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A Hybrid Decision Support Framework for Managing Logistics Infrastructure Relocation Under Crisis Conditions

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Abstract

Background: Relocating logistics infrastructure under wartime conditions requires more than identifying a theoretically suitable location, as available facilities, costs, and emerging risks must also be considered. This study examines the relocation of an enterprise from the frontline Zaporizhzhia region of Ukraine and aims to develop and substantiate a Hybrid Adaptive Model for Relocating Logistics Infrastructure (HAMRLI). *Methods*: The methodology combines resilience assessment, spatial modelling, digital facility screening, and expert evaluation. The Normalized Resilience Index (NRI) was calculated using EWM and TOPSIS. HAMRLI integrates the Center of Gravity (COG) method, digital verification of available warehouses, and enterprise-specific multi-criteria assessment. *Results*: COG identified Zhytomyr as a potential relocation area. Seven warehouse offers were identified, and two were shortlisted for expert evaluation. Weighted assessment selected Offer 6. Sensitivity analysis showed that its preference remained stable across the tested scenarios but changed with substantial shifts in criterion weights. The results support the applicability of HAMRLI for relocation decisions under high uncertainty. *Conclusions*: This study provides an initial empirical application rather than statistical generalization. Further testing of HAMRLI under different enterprise operating conditions is required.

Keywords: logistics infrastructure; relocation management; logistics resilience; decision support; facility location; Center of Gravity; multi criteria decision making; crisis logistics

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1. Introduction

In the current environment of global turbulence caused by military conflicts, geoeconomic shifts, and accelerated digital transformation, the logistics infrastructure of enterprises is facing unprecedented pressure. These challenges are particularly acute in Ukraine, where martial law has led to large-scale disruptions of supply chains, destruction of transport hubs, and the urgent need to relocate production and logistics facilities [1–3]. Under such conditions, the development of hybrid adaptive relocation models becomes a key instrument for ensuring enterprise resilience and cost optimization.

The current state of research indicates the active development of scientific thought in the field of supply chain and logistics system resilience [4]. Resilience has evolved into a central concept in contemporary logistics and supply chain research and is now understood as a multidimensional capability that encompasses operational performance, sustainability, digital transformation, and adaptive decision-making. Mishra and Singh (2022) [5],

for example, proposed a stochastic optimization model for disaster-resilient reverse logistics that simultaneously incorporates facility allocation, production capacity, system failures, and environmental considerations under uncertainty. Their findings demonstrate that combining multiple dimensions of resilience within a unified decision-support framework can substantially improve the robustness of logistics systems operating in disruptive environments [5]. Studies [6–8] demonstrate that digital transformation (including the use of artificial intelligence, IoT, and digital twins) significantly increases the adaptability and flexibility of logistics systems. Research emphasizes the importance of integrating digital technologies with classical logistics approaches to achieve synergy between efficiency and resilience. At the same time, studies [9,10] highlight the role of state policy and institutional support in ensuring successful business relocation during wartime.

A separate stream of research is devoted to the transformation of the logistics paradigm under martial law. In particular, refs. [11,12] focus on the transition from centralized to decentralized logistics models, which helps reduce the risks of infrastructure losses. Meanwhile, studies [13] demonstrate that assessing threats to the economic security of logistics operators through network-based approaches can improve the resilience and adaptability of logistics systems operating under high-risk conditions.

A significant body of scientific work addresses the relocation of enterprises and logistics facilities. Specifically, studies [14–16] examine the spatial aspects of relocation, its economic consequences, and its impact on regional development. At the same time, research [17,18] points to the existence of substantial barriers, including legal restrictions, infrastructure imbalances, and shortages of financial resources.

Despite the considerable number of studies, the scientific literature presents conflicting approaches regarding optimal strategies for adapting logistics systems. On the one hand, some authors justify the feasibility of complete decentralization of logistics networks to enhance their resilience [11,19]. On the other hand, other researchers argue that excessive decentralization may lead to increased costs and the loss of economies of scale [13,20]. Similarly, there is an ongoing debate regarding the role of digitalization: some studies emphasize its decisive importance for improving resilience [6], while others point to cybersecurity risks and high investment costs that limit its effectiveness in the short term [21].

Thus, the analysis of scientific sources makes it possible to conclude that there is a need for a comprehensive approach combining the spatial flexibility of relocation, digital management tools, and economic optimization. Such an approach is represented by the HAMRLI, which integrates centralized and decentralized elements of logistics infrastructure while utilizing digital technologies to support real-time decision-making.

Existing research offers well-established approaches to logistics resilience, enterprise relocation, facility location, and multi-criteria decision-making (MCDM). Resilience-oriented location models incorporate disruption risks and uncertainty, while the facility-location and MCDM literature provides established tools for identifying, evaluating, and ranking potential sites. Studies on enterprise relocation under wartime conditions further address spatial, infrastructural, financial, and security-related constraints.

However, these streams of research typically address distinct stages of the decision-making process rather than the complete sequence required for an enterprise relocation decision. In particular, the transition from a mathematically identified potential relocation area to the verification of facilities that are actually available on the market, followed by the evaluation of these alternatives against enterprise-specific operational, financial, infrastructural, and security constraints, remains insufficiently integrated within a unified decision-support framework.

Against this background, the contribution of this study lies not in developing a new mathematical optimization algorithm or a new MCDM method, but rather in configuring

and integrating established analytical tools within a relocation-oriented decision-support framework. HAMRLI connects three decision-making levels: spatial screening based on the Center of Gravity method and actual logistics flows; digital verification of available warehouse facilities within the identified relocation area; and facility-level multi-criteria assessment based on enterprise-specific criteria.

The purpose of this study is to develop and substantiate a HAMRLI for the relocation of enterprise logistics infrastructure under martial law and digital transformation, ensuring cost optimization and enhanced resilience.

The main results of the study are as follows:

(1) Systematization of the factors influencing logistics infrastructure relocation;
(2) Development of a conceptual model of hybrid adaptation;
(3) Identification of mechanisms for integrating digital technologies into the relocation process;
(4) Substantiation of the economic efficiency of the proposed approach.

Therefore, the proposed study is aimed at overcoming existing scientific discrepancies and developing a holistic approach to logistics infrastructure management under conditions of high uncertainty, which is of significant importance both for the academic community and for enterprise management practice.

The article is structured as follows:

- First, the contemporary conceptual transformation of logistics management under the influence of global and local crises is analyzed;
- Second, the methodology of the HAMRLI is substantiated;
- Third, the results of testing the model using a real case of enterprise relocation from the frontline city of Zaporizhzhia are presented;
- Finally, strategic recommendations for enhancing the technological and infrastructural resilience of logistics systems are formulated.

2. Materials and Methods

The methodology was designed around the sequence of decisions that an enterprise faces when considering the relocation of its logistics infrastructure. For this reason, the study combines conceptual analysis, spatial modelling, resilience assessment and expert-based multi-criteria evaluation. These methods are not applied independently. Each addresses a different part of the relocation problem, and the results obtained at one stage are used to define or support the analysis undertaken at the next stage.

The conceptual part of the study draws on established approaches to logistics management, particularly the total cost concept, the avoidance of sub-optimisation and trade-off analysis. This provides a basis for identifying the factors that become relevant when logistics infrastructure has to be relocated under wartime conditions. The same analytical perspective is used when interpreting information collected from digital warehouse-market sources and when considering expert judgements on the suitability of individual relocation options.

Resilience is examined separately at the level of the logistics system. For this purpose, the Normalised Resilience Index (NRI) is calculated using the Entropy Weight Method (EWM) and TOPSIS. The index provides an indication of the resilience conditions in which the relocation decision is being made. It does not, however, determine which warehouse should be selected. The choice between individual facilities requires a different level of analysis and is therefore based on the K_1–K_8 criteria, which reflect the operational, financial, infrastructural and security requirements of the enterprise. Expert judgements for these criteria are standardised and incorporated into a weighted multi-criteria assessment.

The integration of the methods is therefore procedural rather than purely mathematical. Conceptual analysis establishes what needs to be considered; the spatial calculation defines where the search should be concentrated; market verification establishes what is available; and the K_1–K_8 assessment allows the available facilities to be compared from the perspective of the enterprise. The NRI adds a system-level view of resilience to this sequence. In this way, HAMRLI brings together different forms of evidence within one relocation decision process without assuming that a single analytical method can capture all dimensions of the problem.

2.1. Theoretical Framework and Data Sources

The theoretical basis of the study was formed through a critical review of modern logistics concepts: the Total Cost Concept, the principle of preventing suboptimization, and the Trade-off Analysis concept. The study takes into account the specifics of supply chain functioning under conditions of extreme uncertainty, relying on data regarding Ukraine's infrastructure losses and the dynamics of enterprise relocation.

The information base of the study includes:

- Official reports of the Ministry of Economy of Ukraine and the Kyiv School of Economics (KSE Institute) concerning infrastructure destruction;
- Statistical data from the Opendatabot and Prozorro. Sales platforms regarding business migration;
- Analytical data from the WareTeka digital warehouse real estate marketplace for verification of market offers.

2.2. Hybrid Adaptive Model for Logistics Infrastructure Relocation (HAMRLI)

To solve the problem of logistics network optimization, the Hybrid Adaptive Model for Logistics Infrastructure Relocation (HAMRLI) is proposed:

The HAMRLI includes three elements that ensure the transition from theoretical calculations to practical implementation.

1. Theoretical spatial optimization.

Application of the center-of-gravity method to determine the ideal geographical warehouse location based on actual cargo flows and customer locations.

2. Digital verification and search.

Use of warehouse logistics marketplaces (e.g., WareTeka) to identify real available facilities within the calculated area.

3. Multi-criteria expert selection.

Application of the expert evaluation method for the final selection of premises, taking into account cost, technical condition, security factors, and the reputation of the landlord.

A visual diagram of the algorithm of the Hybrid Adaptive Model for Logistics Infrastructure Relocation (HAMRLI), constructed in the form of sequential decision-making blocks, is presented in Figure 1.

The first stage of the algorithm involves a comprehensive analysis of the external and internal operating environment of the enterprise, including the assessment of logistics disruptions, infrastructure damage, and the level of supply chain destabilization under martial law conditions. Within this stage, the feasibility of relocation is determined in order to ensure operational continuity and minimize risks, while target benchmarks are formed in accordance with the total logistics cost concept. At the same time, the initial parameters of the model are identified, including the coordinates of shipment points (X_i, Y_i) and cargo flow volumes (Q_i), creating an analytical basis for further modeling. An important out-

come of this stage is the formation of a strategic objective that determines the directions for further optimization of the enterprise logistics system.

