Chapter 21
Enhancing Urban Solid Waste Management Through an Integrated Geographic Information System and Multicriteria Decision Analysis: A Case Study in Postwar Reconstruction

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1   Introduction

Urban sanitation is a pressing concern within cities, exacerbated by the sustainability concept (Cirella et al., 2007; Cirella & Tao, 2008, 2009a, 2009b; Cirella & Zerbe, 2014; McGranahan, 2015; Wankhade, 2015; Andersson et al., 2016; Adekola et al., 2021; Ferdous et al., 2022). The surge in population density and urban expansion demands fresh, sustainable strategies in the field of solid waste collection and

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transportation. As recycling technologies diversify in response to sustainability needs (Cirella, 2020; Oniszczuk-Jastrząbek et al., 2020; Cirella et al., 2020; Cirella, 2022), the challenge arises of determining the most efficient and eco-friendly routes for transporting waste from consumers to different recycling facilities, such as waste sorting stations, landfills, or facilities engaged in mechanical-biological or thermal processing (Sulemana et al., 2018; Wu et al., 2020; Wang et al., 2022). A key issue to address is the identification of optimal locations for municipal solid waste transfer stations. These stations serve as key transit points during the initial collection phase enroute to the disposal stage. Municipal solid waste transfer stations are infrastructure points designed to facilitate the transfer of waste from garbage trucks, containers, and other collection equipment to larger containers for onward transportation to recycling plants or landfills (Hu & Yang, 2020; Höke & Yalcinkaya, 2021; Monzambe et al., 2021; Cobos-Mora et al., 2023; Devaki & Shanmugapriya, 2023). These locations must adhere to urban, environmental, and sanitary criteria, limiting the choice of suitable sites and presenting challenges for urban planners and experts. Traditional expert methods are often inadequate due to the inability to simultaneously assess all constraints, especially when parameters are rapidly evolving. A potential solution lies in the utilization of a geographic information system (GIS) in conjunction with multicriteria decision analysis (MCDA). This combination enables the determination of optimal facility locations on urban maps. The incorporation of MCDA includes expert opinions, offering a means to integrate inputs from public hearings, expert discussions, and municipal meetings.

This chapter employs the integration of MCDA and GIS to identify potential locations for a municipal solid waste transfer station while integrating expert opinions and a broad spectrum of parameters. The principal approach for determining the site of sanitation facilities is through expert assessment, a method characterized by selection grounded in the specialized experience of experts. This approach is prevalent in both developed and developing countries. Commonly, expert assessment methods reinforce the selection of sanitation facility locations (Alam & Mondal, 2019; Shermin & Rahaman, 2021; Ferdous et al., 2022; Kahraman et al., 2022; Adugna, 2023). Experts employ a "radius search" approach, wherein the maximum permissible distance between the sanitation facility and potential recycling destinations—such as ground disposal sites, biomechanical processing plants, or recycling companies—is determined (Santana et al., 1990; Budihal & Banakar, 2020; Chen & Güttel, 2023). A waste roadmap is often utilized, schematically depicting the region with the waste-generating point at its center. In instances where multiple waste generation points exist, such as in agglomerations where several settlements form clusters, a compromise center is sought. During the selection of candidate facility locations, experts consider various criteria, including proximity to structures, land use, access to highways, hydrology of the area, and more. However, the aforementioned method exhibits drawbacks, chiefly its reliance on subjective expert judgment and the need for substantial on-site research, leading to financial strain and time consumption.

