for i in range(count)
    ]
# Generate three new shelters based on the central population point
new_shelters = generate_new_shelters(avg_lat, avg_lon, 3)
```

This method ensures that new shelters are systematically positioned within the vicinity of high-density areas, maximizing the number of people they can serve efficiently.

Step 3. Visualizing the data on an interactive map.

To facilitate analysis and decision-making, an interactive map is created to visualize existing shelters, population points, and the newly proposed shelters. The Folium library is used to generate a user-friendly map, where different markers are used to represent population points, current shelters, and new shelters:

```
# Function to create and visualize the map
def create_map(existing_shelters, population_points, new_shelters, map_title):
   m = folium.Map(location=[50.4501, 30.5234], zoom_start=15)
      # Add existing shelters as blue markers
   for shelter in existing_shelters:
      folium.Marker(
         location=[shelter['lat'], shelter['lon']],
         popup=shelter['name'],
         icon=folium.Icon(color='blue', icon='info-sign')
      ).add_to(m)
      # Add population points as green circles
   for point in population_points:
      folium.Circle(
         location=[point['lat'], point['lon']],
         radius=point['population'] * 0.1,
         color='green',
         fill=True,
         fill_opacity=0.6,
         popup=f»{point['name']} - Population: {point['population']}»
      ).add_to(m)
      # Add new shelters as red markers
   for shelter in new_shelters:
      folium.Marker(
         location=[shelter['lat'], shelter['lon']],
         popup=shelter['name'],
         icon=folium.Icon(color='red', icon='info-sign')
      ).add_to(m)
# Define existing shelters
existing_shelters = [
   {'name': 'Shelter 1', 'lat': 50.4501, 'lon': 30.5234},
   {'name': 'Shelter 2', 'lat': 50.4547, 'lon': 30.5238}
]
# Create and display the map
map_object = create_map(existing_shelters, population_points, new_shelters, "Shelter
Optimization Map")
```

The *create_map* function takes lists of shelters and population data and generates a map centered on Kyiv (50.4501, 30.5234) with a zoom level of 15. Existing shelters are marked with blue icons, new shelters with red icons, and population points are represented as green circles, where the circle size is proportional to the population.

The interactive map provides a clear representation of how shelters are distributed relative to population density. It aids decision-makers in evaluating the effectiveness of proposed locations and making necessary adjustments if required.

Research results

Proposed algorithmic-software method ensures that new shelters are placed in optimal locations based on population density. The weighted average calculation enables precise determination of a central reference point, while the radial placement strategy improves accessibility. By integrating an interactive map, decision-makers can analyze shelter distribution and make informed choices to enhance coverage in high-density areas (Fig. 5).

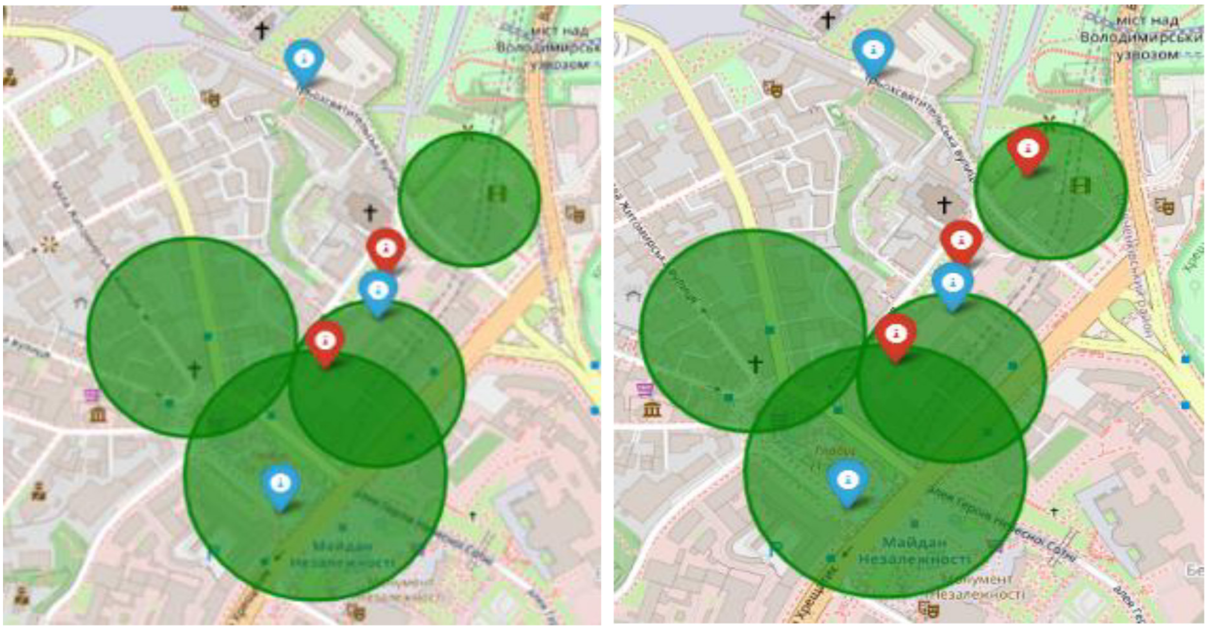

Fig. 5. Software simulation new shelter placements while considering the attractiveness of existing shelters and population density

The images depict an interactive map simulation for optimizing shelter placement based on population density and the attractiveness of existing shelters. The green circles represent the coverage areas of the shelters, while the red and blue markers indicate the locations of existing and newly proposed shelters. The second image appears to illustrate an improved shelter distribution, with optimized placement to cover more densely populated areas effectively. This suggests that the algorithm successfully refines shelter locations to minimize coverage gaps and enhance accessibility. The system supports integration with GIS platforms such as QGIS or ArcGIS via API connections, allowing urban planners to dynamically update shelter locations based on real-time data. APIs enable automated data retrieval from government databases, population statistics, and transportation networks, ensuring