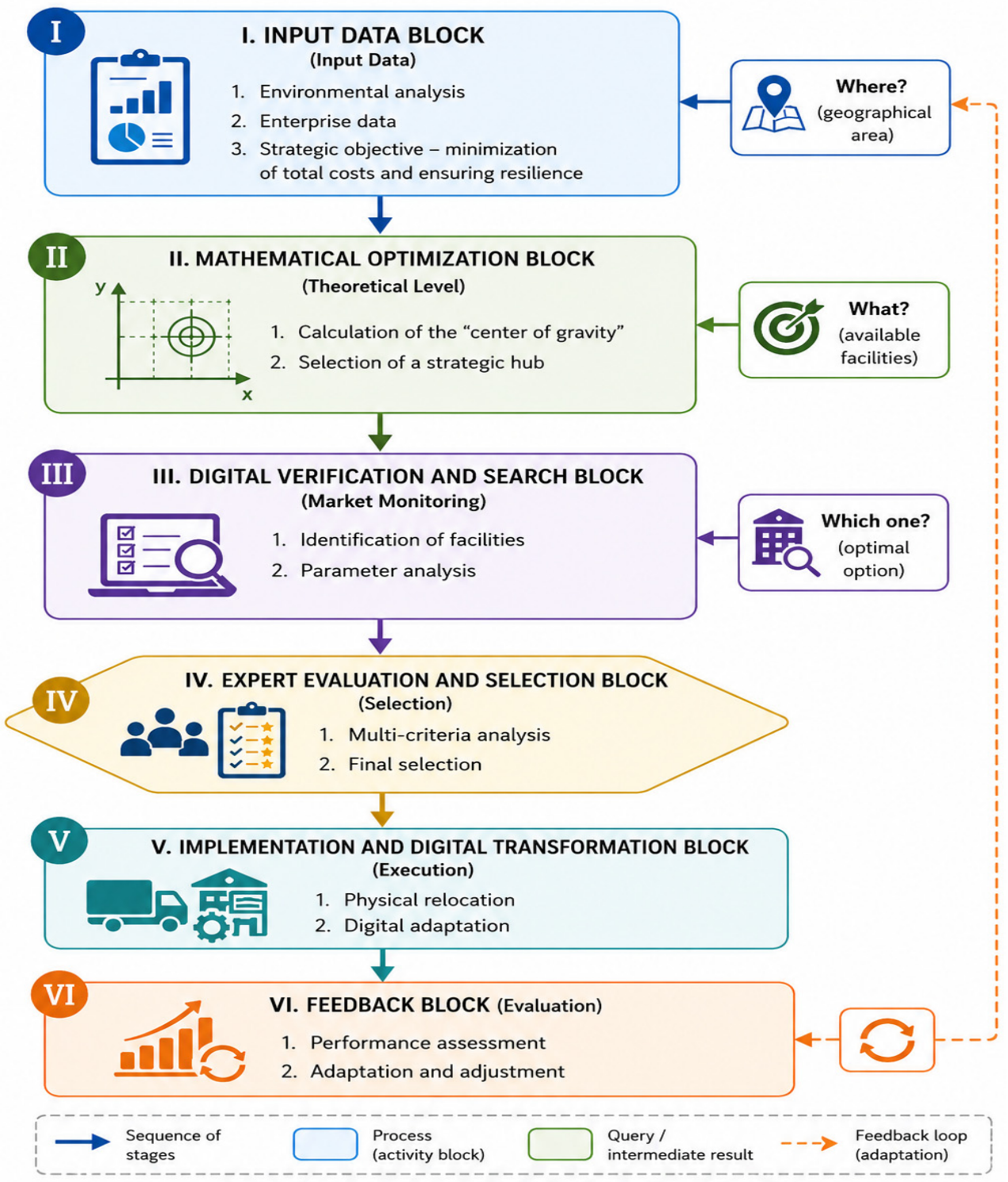


Figure 1. Algorithm of the Hybrid Adaptive Model for Logistics Infrastructure Relocation (HAM-RLI). Source: developed by the authors.

At the second stage of the algorithm, the theoretical warehouse location is determined using the "center of gravity" method, which makes it possible to minimize transportation costs by taking into account the spatial distribution of cargo flows (Formulas (1) and (2)).

$$X_{opt} = \frac{\sum X_i V_i}{\sum V_i} \quad (1)$$

$$Y_{opt} = \frac{\sum Y_i V_i}{\sum V_i} \quad (2)$$

where X_i, Y_i—are the coordinates of shipment points, V_i—the cargo flow volume at the corresponding locations.

In the proposed framework, the Center of Gravity (COG) method is not used as the sole or final decision-making tool. Instead, it serves as a preliminary macro-screening technique for geographical positioning, enabling the identification of the most suitable regional relocation area. In the present case, the analysis supported the transition from the frontline Zaporizhzhia region to the Zhytomyr logistics hub in Central-Western Ukraine. At this stage, the COG method provides a spatial approximation by seeking to reduce the weighted geographical distance between a potential warehouse area and the main freight-flow points. It thus provides an initial indication of the potential transport-cost efficiency of an alternative regional location.

The selection of the COG approach is justified by the specific conditions of wartime logistics in Ukraine. Conventional network optimization models, which rely on stable road networks with fixed travel times and capacities, may produce unreliable results under conditions of damaged transport infrastructure, destroyed bridges, military checkpoints, curfews, and rapidly changing security conditions. Moreover, these models require continuously updated transportation network data, which are difficult to maintain in an active conflict environment. Under such circumstances, a hybrid approach combining geographical positioning based on the Center of Gravity method with expert risk assessment provides a more practical and robust decision-support framework than a purely static network model.

The empirical validation of the proposed framework is based on a real enterprise relocation from the frontline city of Zaporizhzhia to the Zhytomyr logistics hub. The mathematical model was constructed using empirical data from the company's 12 principal customers, including their geographical coordinates (X_i, Y_i) and annual purchase volumes (Q_i), representing a total logistics flow of 58,067 units. The sample included all major customers that maintained stable contractual relationships throughout the study period and collectively accounted for more than 95% of the company's annual logistics volume.

The obtained values reflect the conditional center of concentration of logistics flows. Based on the comparison of the calculated coordinates with the actual logistics map, a strategic hub closest to the theoretically optimal point is selected. As a result, a substantiated decision regarding the placement of the logistics hub is formed, taking into account both quantitative parameters and spatial characteristics of enterprise operations.

The COG calculation in HAMRLI uses the coordinates of the main shipment or customer locations together with the corresponding freight volumes. Its result is a reference point indicating the part of the territory that appears preferable when the existing distribution of freight flows is considered. This is only an approximation. Road configuration and actual travelling conditions are outside the COG calculation. The model therefore does not capture such factors as travel time, route-dependent costs, damaged or closed roads, checkpoints, curfews, congestion, or changes in the security situation.

This distinction becomes particularly important during wartime. A location that is geographically closer may in practice be more difficult, more expensive, or less safe to reach. For that reason, the point obtained from the COG calculation is not treated in this study as the optimal warehouse location. Nor does it define an optimal transport route. Its role in HAMRLI is more limited: it indicates the geographical area in which the search for a new warehouse can reasonably begin.

The next stages of the analysis deal with factors that cannot be captured by coordinates alone. Once the search area has been established, the warehouse market is examined to determine which facilities are actually available there. The identified options are then compared using criteria relevant to the enterprise: rental cost and lease terms, location, technical equipment, the possibility of renting only part of a facility, characteristics of the surrounding area, reputation, and road access. Security and possible disruptions to transport connections are considered separately through expert judgement and the resilience assessment. In this sense, COG does not make the relocation decision. It reduces the geographical search space. The eventual choice of a warehouse is made only after the spatial result has been confronted with what is available on the market and with the operational and security conditions that matter to the enterprise.

The digital technology block (Market Monitoring) involves the use of modern information platforms, in particular specialized systems such as WareTeka, to conduct comprehensive monitoring of the warehouse real estate market. Within this block, the search and selection of available warehouse facilities are carried out with regard to their spatial location, particularly through filtering facilities within the defined theoretical center of the logistics system. An important element is the assessment of technical warehouse characteristics, including facility class, ceiling height, availability of loading docks, and other parameters affecting the efficiency of logistics operations. Alongside this, the financial conditions for warehouse usage are analyzed, particularly rental rates and operating expenses (OPEX), ensuring the validity of further managerial decisions in the field of warehouse infrastructure optimization.

To overcome the limitations of purely coordinate-based calculations, the proposed framework was designed as a hierarchical hybrid model. While the Center of Gravity method provides preliminary geographical positioning and identifies a candidate regional relocation zone, the final warehouse selection is performed through a multi-criteria evaluation of alternative facilities using criteria K_1–K_8, including rental cost, transport accessibility, road infrastructure quality, warehouse characteristics, and other operational factors.

Security-related risks and the broader resilience of the logistics environment are considered at two levels. At the system level, the Normalised Resilience Index (NRI) describes the overall resilience of Ukraine's logistics system. At the facility level, security and operational characteristics of individual warehouse alternatives are included in the enterprise-specific assessment through the K_1–K_8 criteria and expert judgement. The NRI therefore provides the broader context in which relocation is considered, but it does not determine the choice of warehouse. The final selection depends on the characteristics and conditions of the individual facilities.

The expert evaluation and selection stage (Selection) involves conducting a multi-criteria analysis of alternative warehouse facility options, taking into account a system of relevant criteria. In particular, the evaluation is based on such indicators as transportation accessibility, flexibility of lease terms, infrastructure condition, and other parameters reflecting both logistics efficiency and the economic feasibility of facility use. Based on the integrated assessment, the alternatives are ranked, making it possible to justify the selection of the optimal option and determine the specific relocation address in accordance with the enterprise's strategic goals and operating conditions.

The expert panel consisted of five senior specialists representing the participating enterprise, including the Logistics Director, Warehouse Manager, Supply Chain Analytics Manager, Chief Financial Officer, and Security Manager. Experts were selected using purposive (criterion-based) sampling to ensure that all participants possessed the knowledge and practical experience required for the evaluation process.

The eligibility criteria included at least five years of professional experience in logistics management and supply chain management, together with practical experience in managerial decision-making under crisis conditions or business relocation projects.

This configuration limits the generalisability of the expert judgements but increases their contextual relevance to the relocation decision faced by the particular enterprise. An external expert may be better positioned to assess the market, but not necessarily to determine whether a specific warehouse meets the operational needs of the enterprise concerned.

To reduce subjectivity and ensure the reliability of expert judgments, the following evaluation procedure was applied:

(1) Each expert independently evaluated all warehouse alternatives against the eight decision criteria (K_1–K_8).

The criteria weights were determined through direct expert weighting. Each expert assessed the relative importance of criteria K_1–K_8. The individual assessments were then discussed and combined into a consensus set of weights, which was subsequently normalised so that the weights summed to 1.

(2) The level of agreement among experts was assessed using Kendall's coefficient of concordance (W).

To assess the consistency of the expert judgements, Kendall's coefficient of concordance (W) was calculated for the rankings of the eight criteria provided by the five experts. A value of $W \geq 0.70$ was taken to indicate a sufficiently high level of agreement. When W was below 0.70, the experts took part in an additional structured discussion to clarify differences in how the criteria were interpreted and how their relative importance was assessed. The assessments were then reconciled, and the resulting expert scores were aggregated and used in the final multi-criteria evaluation.

(3) Following the achievement of expert consensus, the final criterion scores were calculated as weighted average values and subsequently used to derive the integrated decision index.

The implementation and digital transformation block (Execution) covers the realization of the selected managerial decision through the physical relocation of enterprise assets and personnel, including the possible use of state business support programs. An important component of this stage is the digital adaptation of logistics processes based on Industry 4.0/5.0 technologies, involving the implementation of warehouse management systems (WMS), as well as the application of artificial intelligence and Digital Twins for logistics route modeling and risk forecasting. Simultaneously, remote operational management tools are configured in order to enhance personnel safety and ensure business continuity.

In the empirical case, the digital component of HAMRLI was implemented through online monitoring and verification of the warehouse property market. WareTeka was used to identify warehouse facilities that were actually available within the selected relocation area. WMS, artificial intelligence, and digital twins were not implemented by the participating enterprise as part of this case study. Instead, these technologies are considered possible extensions at the implementation stage of HAMRLI, where they could support further digital adaptation of logistics processes, including warehouse management, route modelling, and risk forecasting. References to these technologies should therefore be understood as proposed technological extensions of the framework rather than evidence of their empirical application in the case examined.

The feedback block (Evaluation) is aimed at assessing the effectiveness of implemented managerial decisions and ensuring system adaptability under dynamic environmental conditions. Within this stage, the Normalized Resilience Index is calculated, allowing a quantitative assessment of the logistics system's ability to withstand external shocks

and operate under conditions of increased uncertainty. Based on the obtained results, feedback is generated to ensure adjustment of the selected strategy, particularly in the event of changes in the intensity of military actions, transformation of logistics routes, or the opening of new transportation corridors. Such an approach ensures the continuity of the management cycle and increases the enterprise's resilience to crisis impacts.

For practical application, HAMRLI requires a minimum set of data collected sequentially as the analysis progresses. At the initial stage, the manager needs information on the main points generating logistics flows, their geographical coordinates, and the corresponding freight volumes. These data are used to calculate the Center of Gravity and identify a potential relocation area. In the empirical case, the calculation was based on 12 major customers accounting for more than 95% of the enterprise's annual logistics volume.

Once the potential relocation area has been identified, information on warehouse facilities available within that area is collected. At a minimum, facility-level data should include location, available space or capacity, key technical characteristics, lease conditions, operating costs, transport accessibility, and relevant security characteristics. This information provides the basis for preliminary screening and for selecting alternatives for more detailed comparison. In this case, WareTeka was used as the digital market source to search for and verify available warehouse offers. A detailed multi-criteria assessment is conducted only after the market alternatives have been identified and screened. The shortlisted facilities are evaluated against criteria K_1–K_8 by the designated enterprise experts. The expert procedure involves independent assessment, a consistency check using Kendall's W, and aggregation of the assessments once an acceptable level of agreement has been reached.

The NRI is calculated separately at the logistics-system level and provides contextual information on the resilience of the operating environment. It should not be interpreted as a direct ranking variable used to select among individual warehouse facilities. The final facility-level decision is based on the enterprise-specific K_1–K_8 criteria, while the NRI provides the broader resilience context within which the relocation decision is made.