This issue can be addressed through the application of GIS technology. GIS assumes a significant role in determining optimal sites for sanitation facilities. The

merits of a GIS-driven placement strategy lie in its capacity to expedite site selection processes, curtail associated expenses, and furnish digital datasets for ongoing site surveillance. The utilization of GIS in the context of sanitation facility siting is backed up by an extensive list of example projects (Karakuş et al., 2020). The matter of modeling the positioning of sanitation facilities within urban environments has also garnered attention from researchers across the world. Notably, methodologies akin to those employed in identifying landfill locations have been explored in the literature (Ahmad et al., 2016; Barzehkar et al., 2019; Kareem et al., 2021; Dolui & Sarkar, 2021; Aslam et al., 2022; Ali et al., 2023). The matter of analyzing the placement of container sites for the separate collection of municipal solid waste is addressed by Kornienko and Koshma (2016). Their research highlights and explores the challenge of managing municipal solid waste during the initial collection stage, using the residential areas of the city of Chernihiv, Ukraine. However, this study falls short of providing a comprehensive overview and assessment of the effectiveness and compliance with norms within the entire solid waste management system of the city. Moreover, the analysis was conducted in isolation without establishing connections with other components of the solid waste management infrastructure.

In another study, the siting of sanitation facilities within urban settings was investigated by Eiselt and Marianov (2015). This research encompassed a spatial analysis that underwent a comparative evaluation against established legal standards across distinct regions of Chile. The authors analyzed the activities of applicable factors in relation to the optimal placement of landfills. Notably, they devoted significant attention to the methodologies associated with landfill location, particularly concerning waste disposal via landfilling. To further explain this, they explored landfill placement, approaching this from both an economic and environmental perspective. However, they did not incorporate an assessment of the potential impacts of diverse urban planning processes on the efficiency of the solid waste management system. Other relevant research includes a unique focus on the subject of incinerator placement, evident from the study by Tavares et al. (2011) who introduce a method of spatial multicriteria assessment to evaluate the suitability of land on the island of Santiago, Cape Verde. This method merges an analytical hierarchical process for evaluating selected criteria with the use of GIS for spatial data analysis. A similar theme is explored by Xue et al. (2015), who examine the placement of waste incineration plants within Singapore. The focus of this study centers on the efficiency of incineration as a means to alleviate strain on the city's transportation system. However, this approach should be considered economically impractical for larger countries such as Ukraine which outrightly prohibit the use of incineration processing within urban limits (as stipulated by the Ukrainian directive DBN B.2.2-12:2019).

Despite the substantial body of literature on this subject, the issue of the location of municipal solid waste transfer stations has not been fully investigated. The challenge arises from the lack of clear coordination of interests among all relevant stakeholders, which, is fair to state, is integral to mitigating societal tension. This research proposes that the integration of GIS and MCDA offers a viable resolution to this predicament and serves as a useful mechanism for addressing the task of

determining sanitary facility locations. In doing so, while GIS facilitates efficient data manipulation and presentation, MCDA ensures a coherent prioritization of potential locations based on a diverse array of criteria. This dual process subdivides the issue into manageable components, systematically analyzing each segment independently before organizing their logical integration (Jelokhani-Niaraki & Malczewski, 2015). As a result, this synergy of MCDA data analysis with GIS improves on conventional methods by delivering heightened speed alongside enhanced comprehensiveness.

2 Methods

2.1 Research Rationale

The rationale behind conducting this research is to contribute to Ukraine's postwar reconstruction effort and to offer insights to decision-makers involved in municipal solid waste management within urban settings, particularly those with high levels of urbanization. As such, the challenge of siting and operating sanitation facilities has gained the attention of various Ukrainian scholars. Significant contributions pertaining to the urban dimension of this issue have been made by Zolotar (2012), Klyushnychenko (2014), and Vlasenko and Ageeva (2019), among others. This chapter seeks to provide additional information regarding optimal site locations. At a foundational level, it functions as a demonstrative illustration of infrastructure development and nation building for the country as it embarks on the postwar reconstruction period.