that shelter placement is continuously adjusted to urban expansion and demographic shifts. Through API-based interaction, users can run optimization queries, visualize different shelter placement scenarios, and simulate emergency response times under varying population densities and traffic conditions. For instance, in a district with a population density of 10,000 people per square kilometer, the algorithm can recommend placing high-capacity shelters within a 500-meter radius of major residential areas. In contrast, suburban areas with lower densities may require smaller shelters distributed over a larger radius (e.g., 2–5 km) to ensure accessibility via road networks. The system can also be used to analyze accessibility during peak traffic hours, suggesting alternative shelter locations based on predicted congestion patterns. By leveraging real-time data and algorithmic optimization, city planners can enhance emergency preparedness, ensuring that shelters are optimally positioned to serve the maximum number of residents efficiently. The model can further be expanded to account for factors such as infrastructure constraints, land-use policies, and multi-modal transportation options. The suggested algorithm presents a scalable and effective solution for optimizing shelter placement in urban environments, particularly in major Ukrainian cities. By utilizing population density data, geospatial analysis, and mathematical modeling, the approach ensures that shelters are positioned strategically to enhance accessibility, reduce coverage gaps, and improve public safety. Its adaptability allows it to accommodate different city sizes, population distributions, and additional factors such as transportation networks and shelter capacities. Unlike existing Ukrainian software, which primarily provides static and informational tools, this method integrates advanced optimization techniques to address spatial disparities and accessibility challenges. While international solutions often emphasize GIS-based modeling and transportation analysis, they may not fully consider the dynamic nature of urban development in Ukraine. By applying the Huff gravity model, proposed approach bridges those gaps, taking into account both the accessibility and attractiveness of shelters.

Conclusions and future work

The proposed method strengthens urban safety by enabling data-driven decision-making and real-time scenario modeling through integration with GIS platforms like QGIS or ArcGIS. Future advancements may include real-time data integration, adaptation for other emergency infrastructures, and the use of machine learning to predict population shifts and urban expansion.

The proposed software method establishes a solid foundation for more sophisticated urban planning strategies, ensuring that safety infrastructure evolves in response to changing demographics and city landscapes.

References

1. Lei He, Ziang Xie. Optimization of Urban Shelter Locations Using Bi-Level Multi-Objective Location-Allocation Model. *International Journal of Environmental Research and Public Health*. 2022. 19(7): 4401. DOI: https://doi.org/10.3390/ijerph19074401
2. Kaili Dou, Qingming Zhan. Accessibility Analysis of Urban Emergency Shelters: Comparing Gravity Model and Space Syntax. *International Conference on Remote Sensing, Environment and Transportation Engineering*. 2011. Nanjing, China. P. 5681–5684. DOI: https://doi.org/10.1109/RSETE.2011.5965642
3. Ma Y., Xu W., Qin L., Zhao X. Site Selection Models in Natural Disaster Shelters: A Review. *Sustainability*. 2019. 11(2): 399. https://doi.org/10.3390/su11020399
4. Chen W., Shi Y., Wang W., Li W., Wu C. The Spatial Optimization of Emergency Shelters Based on an Urban-Scale Evacuation Simulation. *Applied Sciences*. 2021. 11(24): 11909. https://doi.org/10.3390/app112411909
5. Bayram V., Yaman H. Shelter location and evacuation route assignment under uncertainty: A benders decomposition approach. *Transportation Science*. 2018. 52(2). P. 416–436. DOI: https://doi.org/10.1287/trsc.2017.0762
6. Map of shelters in Kyiv. URL: https://gis.kyivcity.gov.ua/shelter/ (access date: 05.12.2024).