Scientific Novelty of the Proposed Method

Unlike traditional approaches that consider warehouse real estate as a static asset, the HAMRLI is based on the principles of "Logistics on Demand." The methodological contribution of the model lies in:

- Interactivity—the integration of analytical calculations with dynamic data from digital platforms to support more timely decision-making and facilitate rapid updates to relocation parameters.
- Adaptability—the possibility of rapid recalculation of parameters in response to changes in demand or the security situation in the region;
- Risk orientation—inclusion in the expert evaluation of criteria specific to wartime conditions (security of surrounding areas, availability of alternative access routes).

2.3. Resilience Assessment Metrics

To examine the applicability of the proposed solutions, the study applies the Normalized Resilience Index (NRI), calculated on the basis of the Entropy Weight Method and the TOPSIS method.

To objectively evaluate the ability of the logistics system to recover and adapt under conditions of extreme shocks, the study employs an integrated approach based on the combination of the Entropy Weight Method (EWM) and the TOPSIS method (Technique for Order of Preference by Similarity to Ideal Solution). This combination was chosen to minimize subjectivity in determining the weighting coefficients and to measure the distance between the current state of the system and the theoretical ideal.

The EWM–TOPSIS combination was selected according to the structure and purpose of the resilience assessment. The NRI includes several heterogeneous indicators observed over a four-year period. They describe operational capacity, relocation and adaptation capabilities, technological maturity, and infrastructure vulnerability. For this reason, two methodological tasks had to be addressed: determining the weights of the indicators without relying only on subjective judgements and combining the weighted indicators into one measure of relative resilience.

EWM was used to determine the weights because it allows them to be derived from the variation in the observed data. This is relevant to the NRI because the indicators have different scales and their changes over the study period are not uniform. In this case, the use of EWM made it possible to determine the relative importance of the indicators from the data rather than relying entirely on expert-assigned weights.

TOPSIS was used at the next stage to combine the weighted indicators. Each observed state of the logistics system was assessed in relation to a positive ideal solution and a negative ideal solution. This approach fits the way resilience is understood in the study. A more resilient state should have higher values for favourable characteristics and, at the same time, lower values for characteristics representing vulnerability. TOPSIS makes it possible to reflect both directions in the resulting NRI.

The reason for combining the two methods is therefore quite practical. EWM is used to establish the weights, while TOPSIS is used to compare the observed states of the system after these weights have been introduced. For the NRI developed in this study, this was considered more suitable than relying entirely on expert weights or using a simple additive procedure.

The use of EWM–TOPSIS does not mean that this combination is superior to other MCDM methods in general. It was selected for this study because the functions performed by the two methods correspond to the specific requirements of the NRI calculation.

The assessment is carried out using four groups of indicators: operational recovery capacity (X_1), relocation and adaptation capability (X_2), digital transformation maturity (X_3) and infrastructure resilience capacity (X_4). Such a comprehensive approach makes it possible to verify the enterprise's ability to recover rapidly after relocation.

The calculation is performed in several stages:

1. Formation and normalization of the decision matrix. Based on the selected resilience indicators, the initial matrix is formed.

$$X = [x_{ij}]_{mn}$$

where m—is the number of periods (years),
n—is the number of indicators.

Since the indicators have different dimensions, they are normalized to the range [0, 1]:

- For stimulant indicators (positive impact on resilience):

$$r_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$

- For destimulant indicators (negative impact):

$$r_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}$$

2. Determination of Weighting Coefficients Using the Entropy Method

For each indicator, the entropy value (e_j), is calculated, reflecting the degree of uncertainty and informativeness of the data:

$$e_j = -k\sum_{i=1}^{m} p_{ij} \ln(p_{ij})$$

where $p_{ij} = \frac{r_{ij}}{\sum r_{ij}}$s is the proportional value of the indicator, k = 1/ln(m).

The weighting coefficient w_j for each criterion is determined through the divergence level ($d_j = 1 - e_j$):

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

3. Construction of the Weighted Normalized Matrix and Determination of Reference Points

The weighted normalized matrix V s constructed by multiplying the normalized values by their corresponding weights. $v_{ij} = r_{ij} w_j$. Based on this matrix, the following are determined:

- Positive ideal solution (A^+): maximum values of stimulant indicators.
- Negative ideal solution (A^-): minimum values of stimulant indicators.

4. Calculation of Distances and the Resilience Index (NRI).

For each period, the Euclidean distances from the current state to the positive (D_i^+) and negative (D_i^-) ideals are calculated:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}$$

The Normalized Resilience Index (NRI) is defined as the relative closeness to the ideal solution:

$$NRI_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

The value of NRI_i ranges from 0 to 1, where values close to 1 indicate maximum resilience and the system's ability to self-recover, while values close to 0 indicate a state of critical vulnerability or collapse of the logistics network. The "Normalized Resilience Index" method was tested on the logistics system of Ukraine as a whole, which demonstrates its universality.

It is important to note that the NRI is a system-level indicator and does not measure the resilience of an individual enterprise or warehouse facility. Within HAMRLI, it is used to characterise the external logistics environment in which relocation decisions are made. Enterprise- and facility-specific characteristics are assessed separately at the final selection stage using the K_1–K_8 criteria. The NRI and the facility-level multi-criteria assessment therefore perform complementary rather than interchangeable functions within the framework.

To ensure the reproducibility of the study, a structured research protocol was established. Data were collected between January 2024 and October 2025 and included official statistics on infrastructure damage, information obtained from the Opendatabot and

WareTeka platforms, and empirical evidence generated during the practical validation of the HAMRLI. The inclusion criteria comprised the availability of official and verifiable information on enterprise logistics flows associated with business relocation, together with the market availability of warehouse facilities within the target relocation area (the Zhytomyr logistics hub).

The following facilities were excluded from the analysis:

- warehouse facilities without valid operating permits;
- facilities located outside the predefined geographical search area;
- facilities lacking sufficient technical specifications required for comparative evaluation.

To ensure a consistent transition from the theoretical foundations to the practical application of the proposed model, the results are structured according to the following sequence: theoretical justification, methodological conceptualisation, empirical implementation, and digital and organisational support mechanisms of HAMRLI. Sections 3.1, 3.2 and 3.4 provide the material needed to interpret the proposed approach and establish its theoretical, methodological, digital, and organisational foundations. In particular, the analysis of current approaches and trends in logistics provides the basis for defining relocation requirements; management theory supports the treatment of relocation as an adaptive management process; and the discussion of digitalisation and artificial intelligence identifies technological mechanisms that can support decision-making. The empirical implementation of HAMRLI is presented in Section 3.3. It includes the spatial identification of a potential relocation area, the digital search and verification of available warehouse facilities, the assessment of alternatives, and the calculation of the composite resilience indicator.

3. Results

3.1. Conceptual Transformation of Logistics Management Under Global and Local Crises

Today, logistics is no longer viewed merely as a technical field related to cargo transportation, but rather as an integrated management system that permeates all business processes of an enterprise and enables the optimization of material, information, and financial flows in real time. The current stage of global economic development is characterized by a state of permanent turbulence, in which traditional planning methods focused on stable markets and predictable demand are losing their effectiveness. For Ukrainian enterprises, the situation is further complicated by the direct impact of military actions, which result in infrastructure destruction, blockage of traditional transport corridors, and the urgent need for the relocation of facilities [22–24].

As of December 2025, the total amount of direct documented damage inflicted on Ukraine's infrastructure reached the staggering figure of USD 195.1 billion in replacement cost terms. In 2025 alone, this indicator increased by 10.8% due to the intensification of missile attacks and hostilities [25–27].

The housing, transport, and energy sectors suffered the greatest damage. Socioeconomic losses increased to USD 666.7 billion, largely due to disruptions in trade, industry, public services, and livelihoods. Recovery and reconstruction needs continue to grow and are currently estimated at USD 587.7 billion over a ten-year period, equivalent to almost three times Ukraine's GDP in 2025 (Table 1).

Table 1. Impact of the War on the Ukrainian Economy by Category, USD Billion.

As of	Direct Damage	Losses	Recovery Need
1 August 2022	97.4	252.0	348.5
1 February 2023	134.7	289.1	410.6
1 December 2023	152.5	499.3	486.2
1 January 2025	176.1	588.8	523.6
1 January 2026	195.1	666.7	587.7

The most critical segment for logistics is transport infrastructure, where road losses are estimated at USD 28.3 billion, railway losses at USD 4.3 billion, and aviation industry losses at USD 2 billion. The destruction of 311 bridges and more than 26 thousand kilometers of highways forced logistics operators to use longer bypass routes, increasing fuel and depreciation costs by 15–35% [28]. In the agricultural sector, the destruction of 4 million tons of grain storage facilities [27] necessitated the urgent deployment of temporary solutions such as "grain bags," which became an example of supply chain flexibility under crisis conditions. The blockade of Black Sea ports, which before the war handled more than 70% of Ukrainian exports, became the most severe blow to logistics stability. The war in Ukraine particularly disrupted energy (oil and gas) and food (grain) supply chains, leading to a global rise in prices. Ukraine was forced to transition to a multi-level system of alternative routes [29]. During 2022–2023, the Danube port cluster (Izmail, Reni, Ust-Dunaisk) gained strategic importance. The share of Danube ports in grain exports increased from the pre-war 5% to nearly 45% in 2023 [30,31]. However, the launch of Ukraine's own "Ukrainian Maritime Corridor" in August 2023, protected by the Naval Forces of the Armed Forces of Ukraine, enabled cargo flows to return to the deep-water ports of Greater Odesa (Table 2).

Table 2. Freight Transportation Indicators by Key Routes [32,33].

Role in 2025	Change Compared to 2023	Freight Turnover 2024 (Million Tons)	Logistics Route
150+ million tons (total)	Record growth	79.9 (76.4 export)	Ukrainian Maritime Corridor
Decline to 8.9 million tons	−46% (due to reorientation)	17.3	Danube ports
Stabilization	−8% (drop from 15% to 7%)	Decrease in share	Railway transportation (EU border)
Flexible reserve	Moderate growth	5.0–6.0	Road transportation

As of October 2025, more than 150 million tons of cargo, including 90 million tons of grain delivered to 55 countries worldwide, had passed through the Ukrainian Maritime Corridor [34]. This indicates the restoration of maritime logistics as the primary export channel (92% of agricultural exports in 2024). At the same time, the intensity of attacks on port infrastructure increased from 36 in 2024 to 96 in 2025, resulting in damage to 325 facilities and cumulative port operation downtime exceeding one month [33]. Relocation became a vital mechanism for preserving production capacity. According to the Ministry of Economy, 885 enterprises were relocated under the state program, of which more than 700 had already resumed operations at new locations [10]. State support included site selection, logistics services provided through Ukrzaliznytsia and Ukrposhta, as well as assistance with employee accommodation [10,35]. Analysis of Opendatabot data demonstrates that the dynamics of business relocation stabilized during 2024–2025,

while the number of relocations in 2025 was even 17.1% lower than the pre-war level of 2021, which may indicate, ceteris paribus, the adaptation of businesses to territorial risks (Table 3).

Table 3. Dynamics of Enterprise Relocation, 2021–2025 [36–39].

2025 (Forecast/Actual)	2024	2023	2021	Relocation Indicator
12,920	11,669	14,136	15,589	Number of relocations (moves)
31.1%	31.5%	32.4%	—	Share of wholesale trade
6.0%	6.0%	6.3%	—	Share of construction
5.2%	5.1%	4.6%	—	Share of agriculture

Kyiv remains the main "donor" and at the same time a relocation hub. In 2024, more than 4000 companies (36.6%) left the capital; however, 28% of all relocated businesses chose Kyiv as their new place of registration. The most popular relocation destinations are the Kyiv region (which received 3150 companies in 2024), the Lviv region (777), the Dnipropetrovsk region (1136), and the Kharkiv region (863). Interestingly, in 2025 the Kharkiv region demonstrated a positive relocation balance (+374 companies), indicating the return of businesses to frontline regions after their stabilization [36,37]. Thus, the defining conditions for the resilience of the Ukrainian business logistics system became stable freight turnover, diversification and relocation of capacities, digitalization, and infrastructure restoration. The calculation of the Normalized Resilience Index (NRI) for Ukraine's logistics system is based on the combination of the Entropy Weight Method [40–44] and the TOPSIS method [45,46].