2.2 Study Area

The city of Vinnytsia, Ukraine, is situated about 250 km southeast of the Ukrainian capital, Kyiv (Fig. 21.1). It serves as the administrative hub for various smaller settlements, encompassing an area of 26,492 km^2. As of 2021, the estimated population of the city was 370,834 inhabitants. The city, i.e., before the full-scale invasion by the Russian Federation in early 2022, experienced a rapid pace of urbanization, and local authorities had been grappling with deficiencies in essential infrastructure, including the sanitation system. The implementation of separate municipal solid waste collection had been initiated in the city. Notably, there exists a methane collection system at the landfill site, effectively fulfilling the landfill's energy requirements. At present, waste management in Vinnytsia poses a substantial challenge for urban planners, primarily due to the absence of viable alternatives to landfilling within the city. The city's geographical positioning exacerbates this issue, with the closest processing facility located at a distance of 195 km. Consequently,

Fig. 21.1 Study area: (*left*) location of Vinnytsia, and (*right*) Dominican church in the center of Vinnytsia [Source: (*left*) authors' own elaboration; (*right*) photograph published by Posterrr from Wikimedia Commons, February 27, 2019]

the proportion of municipal solid waste subjected to processing at such facilities remains minimal.

2.3 Siting Methodology

The application of the proposed model, i.e., to identify potential sites for municipal solid waste transfer stations, was realized through a comprehensive investigation between environmental, social, political, and economic factors. The zoning map of Vinnytsia was used, undergoing digitization and transformation into a model using the GIS software package QGIS Version 3.28.2 with the analytic hierarchy process (AHP) extension. This process yielded various map layers encompassing metrics such as distance from residential areas, distance from surface water, distance from groundwater, aspect and wind direction, slope, land price, and distance from roads. To define specific geographical boundaries, constraint maps were developed via a logical inference methodology. Likewise, factor maps that encapsulated longevity variations were generated and standardized through the utilization of fuzzy logic techniques (Raman et al., 2009; Kumru, 2013; Canavese et al., 2014; Vadiati et al., 2016). The block diagram for selecting the most optimal facility location within the city plan is structured as a flowchart in Fig. 21.2.

The methodology comprises five overarching steps outlined in Fig. 21.3. Multicriteria evaluation has been used to evaluate a range of possible options in the siting process, taking into consideration diverse relevant criteria while also acknowledging frequently conflicting parameters. The initial step involves breaking down the decision-making process into a hierarchical framework. This encompasses defining the central goal and specifying criteria and sub-criteria key in selecting optimal sites for municipal solid waste transfer stations within Vinnytsia. This step involves the creation of spatial layers denoting territory suitability on a scale ranging from 1 (i.e., lowest suitability) to 5 (i.e., highest suitability) for each individual
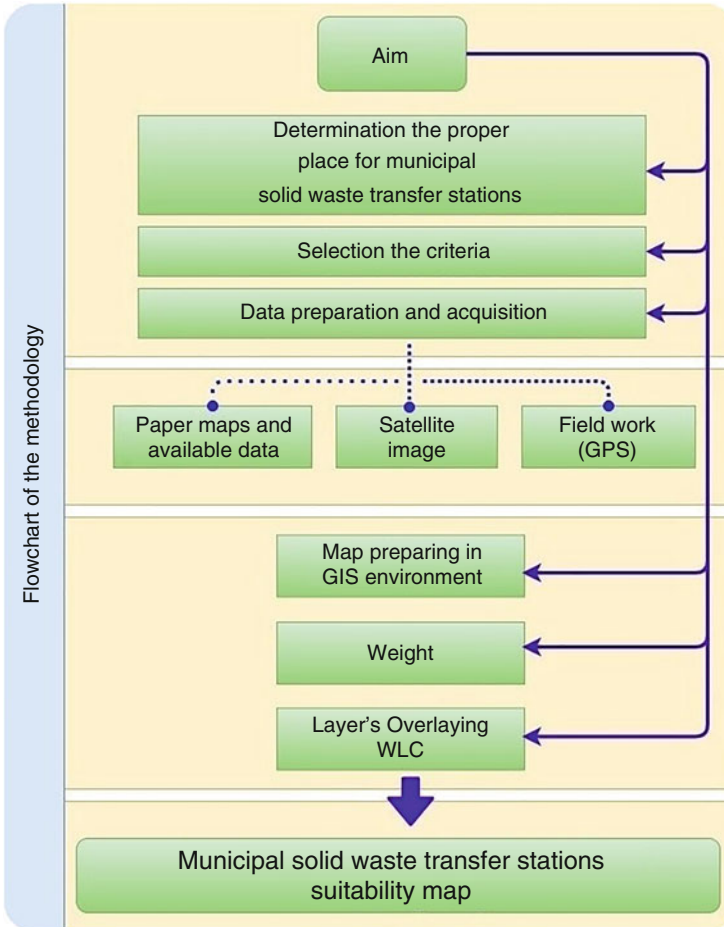
Fig. 21.2 Flowchart of the methodology

criterion and sub-criterion. In the second step, industry experts are interviewed to assess the importance of the selected criteria. This step is important because it facilitates the consensus among principal stakeholders involved in determining the location of sanitation facilities within the community. Often, the process of design and construction is met with notable public resistance, characterized by protests, demonstrations, and opposition, as urban communities frequently adhere to the "not in my backyard" principle. As a result, the utilization of weighted averages emerges as a valuable mechanism for reconciling the interests of local and regional authorities, technical specialists, and community residents. Successful implementation requires the convening of municipal meetings and public hearings involving stakeholders and experts. This collective engagement aids in determining the relative importance of criteria influencing the positioning of sanitation facilities.
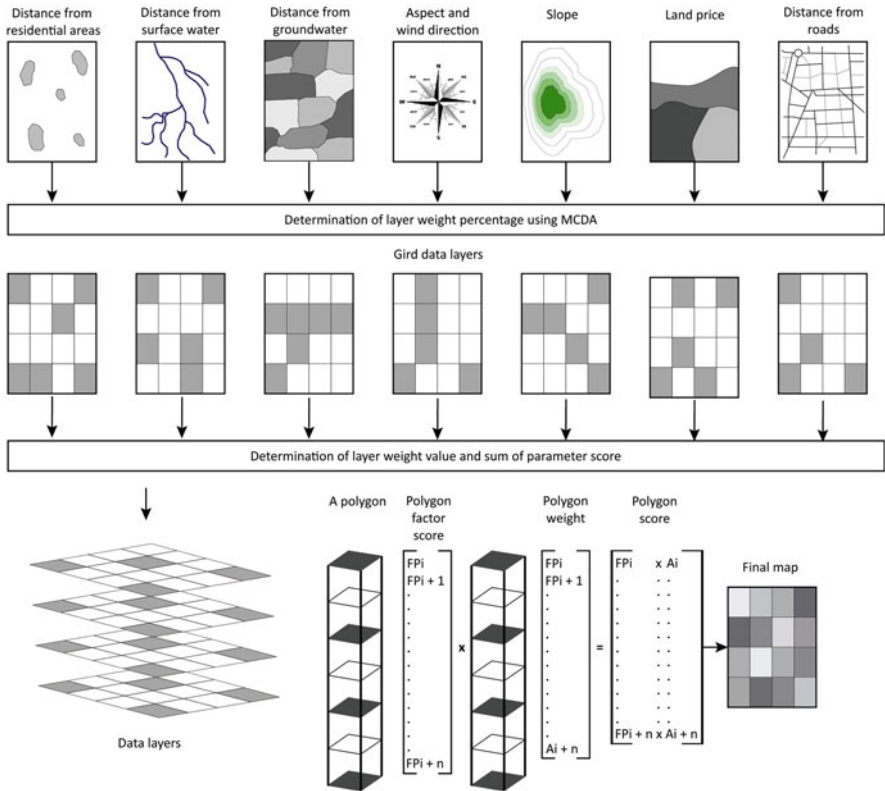
Fig. 21.3 Research methodology

To evaluate the criteria influencing the selection of municipal solid waste transfer station locations, a MCDA termed the best-worst method (BWM) is adopted. This method, originally introduced by Rezaei (2015), involves pairwise comparisons to derive weight coefficients for the criteria. In each comparison, the best and worst criteria are identified from a comprehensive list and juxtaposed against other listed criteria. Moreover, the factors must be independent of each other in which the calculation of weights is carried out by formulating and solving the problem min-max. One key advantage of this method lies in its incorporation of multiple pairwise comparisons, leading to heightened precision and reduced inconsistency, particularly when expert opinions vary. The adequacy of the results obtained is gauged by the estimated value of the index consistency. The consistency indicator reflects reliability. A higher reliability of the results is indicated by an indicator below 0.25, which is a low discrepancy and, consequently, good reliability of the result.