Four indicators (X_j) are proposed for assessing the resilience of Ukraine's logistics system:

1. Operational recovery capacity (port freight turnover, million tons)—X_1. The data were compiled from official statistics published by the Ministry for Communities, Territories and Infrastructure Development of Ukraine on seaport cargo turnover and transport logistics. The values were normalized to the interval [0; 1].
2. Relocation and adaptation capability—X_2. This indicator is not a directly observed statistical measure. It was constructed as a normalized adaptation index reflecting the extent of route diversification, the scale of enterprise relocation, and the operation of alternative logistics corridors, based on data from the Ministry of Economy of Ukraine and Opendatabot.

The X_2 indicator has a dual interpretation. During the initial phase of a crisis, a high number of relocations reflects the need for enterprises to move because they can no longer operate at their previous locations. At later stages, however, a decline in relocation activity, accompanied by the recovery of business operations, indicates greater stability of the logistics system. For this reason, X_2 was transformed using an inverse scale before being included in the composite resilience index.

The values were normalized to the interval [0; 1].

3. Digital transformation maturity—X_3. This composite indicator represents the level of digitalization of logistics processes, including the adoption of artificial intelligence, the use of cloud-based platforms, and the implementation of digital twins. It was constructed using evidence from industry reports published by KPMG, ASCM, Gartner, and other relevant sources. The values were normalized to the interval [0; 1].

Therefore, X_3, as included in the NRI, should be interpreted as a system-level indicator of the technological maturity of the logistics environment rather than as evidence

that digital technologies were implemented by the enterprise examined in the empirical relocation case.

4. Infrastructure resilience capacity—X_4—This indicator was derived by applying reverse normalization to the value of direct infrastructure losses, so that lower losses correspond to a higher level of infrastructure resilience. The resulting values were normalized to the interval [0; 1].

The four indicators used in the NRI do not have the same degree of direct statistical observability. X_1 and X_4 are based on quantitative measures obtained from external statistical and analytical sources, whereas X_2 and X_3 are proxy indicators constructed to capture dimensions of logistics-system resilience that cannot be directly observed through a single standardised set of annual statistics.

X_2 is operationalised through the dynamics of enterprise relocation. The interpretation of relocation intensity depends on the context. A high number of relocations may indicate severe disruption during the initial phase of a crisis, while a decline in relocation activity during the recovery phase may indicate stabilisation, provided that operational activity is maintained. Accordingly, the normalised relocation measure is inverted before aggregation.

X_3 is operationalised through ordinal coding of successive stages of technological maturity. The values 0.25, 0.50, 0.75, and 1.00 represent ordered maturity levels rather than directly measured quantities. This coding assumes that the identified stages can be represented on a comparable normalised scale. X_3 should therefore be interpreted as a proxy for technological resilience rather than as a direct statistical measure of the intensity of digital transformation. For example, Digital Twin Adoption within X_3 represents a system-level characteristic of the technological maturity of the logistics system used in the NRI calculation. It should not be taken as evidence that Digital Twin technology was implemented by the enterprise examined in the empirical case.

These operationalisation assumptions affect the interpretation of the NRI. The index should be understood as a structured composite indicator of changes in resilience rather than as a direct observation of an unobservable "true" level of resilience. The resulting values are most appropriate for comparative assessment across the periods studied and for providing contextual information within the HAMRLI decision-support framework. Accordingly, the indicators can be classified as follows: X_1 and X_4 are directly observed quantitative indicators; X_2 is a constructed proxy; X_3 is an ordinal proxy based on expert-theoretical coding; and the NRI is a research-based composite indicator rather than a precise statistical estimate of "actual resilience".

The choice of the 2022–2025 period is determined by the nature of the phenomenon under study. This period covers the full-scale war and active hostilities, during which Ukraine's logistics system was simultaneously exposed to major negative shocks and developing mechanisms of adaptation. Military risks resulted in infrastructure damage and constraints on operational capacity, while at the same time accelerating enterprise relocation, the diversification of logistics routes, and the adoption of digital management tools. Changes in X_1–X_4 over this period therefore reflect not only their evolution over time but also the response of the logistics system to a major common external shock.

The detailed calculations for all indicators are provided in Appendix A.

The selected indicators are consistent with contemporary approaches to logistics resilience, which conceptualize resilience as a combination of operational, organizational, digital, and physical capacities. Expanding the indicator set would not necessarily provide a substantial increase in the explanatory value of the index, while it could considerably reduce its interpretability. The values of the indicators for 2022–2025 are presented in Table 4.

Table 4. Assessment of the Resilience Level of Ukraine's Logistics System.

Analytical Impact	2022 (Critical Shock)	2023 (Adaptation)	2024 (Recovery)	2025 (Prospective Development)	Resilience Parameter
This indicator represents the capacity of the logistics system to recover and maintain operational performance after crisis-induced disruptions. Accordingly, higher values correspond to a greater level of logistics resilience and make a positive contribution to the overall resilience index.	0.0000	0.5125	1.0000	0.7922	X_1—Operational recovery capacity
This indicator captures the speed and scale of organizational adjustment among logistics-system actors in response to external shocks. Higher adaptive capacity indicates greater operational flexibility under changing conditions.	0.0000	0.3707	1.0000	0.6809	X_2—Relocation and adaptation capability
This indicator captures the contribution of digital technologies to improving the transparency, controllability, and predictability of logistics processes, thereby strengthening the system's capacity to adapt under uncertainty.	0.2500	0.5000	0.7500	1.0000	X_3—Digital transformation maturity
This indicator represents the capacity of logistics infrastructure to maintain operational functionality and recover rapidly following physical damage. Higher levels of infrastructure resilience reduce the adverse effects of crisis-related disruptions and enhance the overall stability of the logistics system.	1.0000	0.7345	0.3259	0.0000	X_4—Infrastructure resilience capacity
Integral assessment of proximity to stability	0.434	0.540	0.663	0.477	Normalized Resilience Index (NRI)

The NRI results indicate a gradual strengthening of the resilience of Ukraine's logistics system between 2022 and 2024. In 2022, the index reached 0.434, reflecting the period of the most severe crisis impact, marked by disrupted logistics chains, restrictions on operational activity, and the need for large-scale system restructuring. In 2023, the increase in the NRI to 0.540 suggests a transition toward an adaptation phase supported by the recovery of operational capacity, the intensification of relocation processes, and the gradual introduction of digital management tools.

The highest NRI value over the observed period was recorded in 2024 (NRI = 0.663), indicating the strongest relative position of the logistics system's resilience components among the four years considered. This result should be interpreted within the 2022–2025 observation period and in the context of the simultaneous effects of military operations and the adaptive responses of the logistics system. This improvement was associated with the simultaneous strengthening of several components, including operational recovery capacity, the adaptive capability of logistics actors, and the advancement of digital transformation. The result suggests that resilience under crisis conditions depends not only on the

restoration of physical infrastructure but also on organizational flexibility and technological modernization.

In 2025, the NRI declined to 0.477. This decrease should not be interpreted as a complete loss of the resilience capacity developed in previous years. Rather, it reflects the growing effect of accumulated infrastructure risks and constraints on further recovery. The infrastructure component receives one of the highest weights in the model, indicating its substantial influence on the long-term resilience of the logistics system.

Ukraine remains a strategic player in global food security (accounting for 9% of global wheat exports before the war), and the restoration of its logistics capacities is critical not only for the national economy but also for the stability of global markets [47].

Under such conditions, logistics management occupies an important place in ensuring the viability of companies and the logistics system as a whole.

In the modern globalized economic landscape, characterized by unprecedented volatility, rapid technological progress, and increasing pressure from environmental standards, logistics management has transformed from a supporting operational function into a strategic core of enterprise competitiveness. Logistics management is no longer considered an isolated process of cargo movement, but rather a complex integrated value management system that combines physical assets, digital ecosystems, and human capital.

The understanding of logistics management in the mid-2020s is inseparably linked to its place within the broader structure of Supply Chain Management (SCM).

According to the official position of the CSCMP, which remains fundamental for practitioners: «Logistics management is that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements. Logistics management activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfillment, logistics network design, inventory management, supply/demand planning, and management of third-party logistics service providers. To varying degrees, the logistics function also includes sourcing and procurement, production planning and scheduling, packaging and assembly, and customer service. It is involved in all levels of planning and execution--strategic, operational and tactical. Logistics management is an integrating function, which coordinates and optimizes all logistics activities, as well as integrates logistics activities with other functions including marketing, sales, manufacturing, finance, and information technology [48].

According to CSCMP, the boundaries of logistics management encompass a wide range of activities, including inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfillment, logistics network design, inventory management, supply and demand planning, as well as the management of third-party logistics providers (3PL). An important feature of this approach is the recognition of logistics as an integrating function that coordinates and optimizes all logistics activities while ensuring their alignment with other functions such as marketing, sales, manufacturing, finance, and information technology [49].

The Association for Supply Chain Management (ASCM) offers a somewhat different emphasis, defining logistics management as the process of supervising and optimizing the productivity and efficiency of the entire logistics function. In this context, logistics is viewed as a subset of SCM that controls the planning, coordination, and movement of resources—people, materials, inventory, and equipment—from one location to another [50].

The ASCM approach highlights the critical role of logistics in ensuring delivery accuracy and speed as key factors of customer satisfaction. Here, logistics management acts as

the orchestrator of processes that ensure the delivery of the required product to the right place at the right time, which is crucial for avoiding shortages or excess inventory [50].

The European Logistics Association (ELA) views logistics as a business planning framework for managing flows of materials, services, information, and capital. The ELA definition emphasizes the organization, planning, and control of the movement of goods from development and procurement through production and distribution to the final consumer [51].

A distinctive feature of the ELA approach is its focus on professional competencies. The ELA standards system (ELAQF), harmonized with the European Qualifications Framework (EQF), defines a logistics manager as a professional capable of managing all logistics functions and teams while focusing on specific results. The ELA certification program distinguishes operational (EJLog), strategic (ESLog), and executive management (EMLog) levels, making it possible to differentiate the definition of logistics management depending on the scale of responsibility [52,53].

Comparative analysis of institutional approaches to the definition of logistics management is presented in Table 5.

Table 5. Analysis of Institutional Approaches to Defining Logistics Management.

ELA (European Logistics Association)	ASCM (Association for Supply Chain Management)	CSCMP (Council of Supply Chain Management Professionals)	Characteristic
Organization of flow from development to consumption	Optimization of resource productivity	Control of flows and information	Main focus
Goods, capital, market requirements	People, materials, inventory, equipment	Goods, services, information	Objects
Cost minimization and capital utilization	Maximization of performance and efficiency	Customer satisfaction	Goal orientation
Market-oriented customer focus	End-to-end operational perspective	Strategic, tactical, operational	Scale

Source: developed by the authors based on [49–53].

Analysis of contemporary sources suggests that the functional composition of logistics management has expanded significantly. Traditional operations are now integrated with advanced technological solutions, transforming the very essence of management [54–56].

Transportation remains the "heart" of logistics, ensuring physical connectivity between supply chain nodes. Management in this area includes not only the selection of carriers and delivery modes, but also route optimization using artificial intelligence, management of proprietary transport assets to mitigate delay risks, and monitoring of carbon emissions. The increasing complexity of international logistics requires deep expertise in customs procedures, tariffs, and regulatory requirements, which has become an integral part of logistics management [57,58].

The modern warehouse has evolved from a place of static storage into a dynamic order-processing hub. Logistics management in this context includes warehouse facility design, labor management, automation of picking and packaging processes, and the implementation of micro-fulfillment centers (MFCs) in urban areas to accelerate last-mile delivery. Effective warehouse management under modern conditions is impossible without warehouse management systems (WMS), which ensure inventory accuracy and the speed of internal operations [57,59,60].

Inventory management is shifting from reactive to proactive modeling. Logistics management utilizes machine learning algorithms for demand forecasting and inventory replenishment decisions, enabling the minimization of capital frozen in goods while maintaining a high level of service. An important aspect is the differentiation of inventory management strategies based on ABC analysis and volatility forecasting [57,61].

The growth of e-commerce has made reverse logistics an important element of logistics management. This includes the processing of returned goods due to damage, seasonality, recalls, or excess inventory, as well as the management of packaging and recyclable materials. Reverse logistics is becoming part of the "circular economy" strategy, where product value recovery is a priority [59,60,62].

Digital transformation is radically changing the definition of logistics management, turning it into a "digital orchestrator." The Logistics 4.0 concept is based on the use of cyber-physical systems and intelligent networks [54–56].

Artificial intelligence is evolving from predictive analytics to Agentic AI, capable of independently executing decisions: reviewing carrier contracts, rerouting cargo in the event of port closures, or automatically adjusting inventory levels. This leads to the creation of "self-healing supply chains" [60].

Digital twins are becoming a key tool of logistics management. They create virtual replicas of physical logistics networks using real-time data from IoT sensors. This enables managers to simulate thousands of "what-if" scenarios, minimizing risks and optimizing resources before physical operations begin [58,60,61].

Blockchain is being applied to ensure transparency and traceability of goods throughout the entire supply chain. In international logistics, this allows the automation of documentation processes and significantly reduces fraud in documentation [63,64].

Industry 4.0 technologies and their impact on logistics management are presented in Table 6.

Table 6. Impact of Industry 4.0 Technologies on Logistics Management.

Expected Benefits (Impacts)	Impact on Logistics Management	Technology
Reduction in delivery time by 15%	Autonomous decision-making and route optimization	Artificial Intelligence (AI)
Improvement of inventory accuracy by 12%	End-to-end real-time visibility of assets	Internet of Things (IoT)
Reduction in document fraud by 23%	Verified traceability and data security	Blockchain
Minimization of response time to disruptions	High-precision scenario modeling and risk simulation	Digital Twins
Reduction in operating costs by up to 30%	Continuous execution of warehouse operations	Automation and Robotics

Source: developed by the authors based on [58,60,61,63,64].

Environmental, Social, and Governance (ESG) factors are becoming an integral part of the definition of logistics management. "Green logistics" is no longer an option but a necessity for maintaining competitiveness [65,66].

Management in the field of sustainable logistics includes the use of environmentally friendly transportation, the implementation of energy-efficient warehouses, and the transition to eco-friendly packaging. The application of Industry 4.0 technologies is considered the primary path toward achieving sustainable development goals through resource optimization and waste minimization [55,64–67].

Modern logistics management also focuses on "human-centricity" (Human-centric Logistics 4.0). This involves creating safe working conditions, developing employees' digi-

tal skills, and ensuring the ethical use of automation that complements rather than replaces human labor [55,68].

Recent scientific publications emphasize the direct relationship between the quality of logistics management and organizational performance [69,70].

Studies show that the implementation of inventory, transportation, and warehousing management procedures helps firms improve net margins and asset turnover. Logistics efficiency, effectiveness, and service differentiation are key predictors of market success [69,71].

In a volatile environment, logistics management is transforming into a resilience instrument that includes supplier base diversification, regionalization of warehouse capacities, and the creation of flexible disruption response systems [58,61,72].

Data on the impact of logistics strategies on enterprise performance indicators are presented in Table 7.

Table 7. Impact of Logistics Strategies on Enterprise Performance Indicators.

Performance Metrics	Impact on Efficiency	Management Aspect
Inventory turnover, shortage level	Minimization of frozen capital	Inventory management
Cost per mile, on-time delivery accuracy	Optimization of costs and delivery time	Transportation management
Picking accuracy, throughput	Increased order processing speed	Warehouse management
Order cycle time, complaint rate	Growth of loyalty and repeat sales	Customer service
Carbon footprint, recycling rate	Compliance with regulatory standards and corporate image	ESG management

Source: developed by the authors based on [69].

Ukrainian researchers consider logistics management as a synergy of managerial functions aimed at solving production tasks in order to generate profit and ensure sustainable development [73,74].

M.A. Oklander emphasizes the formation of logistics systems in accordance with the conceptual principles of general management [75]. Ye. Krykavskyi considers logistics management as a tool for coordinating different stages of supply from supplier to final consumer [76]. S.V. Smerichevska defines this category as "high-level management aerobatics," based on the total implementation of logistics concepts such as JIT, KANBAN, Lean Production, and SCM [77].

Contemporary Ukrainian scholarship identifies the following key aspects of successful logistics management implementation [74,78]:

- A systemic approach to planning and coordination of all stages of the supply chain;
- Implementation of modern information systems and personnel training;
- Active cooperation with partners and adaptation to changes in the external environment.

Analysis of forecasts from leading consulting groups and associations (KPMG, Ziegler, ASCM) makes it possible to identify the directions that will shape the content of logistics management in the coming years [60,79–83]:

- Total Value as a strategic priority. Leading companies are shifting from a focus on resilience toward a focus on "Total Value." Logistics management will be oriented toward creating added value for customers through personalized experiences and immediate response to market needs.
- Logistics as a Service (LaaS) and cloud solutions. The "Logistics as a Service" model is gaining popularity, where companies outsource modular functions (warehousing,

fulfillment) through cloud-based API-integrated platforms. This enables businesses to remain flexible and scalable without significant investments in physical assets.

- Hyperlocalization and urban logistics. Growing customer expectations regarding delivery speed stimulate the development of hyperlocal networks. Logistics management is increasingly focused on managing micro-warehouses and autonomous delivery systems (drones, robots) in large cities.

The most significant trends in logistics management are presented in Table 8.

Table 8. TOP-10 Strategic Trends in Logistics Management 2026.

Description and Significance	Trend
Route optimization and autonomous management	Artificial Intelligence (AI)
Adaptation to tariffs and geopolitical changes	Trade policy and market dynamics
Integration of robotics across all logistics stages	Automation
Ability to recover quickly after disruptions	Agility and Resilience
Transition toward cognitive labor alongside AI	Workforce evolution
End-to-end real-time flow control	Visibility and Traceability
Protection of logistics data and intelligent systems	Cybersecurity
Search for efficiency sources through technology	Cost optimization
Supplier diversification to reduce risks	Flexible sourcing
Green strategies and reverse logistics	Climate and Circularity

In summary, it can be argued that logistics management has evolved from a simple operational discipline into a comprehensive system for managing intellectual assets and value flows. Traditional definitions focused solely on "movement and storage" are now complemented by the concepts of "digital orchestration," "autonomy," and "social responsibility." Today, logistics management is not merely a part of supply chain management, but rather its "nervous system," ensuring the viability of the business model in a volatile world.

Based on the above, logistics management can be defined as a dynamic system of integrated management which, through the synergy of human intelligence and advanced technologies (Logistics 4.0), ensures strategic planning, autonomous execution, and continuous control of forward and reverse flows of material assets, services, and related data. The purpose of logistics management is to maximize Total Value for stakeholders through the creation of agile, transparent, and environmentally sustainable supply chains capable of instantly adapting to market disruptions and individual consumer requirements.

This definition is based on the following conceptual pillars:

1. Intelligent technological capability—the use of AI and digital twins as the foundation for decision-making;
2. Agility—the ability to instantly transform processes in response to external challenges;
3. Value orientation—shifting the focus from cost minimization to the creation of a comprehensive customer experience;
4. Ethical sustainability (ESG)—the inseparability of logistics operations from decarbonization goals and social well-being.

3.2. Logistics Cost Management

The dynamics of competition require management not merely to minimize costs, but to seek an optimal balance between service quality and operational flexibility. The experience of many business entities that have implemented the logistics concept demonstrates a significant strengthening of their market positions—customer acquisition potential increases, the implementation of innovative transportation technologies accelerates, and the service level for end consumers improves.

The central element of the modern logistics approach is systems thinking. This involves the application of three interrelated concepts that form the foundation of effective management (Table 9).

Table 9. Concepts of Effective Management.

Concept	Essence and Mechanism of Action	Impact on the Logistics System
Total Cost Concept	Consideration of all logistics costs as a single whole to ensure the required level of service	Makes it possible to identify the alternative with the lowest total costs, even if individual elements become more expensive
Prevention of Suboptimization	Rejection of maximizing the efficiency of individual functions in favor of the integrity of the entire process	Ensures the optimal "cost–efficiency" balance for the system as a whole
Trade-off Analysis	Deliberate increase in certain costs (e.g., transportation) in order to achieve greater reductions in others (e.g., inventory)	Contributes to reducing total distribution costs and increasing capital turnover

Source: developed by the authors based on [84,85].

These concepts require enterprise management to shift from function-oriented management to process-oriented management, where logistics management integrates procurement, production, and sales into a unified value creation chain.

The efficiency of a logistics system directly depends on the enterprise's ability to identify and control costs at every stage of product movement. Under conditions of working capital shortages, which characterize the current state of the economy, the issue of cost rationalization becomes critically important.

In the procurement sphere, costs are not limited solely to the price of raw materials or goods. The logistics approach focuses on expenses related to order processing, delivery organization, proper packaging, and cargo securing within transport vehicles. Optimization here is achieved through long-term partnerships with reliable suppliers and the use of modern IT solutions for calculating optimal supply batch sizes, making it possible to avoid both shortages and excessive inventories [86].

At the production stage, logistics management allows for a significant reduction in costs associated with intra-factory movement of components, storage of work-in-progress inventory, and downtime caused by the absence of necessary components at workstations. Of particular importance is the management of storage costs, which include the cost of invested capital, warehousing expenses, taxes, insurance, and the risks of product obsolescence [87].

Sales activity represents the final stage that ensures the inflow of financial resources. Logistics management in this sphere is aimed at minimizing finished goods storage costs, transportation expenses related to customer delivery, and costs caused by stockouts (lost profit). Improvement of sales operations is a strategic decision that directly affects enterprise profitability [88].

Warehouse support is the link that transforms fragmented material flows into a stable system, enabling the enterprise to effectively eliminate temporal and spatial gaps between

supply, production, and consumption. It serves not only as a storage location for inventories, but also as a strategic logistics management instrument that ensures business process continuity, optimizes transportation costs through cargo consolidation, and enhances customer service levels through the speed and accuracy of order fulfillment (Figure 2).

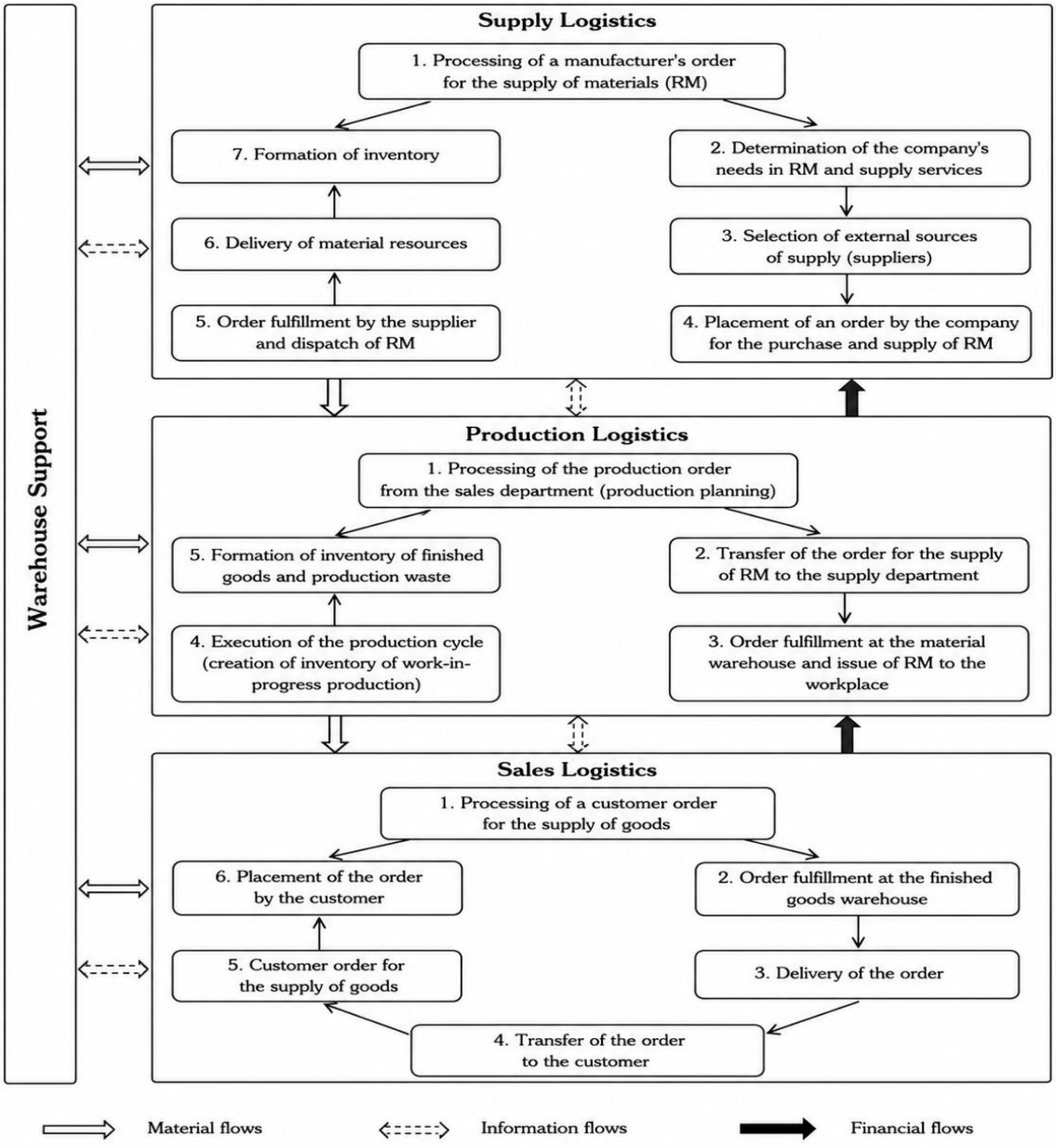


Figure 2. Enterprise Logistics System. Source: developed by the authors.