Weights, according to expert estimates, are calculated using BWM in Microsoft Excel 2021, adapted in terms of the number of comparisons and the number of factors in each comparison. This is based on the BWM linear solution model sheet,

i.e., the filename BWM-Solver-6.xlsx, which can be downloaded from the BWM Rezaei (2015) website [www.bestworstmethod.com]. The task of the experts was to assess the selected criteria and sub-criteria as well as the groups of factors to establish a top-down hierarchy. The third step involved ascertaining the weights of criteria and sub-criteria, followed by their aggregation to determine local ratings for each group of factors. Next, the fourth step saw the utilization of the maps developed in the first step as input maps for decision-making tiers. The combination of GIS and MCDA was executed through the application of the AHP extension within QGIS. The fifth and final stage involves generating a comprehensive territory suitability map, incorporating the weighted criteria and constraints for the optimal selection of municipal solid waste transfer station locations in Vinnytsia.

3   Results

The study outcomes are outlined through the segmentation of fuzzy set memberships and the incorporation of membership functions featuring control points, which were employed in the selection of sites for municipal solid waste transfer stations (Table 21.1).

3.1   Criteria Preparation and Standardization

The utilization of GIS provides the capacity to visualize the geographical area, offering a platform for efficiently managing spatial data related to the city's landscape. This, in turn, enhances the comprehension of the implications of alterations

Table 21.1 Fuzzy set memberships and membership functions with control points used for municipal solid waste transfer stations site selection

Criteria	Minimal parameter value	Optimum parameter value	Weight of the criteria using BWM
Distance from residential areas	100 m	2 km	15%
Distance from surface water	100 m	1 km	15%
Distance from groundwater	100 m	800 m	30%
Aspect and wind direction[a]	3x	3x	20%
Slope	0%–50%	5%–10%	5%
Land price			5%
Distance from roads	20 m	100 m	10%

[a]Calculated in terms of drift potential (DP)

through the provision of illustrative means. The most important factors that affect the location of the object, i.e., municipal solid waste transfer stations, revolve around the careful assessment of location constraints. In compliance with Ukraine's urban planning regulations, sanitation guidelines, and other stipulations, it is impermissible to position municipal solid waste transfer stations in close proximity to public areas. The placement of the facility must adhere to the urban layout and specifically align with zones designated for objects of the 4th classification in terms of sanitation criteria. The sanitary safeguard zone for municipal solid waste transfer stations should span 100 m. The sizing of the land parcel should be determined based on the potential expansion requirements of the station, in alignment with the city's waste management scheme.

Designated zones for establishing reloading stations should be situated outside of residential areas or within industrial and warehouse districts. The chosen site for constructing a waste transfer station must also adhere to established sanitary regulations, conform to environmental legislation requirements, and be in close proximity to the area designated for solid waste collection. Moreover, it should feature a natural elevation difference between the garbage collection points and the garbage transport trucks. Essential requisites encompass the presence of paved roads, utility connections for power, water supply, and sanitation. Building upon these specifications, areas deemed unsuitable can be excluded from consideration by implementing buffer zones in GIS, accompanied by the formulation of a set of regulations that proscribe the construction of municipal solid waste transfer stations. Subsequently, the focus shifts toward addressing specific constraints in terms of site selection standardization in Ukraine.