Under conditions of market volatility, the rational organization of warehouse operations is one of the key factors ensuring the flexibility of enterprise logistics systems, minimizing shortage risks, and achieving a synergistic effect in material flow management. The formation of an effective warehousing system involves determining technical-economic and organizational parameters, objectives, and performance criteria, among which cost-efficiency and profitability are decisive. An important role is played by the choice of warehouse location, storage methods, and technical equipment, all of which directly affect circulation costs, inventory levels, and the speed of inventory movement within the logistics chain.

The efficiency of warehouse operations largely depends on the justified choice of the warehousing organization model—the use of private warehouses or public warehouses. Private warehouses are advisable under conditions of significant trade turnover and high inventory turnover, ensuring better quality control and greater process flexibility, whereas leased warehouses make it possible to reduce investment costs and risks under unstable or seasonal demand. Optimization of the warehouse network requires consideration of demand, the geography of consumers and suppliers, the intensity of material flows, as well as balancing transportation costs against inventory holding costs, which is implemented on the basis of the total logistics cost minimization principle.

At the same time, the specifics of Ukrainian enterprises operating under martial law significantly complicate the organization of warehouse logistics. Infrastructure destruction, business relocation, shortages of warehouse space in relatively safe regions, and the need for rapid proximity to consumers increase the importance of flexible logistics solutions and crisis management. Enterprises are forced to adapt warehouse systems to a high level of uncertainty, ensure continuity of supply, and respond quickly to demand changes, which increases the importance of strategic planning, diversification of warehouse capacities, and the use of combined warehousing models [89].

3.3. Algorithm and Practical Implementation of the Hybrid Adaptive Model for Logistics Infrastructure Relocation (HAMRLI)

Under martial law conditions and the need for rapid adaptation of distribution networks, the authors propose a new method for managing infrastructural changes—the Hybrid Adaptive Model for Logistics Infrastructure Relocation (HAMRLI). This model is based on the integration of the mathematical apparatus of spatial optimization with the capabilities of modern digital platforms and expert analysis [86,90].

Practical Testing of the HAMRLI: Relocation Case to the Zhytomyr Hub

To demonstrate the practical application of the proposed framework, a case study was conducted on the warehouse relocation process of an enterprise facing critical risks in the Zaporizhzhia region and requiring closer proximity to customers in the central and western regions of Ukraine.

The purpose of this case study is not to provide statistical generalization but to demonstrate the step-by-step application of the proposed HAMRLI, from the mathematical identification of the Center of Gravity to digital facility screening through logistics platforms and the subsequent expert-based evaluation of relocation alternatives. The presented case serves as an initial empirical application and test of the proposed framework for enterprises operating in frontline regions. Future research will focus on expanding the empirical dataset, validating the model across multiple relocation cases, and assessing its applicability to different industries and operating environments.

Stage 1: Calculation of the Center-of-Gravity Coordinates

Based on data regarding the company's 12 major customers, their geographical locations, and purchase volumes (Q_i), the theoretical coordinates of the warehouse were calculated (Table 10).

The calculated coordinates (X_{opt} = 18.4, Y_{opt} = 32.9) practically coincided with the geographical location of the city of Zhytomyr, confirming the feasibility of searching for warehouse facilities precisely within this logistics hub (Figure 3).

Table 10. Calculation of Center-of-Gravity Coordinates.

Y_iQ_i	X_iQ_i	Q_i	Y_i	X_i	Customer
72,703	79,025	3161	23	25	№1
49,487	33,796	1207	41	28	№2
72,072	58,968	2184	33	27	№3
108,050	103,728	4322	25	24	№4
609,224	263,074	13,846	44	19	№5
345,746	50,845	10,169	34	5	№6
169,917	46,341	5149	33	9	№7
79,530	39,765	2651	30	15	№8
294,066	246,636	9486	31	26	№9
27,525	37,434	1101	25	34	№10
32,162	35,873	1237	26	29	№11
53,310	74,634	3554	15	21	№12
1,913,792	1,070,119	58,067	-	-	Total



Figure 3. Geographic Distribution of Customers and the Selected Warehouse Location in Ukraine. Source: Base map adapted from "Map of Ukraine blank.png" (Wikimedia Commons, Public Domain). Customer locations, the selected warehouse location, and analytical visualization were added by the authors. https://commons.wikimedia.org/wiki/File:Map_of_Ukraine_blank.png (accessed on 24 August 2026).

In this study, the coordinates of customers (X_i, Y_i) and potential logistics hubs are based on actual geographical locations rather than abstract coordinate values. Geographic coordinates (latitude and longitude in the WGS 84 reference system) were transformed into

a projected metric coordinate system using standard GIS procedures to ensure the accuracy of spatial calculations. A comparison between the calculated Center of Gravity location and the available warehouse facilities within the Zhytomyr logistics hub demonstrated a close spatial correspondence between the theoretical optimum and the selected relocation alternative, while also satisfying the predefined security and infrastructure requirements.

Stage 2: Digital Search via the WareTeka Platform

The use of the specialized WareTeka platform enabled the rapid acquisition of 7 actual offers in the Zhytomyr region (Table 11).

Table 11. Warehouse Search Results on the WareTeka Platform.



№	Area (m^2)	Monthly Rental Cost (UAH/Month)
Alternative 1	1175 m^2	129,250 (110 UAH/m^2)
Alternative 2	1265 m^2	123,970 (98 UAH/m^2)
Alternative 3	1400 m^2	196,000 (140 UAH/m^2)
Alternative 4	2000 m^2	200,000 (100 UAH/m^2)
Alternative 5	1211 m^2	107,799 (89 UAH/m^2)
Alternative 6	1500 m^2	133,500 (89 UAH/m^2)
Alternative 7	1211 m^2	107,799 (89 UAH/m^2)

This was critically important, as the availability of free warehouse space in safe regions (for example, in Lviv) at that time was only 1% [91]. The seven facilities identified through the WareTeka platform formed the initial set of market offers available within the defined relocation area. The preliminary eligibility requirements included valid operating permits, location within the predefined geographical search area, and sufficient technical information for comparative assessment. These requirements were used to exclude facilities that clearly did not meet the basic conditions. Facility size ($\geq$1500 m^2) and rental cost ($\leq$UAH 100/m^2) were also important criteria at the initial screening stage.

Of the remaining market offers, offers 4 and 6 were selected for detailed expert assessment as the two most promising alternatives for the enterprise-specific decision stage. The final selection was then made using the eight K_1–K_8 criteria and a weighted additive aggregation method.

Results of monitoring available warehouse facilities:

- Offer 4: Area—2000 m^2, cost—UAH 200,000/month (UAH 100/m^2);
- Offer 6: Area—1500 m^2, cost—UAH 133,500/month (UAH 89/m^2).

Stage 3: Final Selection Based on Weighted Criteria

The consistency of expert judgements was assessed using Kendall's coefficient of concordance (W). Five experts independently ranked the eight decision criteria (K_1–K_8) for each shortlisted warehouse alternative, assigning ranks from 1 to 8, with 8 indicating the highest priority. For each alternative, the ranks assigned to each criterion were summed to obtain R_j. Deviations from the mean rank sum were then calculated, followed by the sum of squared deviations, S.

A value of $W \geq 0.70$ was considered to indicate a sufficiently high level of agreement among the expert rankings. When Kendall's W was below 0.70, the initial rankings were treated as showing insufficient agreement. In such cases, an additional structured discussion was held among the experts to clarify the interpretation of the criteria and resolve substantial differences in judgement before the final aggregated assessments were produced (Appendix B).

For the final selection, a group of company employees acting as experts evaluated the two most promising options according to 8 criteria (Table 12).

Table 12. Expert Evaluation of Selected Offers.

Weighted Score		Offer 6 Score		Weight (%)	Evaluation Criterion
Weighted Score	**Offer 4 Score**	**Weighted Score**	**Offer 6 Score**		
2.05	8.2	2.325	9.3	25.0	K_1—Rental cost
1.343	7.5	1.128	6.3	17.9	K_2—Lease term
0.994	7.0	0.895	6.3	14.2	K_3—Territorial location
1.079	7.6	1.037	7.3	14.2	K_4—Technical equipment
0.809	5.7	0.966	6.8	14.2	K_5—Possibility of partial lease
0.375	5.0	0.353	4.7	7.5	K_6—Adjacent territory
0.21	6.0	0.217	6.2	3.5	K_7—Reputation
0.189	5.4	0.165	4.7	3.5	K_8—Access roads
7.049	52.4	7.086	51.6	100.0	Integrated indicator

The scores presented in the table represent the aggregated expert judgements obtained after the expert assessment and consensus procedure described above. Kendall's W was calculated from the individual expert rankings and used to assess the level of agreement among the experts. For the warehouse selection criteria (K_1–K_8), the criterion weights were determined on the basis of the consensus judgments of an expert panel representing the participating enterprise. For example, rental cost received the highest weight (25.0%), followed by lease duration (17.9%), while territorial location and technical infrastructure each accounted for 14.2%. A standardized 10-point rating scale was used to evaluate each warehouse alternative against all selection criteria. The final ranking of warehouse alternatives was obtained using a weighted additive aggregation method (weighted sum model), in which the overall score of each alternative was calculated as the weighted sum of its criterion-specific evaluations.

The higher integrated score of Offer 6 (7.086 compared to 7.049 for Offer 4) is primarily due to its advantages in the criteria with the greatest weight significance. An important role is played by the rental cost criterion (K_1, weight 25%), where Offer 6 received a significantly higher score (2.32 versus 2.05), providing the largest contribution to the overall result. An additional advantage is the possibility of partial leasing criterion (K_5, weight 14.2%), where Offer 6 also demonstrated a better result (0.96 versus 0.80), increasing its flexibility and adaptability to the enterprise's needs.

For the sensitivity analysis, the calculations assume that a change in the weight of a given criterion is accompanied by a proportional redistribution of the weights assigned to the remaining seven criteria, while preserving their relative proportions. A weight adjustment coefficient for the remaining criteria was used to ensure that the sum of all weights remained equal to 100%. This approach makes it possible to examine how changes in the weight of a particular criterion affect the overall scores of the alternatives, while leaving the expert scores for the other criteria unchanged (Appendix C).

To evaluate the robustness of the obtained results, a sensitivity analysis was conducted by varying the weights of the key decision criteria, including the rental cost criterion (K_1) and lease term (K_2), as the criteria that received the highest expert ratings in terms of their importance for the decision-making process, within a ±20% range (Table 13).

Table 13. Sensitivity Analysis of Alternative Rankings to Changes in the Weight of the Rental Cost Criterion (K_1) and lease term (K_2).

Scenario	K_1					K_2				
	K_1 Weight	Offer 6	Offer 4	Δ(6-4)	Preferred Alternative	K_2 Weight	Offer 6	Offer 4	Δ(6-4)	Preferred Alternative
−20%	20%	6.935	6.973	−0.038	Offer 4	14.32%	7.118	7.029	+0.089	Offer 6
−10%	22.5%	7.010	7.011	0	Offer 4 = Offer 6	16.11%	7.101	7.039	+0.062	Offer 6
Baseline	25%	7.086	7.049	+0.037	Offer 6	17.90%	7.086	7.049	+0.037	Offer 6
+10%	27.5%	7.157	7.087	+0.070	Offer 6	19.69%	7.066	7.059	+0.007	Offer 6
+20%	30%	7.231	7.126	+0.105	Offer 6	21.48%	7.049	7.069	−0.020	Offer 4

The sensitivity test did not substantially change the initial preference for Offer 6, although two changes in the criteria weights produced a reversal in the ranking. With the original weights, the scores were 7.086 for Offer 6 and 7.049 for Offer 4, giving a difference in only 0.037. K_1 proved to be important for this result. Reducing its weight by 20% changed the order of the alternatives: Offer 4 scored 6.973 compared with 6.935 for Offer 6. When more weight was assigned to K_1, the opposite pattern was observed. A 10% increase produced a difference of +0.070 in favour of Offer 6, and a 20% increase raised this difference to +0.105. The point at which the choice becomes practically neutral is around K_1 = 22.5%, where the scores are 7.010 for Offer 4 and 7.011 for Offer 6.

The response to changes in K_2 was not the same. Reductions of 10% and 20% did not alter the original ranking, and neither did a 10% increase. Only when the weight of K_2 was increased by 20% did Offer 4 move ahead, with a score of 7.069 against 7.049 for Offer 6 (Δ = −0.020).

These calculations suggest that the selection of Offer 6 is not dependent on one exact set of weights. It remains the leading option in the baseline calculation and in most of the variations considered. At the same time, the reversals observed for K_1 and K_2 show where the decision is sensitive to changes in managerial priorities.

3.4. Paradigm of Intelligent Logistics: Synergy of Digitalization, Artificial Intelligence, and Human Capital Under Turbulent Conditions

3.4.1. Digitalization and Artificial Intelligence in the Logistics of the Future

The current stage of logistics development is characterized by the transition to the concept of "intelligent logistics." The use of AI-based IT solutions makes it possible to automate routine operations and focus on the future—operating proactively. In the context of martial law and high uncertainty, such a paradigm represents not only an evolutionary stage in logistics development, but also a necessary condition for ensuring business continuity and enterprise resilience.

Within the proposed HAMRLI for logistics infrastructure relocation, intelligent logistics performs the function of a system-forming core that ensures the coordination of spatial, informational, and managerial transformations. In particular, digitalization creates the basis for integrating distributed logistics facilities into a unified information system, making it possible to implement relocation not as a one-time action, but as a continuous adaptive process.

3.4.2. Automation and Information Flow Management

Today, logistics managers are forced to process enormous volumes of data, from monitoring fuel cards to synchronizing routes in real time. Investment in automated IT solutions allows managers to free up time for strategic planning and business process optimiza-

tion. Modern CRM systems integrated with logistics modules make it possible to create personalized customer offers by combining warehouse and transportation services in optimal configurations [92].

Automation and information flow management are critically important for the effective implementation of the hybrid model. Integrated digital platforms, CRM, and ERP systems ensure synchronization of operations across different locations, which is especially important under conditions of logistics infrastructure decentralization. This makes it possible to reduce transaction costs, increase process transparency, and ensure prompt managerial decision-making.

3.4.3. The Role of Artificial Intelligence in Supply Chain Management

AI is becoming an indispensable tool for identifying "weak points" in supply chains. It enables monitoring of equipment operations and navigation control. This ensures ideal synchronization of processes and creates unique competitive advantages for each organization.

The use of artificial intelligence technologies within the relocation model ensures the transition from reactive to proactive management. AI tools make it possible to forecast risks, optimize supply routes, model alternative scenarios for logistics facility placement, and minimize costs associated with resource relocation. Thus, relocation is transformed from a forced measure into a strategic instrument for enhancing enterprise competitiveness.

3.4.4. Human Capital as the Foundation of a Resilient Logistics System

Despite the high level of automation, the role of humans in logistics is not diminishing but qualitatively transforming, as knowledge, professional competencies, and employee creativity become the enterprise's primary resources [93,94].

Within the framework of the hybrid relocation model, it is precisely the competence, adaptability, and creativity of personnel that ensures the effective use of digital tools and the implementation of complex managerial decisions. In accordance with the Industry 5.0 concept, the emphasis shifts from process automation to strengthening the role of humans as carriers of knowledge and innovation.

3.4.5. Formation of a Creative Management Team

Enterprises must create conditions for the development of an "entrepreneurial climate" within the system. The role of management lies in ensuring continuous improvement of employee qualifications. The creative approach of logistics managers makes it possible to find unconventional solutions under conditions of resource constraints and wartime risks [95,96].

The formation of creative management teams is a necessary condition for successful relocation of logistics systems. Under conditions of high uncertainty, it is precisely the ability for unconventional thinking that makes it possible to identify optimal solutions regarding the selection of new locations, the configuration of logistics networks, and resource allocation.

3.4.6. Remote Work and Flexibility

Digitalization has enabled a significant share of logistics personnel to work remotely, which not only increases employee safety but also ensures continuity of logistics process management regardless of the geographical location of facilities. The reduction in manual and mechanical labor through robotization does not simply replace people, but rather increases overall productivity and quality of work performance [97]. Combined with au-

tomation, this forms a new labor organization model focused on efficiency, flexibility, and resilience.

Thus, the integration of digitalization, artificial intelligence, and human capital forms the conceptual foundation of the HAMRLI for logistics infrastructure relocation. In this context, intelligent logistics acts not only as a tool for improving efficiency, but also as a key factor in ensuring enterprise resilience under turbulent environmental conditions. Its implementation makes it possible to transform relocation from a reactive measure into a strategic mechanism for long-term development and cost optimization.

4. Discussion

The results of the study support the hypothesis that, under conditions of high environmental turbulence, logistics management transforms from a functional subsystem of the enterprise into a strategically important factor in ensuring its resilience and adaptability. In particular, the observed dynamics of the normalized resilience index (NRI) of Ukraine's logistics system demonstrate a transition from a crisis state to the recovery stage, which is consistent with the concepts of resilience management presented in recent supply chain management research. The interpretation of the NRI takes into account the relatively short observation period of 2022–2025. This four-year period was selected because it covers the functioning and adaptation of Ukraine's logistics system during the full-scale war and active hostilities. It is particularly relevant for resilience assessment, as the logistics system was exposed to severe external shocks while simultaneously developing mechanisms of adaptation.

Military risks affected physical infrastructure, operational capacity, and the continuity of logistics processes, while also stimulating organisational and technological adaptation. In particular, the crisis led to increased enterprise relocation, changes in logistics routes, and more rapid adoption of digital management technologies. Changes in X_1–X_4 during 2022–2025 should therefore not be interpreted solely as independent long-term trends. They also reflect the response of the logistics system to a common and exceptionally strong external shock.

This feature is both an advantage and a limitation of the NRI. On the one hand, the selected period provides a relevant empirical setting for studying resilience, since the ability of a system to withstand and adapt to disruption becomes particularly visible under severe stress. On the other hand, the short observation period makes it difficult to distinguish structural changes in the logistics system from temporary or crisis-induced responses. This is particularly relevant for the relocation and digital transformation indicators, whose dynamics may have been accelerated by the exceptional conditions of the war.

The limited number of observations also affects the entropy-based weighting procedure. The resulting weights are determined by the variation in the four indicators within the 2022–2025 observation period and may therefore be sensitive to the specific characteristics of these years. They should not be interpreted as universal or time-invariant weights of logistics resilience. Similarly, the NRI ranking reflects the relative position of the observed years within the selected crisis period rather than a statistically generalisable ranking applicable to other periods.

Accordingly, the NRI used in this study is interpreted as a comparative and exploratory indicator of resilience dynamics during the period of active hostilities, rather than as a definitive estimate of the underlying resilience of Ukraine's logistics system. Future research should extend the observation period and, where data availability permits, use higher-frequency observations and a broader set of directly observable indicators to examine the stability of the resulting weights and rankings.

The findings of this study are consistent with the approaches adopted by the Council of Supply Chain Management Professionals and the Association for Supply Chain Management, which view logistics management as an integrating function for managing resource flows. The present study develops this perspective further by considering the conditions of a wartime economy and infrastructure destruction, thereby extending the traditional understanding of logistics towards a system capable of adaptation and recovery under extreme risk.

The analysis also supports findings from previous studies concerning the growing role of digital technologies in logistics management, particularly within the Logistics 4.0 concept. The use of artificial intelligence, digital twins, and IoT can facilitate a shift from reactive towards more proactive forms of management. This is consistent with current research on so-called "self-healing supply chains", which emphasises the capacity of supply chains to adapt to changes in their operating environment. In this respect, the findings support the view that digitalisation can be an important driver of logistics-system resilience.

At the same time, while much of the previous literature considers digitalisation primarily as a means of improving efficiency, the present study also points to its role in maintaining business-process continuity under wartime conditions. This broadens the interpretation of logistics management by bringing security and risk-related considerations into the analysis.

Particular attention should be given to the proposed Hybrid Adaptive Model for Relocation of Logistics Infrastructure (HAMRLI). Its empirical application demonstrates the practical value of combining mathematical methods, including the Center of Gravity method, with digital platforms and expert assessment. This approach is consistent with current developments in decision-support systems, while adding an important practical element: the incorporation of current market data into the relocation process. In this respect, HAMRLI extends existing approaches to logistics infrastructure management by providing a more flexible and adaptive basis for decision-making.

The results also reveal several constraints. The effectiveness of the digital component of HAMRLI depends substantially on the availability and timeliness of information on the warehouse property market. The analysis indicates that the limited development of national digital platforms offering "on-demand logistics" services restricts the possibilities for automating the search and selection of logistics facilities. This points to the institutional immaturity of this part of the market and to the need for further development of the relevant digital infrastructure.

The composition of the expert group should also be considered. All experts represented the enterprise involved in the case, which may introduce organisational bias. This configuration was chosen because the final warehouse decision depends on internal operational, financial, logistics, and security requirements that are not fully observable to external experts. The resulting expert judgements should therefore be interpreted as context-specific rather than universally generalisable. Future studies could repeat the assessment with experts from several enterprises and/or independent logistics specialists to examine the stability of the criteria weights and the resulting rankings.

The findings further indicate that enterprise relocation under wartime conditions has not only an economic but also a spatial and structural dimension. The observed tendency towards the formation of new logistics hubs in relatively safer regions is consistent with concepts from regional economics and theories of spatial agglomeration. At the same time, the return of businesses to frontline regions suggests the presence of a "reverse relocation" effect that deserves further investigation.

Another important aspect concerns the role of human capital under digital transformation. Despite increasing automation, the ability to use new technologies effectively and

to adapt organisational processes still depends substantially on staff competencies. This observation is consistent with the human-centred perspective of Industry 5.0, in which technological development is considered together with the role of people in contemporary production and logistics systems.

From a practical perspective, the findings have several implications for Ukrainian enterprises. First, they support the use of flexible logistics arrangements based on the diversification of routes and warehouse capacity. Second, they indicate the importance of integrating digital technologies into different stages of logistics management. Third, HAMRLI can be used as a decision-support framework when enterprises consider relocation and the reconfiguration of their logistics infrastructure.

In a broader context, the findings indicate that the development of logistics management is an important condition for Ukraine's economic recovery and its integration into global supply chains. Logistics in this setting is not only a means of improving efficiency but also an element of national economic security.

The study nevertheless has several limitations that define the boundaries within which its findings should be interpreted. First, the empirical application of HAMRLI is based on a single case involving the relocation of the warehouse infrastructure of one enterprise. The results therefore cannot be statistically generalised to a wider population of enterprises. The case demonstrates how HAMRLI can be applied in a specific managerial setting and shows the sequence of its analytical stages, but it does not establish external validity across other industries, regions, or types of logistics systems.

Second, the expert assessment involved five representatives of the same enterprise. This made it possible to incorporate the enterprise's specific operational, financial, logistics, and security requirements, but it may also introduce organisational bias. The resulting criteria weights and evaluations of the alternatives should therefore be treated as context-specific rather than universal.

Third, the empirical case reflects the particular conditions under which Ukraine's logistics system operates during wartime, including infrastructure damage, security restrictions, and a high degree of uncertainty in the transport environment. These circumstances limit the direct transferability of the findings to stable logistics environments or to other countries without additional validation.

Fourth, the empirical test covers the main analytical sequence of HAMRLI but not all of its potential technological capabilities. In particular, automated data updating, real-time market monitoring, AI, Digital Twins, and automated decision-making were not implemented in the case presented here. These elements should therefore be regarded as possible directions for further development rather than as empirically validated components of the present application.