- Distance from residential areas: According to the urban planning requirements for the location of waste transfer stations, a sanitary protection zone for the treatment of solid waste and landfill criteria must be implemented and cannot be located within 100 m of residential areas. Therefore, a buffer zone of 100 m was used for modern urban and industrial areas. Specifically, areas encompassing a 100 m buffer zone were assigned a weight of 1, while 500 m = 2, 1 km = 3, 1.5 km = 4, and 2+ km = 5.
- Distance from surface water: According to the urban planning requirements, the establishment of municipal solid waste transfer stations requires prescribed widths when flanking rivers and water bodies. For large rivers, reservoirs, and lakes, the exclusion zone is set at 100 m; for moderate rivers, streams, and waterways, the distance is reduced to 50 m; while for minor rivers, brooks, streams, and smaller ponds, it narrows to 25 m. Notably, these regulatory parameters are under scrutiny due to research conducted by European academic institutions, revealing the inadequacy of these set distances (Khodaparast et al., 2018; Kůdela et al., 2019; Cobos Mora & Solano Peláez, 2020). As a result, a standardized buffer zone of 100 m is recommended around surface water bodies, irrespective of specific characteristics. Hence, a buffer zone should be maintained around surface water bodies for 100 m regardless of the waterbody size. In the study, a zone is created around lakes, swamps, and rivers for 100 m. The buffer

zone for 100 m was equated as 1, 300 m = 2, 500 m = 3, 1 km = 4, and 1+ km = 5.

- Distance from groundwater: The landfill site should not be located in areas with a high risk of groundwater contamination. Sanitary sites can potentially have serious environmental consequences for aquifers and groundwater. The geographical coordinate system of wells, springs, and aqueducts was obtained from the Southern Bug River Basin Management. A 100 m zone was considered around groundwater resources. Distances less than 100 m are not suitable, and distances greater than 800 m are the most suitable. The most vulnerable areas of groundwater are rated as 1 with scores of other zones increasing by a degree with values ranging from 1 (i.e., most vulnerable areas) to 5 (i.e., least vulnerable areas).

- Aspect and wind direction: Municipal solid waste transfer stations can have potentially harmful effects due to emissions of odors and pollutants carried by the wind. These negative effects increase especially when the prevailing wind direction blows into residential areas (Zelenović Vasiljević et al., 2012). Therefore, when choosing the location of the object one must take into account the prevailing wind direction. Here, a map of aspects was prepared using a digital elevation model (DEM) with a resolution of 30 m. The western and southwestern directions were the predominant wind direction that was assessed using DP (Byliński et al., 2019; Liu et al., 2019; Tansel & Inanloo, 2019; Bax et al., 2020; Shi et al., 2022; Kibria et al., 2023).

- Slope: The slope of the surface is a decisive factor when it comes to building costs. For example, very steep slopes will increase costs during the site preparation and construction phase. The slope of the land surface was calculated on the basis of points using DEM as a percentage from 0% to 50%. The values of the slope of the land surface were normalized on a scale from 1 to 5, i.e., 40%–50% = 1 is scored as the lowest level of suitability to 5%–10% = 5 is scored as the highest level of suitability.

- Land price: The price of land in Vinnytsia is divided into five categories according to the norms and rates of land tax with the first equating to the highest price. The divided classes were superimposed and followed the scaling as the city's land tax rates, i.e., the area with the highest land price, category one was the least suitable and was rated 1, category two = 2, category three = 3, category four = 4, and category five = 5. Hence, suitability indicators increased with decreasing land prices.

- Distance from roads: Waste transfer stations should be close to the road network to reduce transport costs (Chang & Lin, 1997). National legislation in Ukraine does not define the minimum distance of the station to the roads. However, in this study, considering environmental concerns, a 20 m buffer for roads was considered. Distances over 20 m and less than 100 m are most suitable, while distances over 100 m or less are least suitable.

3.2   Site Selection

Within Vinnytsia, there is a need to improve the steps of municipal solid waste transfer stations in order to reduce operating costs and reduce the tariff component for this service. The main reasons for the need to build a reloading station in the city are the constant growth of solid waste, the location of recycling sites relatively far from collection points (i.e., usually at a distance of more than 25 km, the use of light trucks—from 2 to 3 tons for collection and transportation of waste along narrow residential streets), the complex network of residential streets, and the existence of residential areas with low density and high cost of waste collection and disposal. The attributes of these layers have been selected, classified, normalized, and combined to highlight the locations suitable for the municipal solid waste transfer stations. Buffered themed layers were combined to create a combined layer of processed attributes. With these layers of thematic search potential, sites were narrowed to an area covering about 420 ha within the industrial zone. That is, a mere 3.7% of Vinnytsia emerged as an optimal candidate for the housing of municipal solid waste transfer stations. This area was further assessed using a ten-point weight estimate based on maps drawn up in the first step which assesses distance from residential areas, distance from surface water, distance from groundwater, aspect and wind direction, slope, land price, and distance from roads. Moreover, environmental factors and residential problems were assessed with the best selected site found to be a mere 30 m from the main primary road. This connectivity to the road network complements the quick and easy access for large waste collection trucks to move and leave the area without undue interference. Being in an industrial area also has distinct advantages, facilitating the sale of recyclable materials to other enterprises, such as paper, glass, and metals.

Since the locations were judiciously chosen in proximate to major highways, facilitating waste transit to landfills with minimal public disruption and traffic inconvenience, residential housing was not within the selected territory. In addition, this meant that the selected sites were not visible from the residential housing area. As a result, people living nearby will not be able to see the activities, and the municipal solid waste transfer stations will remain discreet to those residing in proximity. In sum, through the integration of GIS and MCDA, the suitability of the location of the reloading station considered a number of factors, including sanitary and hygienic, city planning, and ecological. These factors alongside the seven criteria were integrated into the calculation process. For all criteria, intermediate suitability maps were compiled and combined to create a final suitability map. The MCDA proposed an objective weight assignment process. Hence, the process of identifying the optimal location serves as a highly valuable instrument for selecting sanitation facilities in urban environments and, with appropriate methodological consideration, holds potential for application in other infrastructure projects as well.

4   Conclusions

The mounting buildup of municipal solid waste in cities with a high level of urbanization is a formidable challenge, requiring the rapid modernization of the sanitation system (Osuhor & Essien, 1978; Reymond et al., 2016; Andersson et al., 2016; McFarlane, 2019). As such, the development of the presented model is geared toward optimizing the costs during the waste transportation phase, with the ultimate goal of curbing the expenses associated with solid household waste disposal. Cross-disciplinary studies that have also looked at optimizing transport and external costs highlight some important factors worth considering; see Grzelakowski (2020), Czermanski et al. (2021), and Han et al. (2021). To improve results, it would be recommended to hold a special feasibility study on the selected territory, incorporating supplementary parameters related to facility financing and a comprehensive environmental impact assessment. These additional measures serve the dual purpose of mitigating environmental contamination risks and assessing the economic viability of constructing such a facility.

Within a broader context, however, the expanding capabilities of GIS in spatial analysis and modeling have been instrumental in shaping scenarios for optimal municipal solid waste transfer station site selection. This multifaceted process encompasses sociocultural, environmental, physical, and operational factors linked to waste transportation and management. While numerous waste management initiatives incorporate GIS functionalities, they often fall short of harnessing the complete GIS potential required for robust spatial and model analysis in the selection of transfer station sites (Head et al., 2013; Singh, 2019; Asefa et al., 2022; Elkhrachy, 2022; Lewandowski & Cirella, 2022). By using the method in this study, MCDA processes the selected criteria in a simplified hierarchy. This is important because it takes into account public concern, which is extremely significant when dealing with waste management. In this regard, GIS proves instrumental in mitigating environmental and socioeconomic concerns through spatial factors. The developed modeling also exhibits adaptability, poised for implementation in other study areas with a different set of criteria and constraints. In terms of Ukraine's future, the presented method holds importance since it can effectively fast-track data compilation, organization, analysis, and manipulation—increasing environmental awareness to identify the location of selected sites in a postwar context. This holds significance as postwar reconstruction will necessitate a skilled workforce and a repository of expertise and knowledge to facilitate the country's advancement and the judicious construction of infrastructure.

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