Finally, this study does not provide a multi-case or comparative evaluation of HAMRLI against other decision-making approaches. It therefore does not establish that HAMRLI is superior to alternative models across a broad range of logistics situations. Further validation should include applications to multiple enterprises, industries, and types of relocation scenarios, as well as the involvement of independent experts to examine the stability of the criteria weights and ranking results.

Several issues remain open for future research. One is the possible extension of HAMRLI with machine-learning tools that could support or partially automate individual stages of decision-making. Another concerns ESG factors and the extent to which they influence logistics strategies at the enterprise level. A separate research direction is the development of national digital logistics platforms based on the "Logistics-as-a-Service" concept. Such platforms could bring together information on available warehouse facilities, transport services, and supply chain management within a common digital environment. In

this context, future research should also focus on integrating automated data updates, automated market monitoring, and machine-readable data interfaces into HAMRLI, as these functionalities were not empirically implemented in the case presented in this study.

Accordingly, the proposed HAMRLI introduces three principal methodological contributions:

(1) Integration of spatial optimization with digital real-estate intelligence under force majeure conditions. In conventional location models, the Center of Gravity (COG) method is primarily applied to long-term planning based on relatively stable geographical coordinates. In contrast, HAMRLI adapts the COG method as a rapid regional screening tool that links the mathematically derived geographical optimum with available commercial warehouse market information through digital logistics platforms.

(2) Integration of System-Level Resilience Assessment into the Relocation Decision-Support Framework. The NRI provides a system-level assessment of changes in Ukraine's logistics resilience and establishes the broader crisis context in which enterprise relocation takes place, while EWM–TOPSIS is used to quantify changes in logistics-system resilience over time. At the enterprise level, individual warehouse alternatives are assessed separately using the K_1–K_8 criteria and weighted additive aggregation. The two assessments therefore serve complementary purposes: the NRI characterises the external resilience context, while the K_1–K_8 assessment supports the selection of a specific facility.

(3) Adaptation to crisis-induced operational dynamics. The framework explicitly considers the capability of relocation alternatives to maintain and restore operational performance under conditions of infrastructure disruption, resource shortages, and rapidly changing security constraints.

The scientific contribution of HAMRLI does not lie in the development of a new optimization algorithm. Rather, it lies in the integration of spatial optimization, real-time digital warehouse market information, resilience assessment, and expert decision support into a unified adaptive framework for strategic logistics relocation under wartime conditions.

The empirical findings should be interpreted in relation to three partly overlapping streams of research. First, studies on resilience-oriented logistics and facility location show that disruption risks can be incorporated directly into network or facility-location optimisation, often through stochastic, robust, or risk-averse formulations. HAMRLI differs in its decision architecture rather than by excluding such approaches. Instead of formulating the entire relocation problem as a single stochastic optimisation model, it uses spatial screening to narrow the relocation area and subsequently incorporates resilience-related information into decision-making at both the system and facility levels. Second, research on warehouse and logistics-centre location demonstrates the usefulness of MCDM methods for ranking predefined alternatives. The present case extends this logic by placing the MCDM stage after the identification and digital verification of facilities that are actually available within the selected relocation area. Third, studies of business relocation and logistics transformation in Ukraine provide important evidence on spatial, infrastructural, institutional, and security constraints. However, these constraints are generally not operationalised as a sequential facility-level decision procedure. The empirical case therefore suggests that the practical value of HAMRLI lies less in the individual analytical methods themselves than in their coordinated use across different levels of the relocation decision. At the same time, a single-case design does not provide a basis for claiming that the framework is superior to alternative optimisation or MCDM approaches. Rather, the case demonstrates its applicability in a specific crisis-relocation context and provides a structured approach that can be subjected to comparative testing in future multi-case studies. Unlike conventional

facility location models, which generally assume relatively stable operating environments, HAMRLI explicitly incorporates dynamic security constraints, currently available warehouse offers, and resilience indicators into the strategic relocation process, thereby providing a decision-support framework better suited to highly uncertain operating conditions (Table 14).

Table 14. Positioning HAMRLI relative to three streams of existing approaches.

Dimension	Relocation and Resilience Studies	Facility-Location and Resilient Location Models	Hybrid MCDM Location Studies	HAMRLI
Primary decision	Relocation, adaptation, continuity and resilience under disruptive conditions	Facility or network configuration under specified demand, cost and disruption conditions	Ranking and selection of predefined location alternatives	Sequential decision support for enterprise logistics infrastructure relocation
Spatial screening	Context-dependent; may focus on regions, relocation destinations or adaptation patterns	Usually an integral part of facility/network location modelling	Candidate locations are generally predefined before MCDM evaluation	COG-based identification of a potential relocation area
Market availability	May be considered as a relocation constraint or location factor	Usually represented through candidate facilities, site parameters or availability assumptions	Generally assumes a predefined set of feasible alternatives	Separate digital search and verification of currently available warehouse facilities
Facility-level selection	Varies depending on the relocation context	Typically determined through optimization or scenario-based selection	Central stage based on multi-criteria ranking	Enterprise-specific multi-criteria evaluation of shortlisted facilities
Resilience	Often a central analytical concern	Explicitly incorporated in resilient, stochastic or risk-aware location models	Depends on the criteria included in the decision model	Considered at two levels: NRI provides system-level resilience context, while security and operational resilience are reflected in facility-level criteria
Crisis context	Frequently addresses disasters, war, displacement or other disruptions	May explicitly model disruption, uncertainty and risk scenarios	Usually applied to sector-, region- or location-specific decisions	Empirical application to warehouse relocation under wartime conditions in Ukraine
Data logic	Statistical, qualitative, scenario-based or empirical relocation data	Model parameters, demand data, costs, capacities and disruption scenarios	Quantitative indicators combined with expert or decision-maker judgments	Logistics-flow data → geographical screening → digital market offers → expert facility evaluation
Role of MCDM	Varies across studies	Not necessarily central; may complement optimization	Usually the principal decision-ranking mechanism	Final facility-level decision layer after spatial and market screening
Empirical output	Relocation patterns, adaptation mechanisms, resilience implications or destination factors	Optimal or robust facility/network configuration	Ranked set of predefined alternatives	Potential relocation area, verified market alternatives and enterprise-specific facility ranking

5. Conclusions

The study examined the relocation of enterprise logistics infrastructure under wartime risks, infrastructure damage, unstable logistics flows, and the need for rapid operational adaptation. To address this problem, the Hybrid Adaptive Model for Logistics Infrastructure Relocation (HAMRLI) was proposed. The model combines spatial optimization, digital monitoring of available logistics facilities, and multi-criteria expert evaluation of alternatives.

The practical application of HAMRLI involves identifying a potential candidate regional relocation area using the Center of Gravity method, searching for and digitally verifying available warehouse facilities within this area, and selecting a specific facility through multi-criteria evaluation that considers cost, technical condition, security characteristics, and other relevant parameters.

HAMRLI was tested using the case of an enterprise relocating its warehouse infrastructure from the Zaporizhzhia region to the Zhytomyr logistics hub. The case demonstrates the sequential application of the model, from the mathematical determination of the Center of Gravity to digital screening of available facilities and their subsequent expert evaluation. At the same time, this case represents an initial empirical test of the model rather than a statistical generalization applicable to all enterprises.

To quantify the resilience of the logistics system, the Normalized Resilience Index (NRI) was calculated by combining the Entropy Weight Method (EWM) and TOPSIS. This approach made it possible to incorporate operational capacity, adaptive capacity, technological resilience, and infrastructure resilience into the overall assessment. When evaluating logistics alternatives, the NRI is used as a quantitative resilience criterion alongside economic and operational characteristics.

The NRI calculations for 2022–2025 made it possible to assess changes in the resilience of Ukraine's logistics system over the period studied. The results show an increase in the integrated indicator from 2022 to 2024, followed by a decline in 2025. These changes are associated with the dynamics of individual resilience components, particularly operational capacity, adaptive capacity, technological maturity, and infrastructure conditions.

The study also examined the criteria used to select warehouse alternatives. Integrated scores for the compared offers were obtained through expert evaluation. Under the adopted weighting system, the selected alternative gained an advantage due, among other factors, to more favorable financial conditions and greater flexibility in the use of warehouse space.

A sensitivity analysis was conducted to examine the stability of the decision when the weights of K_1 and K_2 were varied, as these criteria received the highest weights in the managerial decision. The results indicate that Offer 6 remains the leading option in the baseline calculation and in most of the variations considered. At the same time, the reversals observed for K_1 and K_2 show where the decision is sensitive to changes in managerial priorities.

The analysis also confirmed the importance of digitalization within the proposed approach. Digital technologies are considered a basis for coordinating spatial, informational, and managerial changes, while digital platforms provide tools for synchronizing operations across different locations and supporting timely managerial decision-making.

The roles of artificial intelligence and human capital in developing an adaptive logistics system were also considered. Within the model, AI tools can be used for risk forecasting, route optimization, modelling alternative location scenarios, and estimating relocation costs. At the same time, digitalization does not eliminate the role of personnel. Professional competence, adaptability, and employee creativity remain important for implementing complex managerial decisions.

Based on the results, three main methodological components of HAMRLI can be identified. These are the integration of spatial optimization with digital real estate market information, the incorporation of the NRI into multi-criteria decision-making through EWM and TOPSIS, and consideration of the ability of logistics alternatives to maintain and restore operations under infrastructure disruption, resource shortages, and changing security constraints.

The methodological contribution of HAMRLI lies in integrating spatial optimization, digital warehouse market information, resilience assessment, and expert decision support within a single adaptive framework for the strategic relocation of logistics infrastructure under wartime risks.

Overall, the study proposes and empirically tests an integrated decision support approach to logistics infrastructure relocation. It combines mathematical identification of

a potential location, digital searches for available facilities, quantitative resilience assessment, and expert comparison of alternatives. The results indicate that this approach can support managerial decisions in enterprises operating under high uncertainty and facing the need to adapt their logistics infrastructure.

Since the case presented in this study represents an initial empirical application, further research should expand the empirical base and test HAMRLI across a larger number of relocation cases. Further validation across different industries, relocation settings, and operating environments would also help assess the broader applicability of the framework.

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Institutional Review Board Statement: Ethical review and approval were not required for this study under the applicable Ukrainian regulatory framework. The study was non-medical and non-biomedical and did not constitute a clinical trial or a medico-biological experiment involving human subjects. Under Ukrainian legislation, ethics committee review requirements relevant to human-subject research apply to clinical trials of medicinal products and medico-biological research (in particular, Order No. 690 of the Ministry of Health of Ukraine of 23 September 2009 and Article 45 of the Fundamentals of Ukrainian Legislation on Health Care, Law No. 2801-XII). The present study involved only voluntary professional expert assessment by academic and industrial specialists. Responses were anonymized and analyzed only in aggregated form, and no medical interventions, biological samples, health data, or other sensitive personal data were collected. Therefore, the study did not fall within the scope of the above requirements for ethics committee approval.

Informed Consent Statement: Verbal informed consent was obtained from all experts participating in the assessment. Participation was voluntary, and all participants were informed about the purpose of the study and the use of their responses for research purposes. Responses were anonymized and analyzed only in aggregated form. No identifying or sensitive personal information is reported in the manuscript.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Source Data for Calculation

Table A1. Initial Decision Matrix.

Year	X_1: Freight Throughput (Million Tons)	X_2: Number of Relocations	X_3: Level of Digitalization	X_4: Infrastructure Losses (UAH Billion)
2022	25.0	15,589	Basic Digitalization	136.5
2023	62.0	14,136	Cloud Computing Adoption	152.0
2024	97.2	11,669	Investment in Artificial Intelligence	176.0
2025	82.2	12,920	Digital Twin Adoption	195.1

Table A2. Operationalisation of the Indicators.

Indicator	Measurement/Operationalization	Type	Data Source	Transformation
X_1	Port freight turnover, million tons	Stimulant	Official transport/infrastructure statistics	Min–max normalization
X_2	Enterprise relocation intensity used as a proxy for adaptation/stabilization	Context-dependent; transformed to resilience scale	Ministry of Economy, Opendatabot	Min–max normalization + inversion
X_3	Ordinal coding of digital maturity stages	Stimulant proxy	Documented technological development stages used in the study	Ordinal coding 0.25–1.00
X_4	Infrastructure vulnerability/damage, USD billion	Destimulant	Infrastructure damage assessments	Inverse min–max normalization

Appendix A.2. Indicator Normalization

Appendix A.2.1. Indicator X_1

Indicator X_1 is an absolute quantitative indicator (million tons of freight throughput) expressed in a consistent unit of measurement throughout the study period. The indicator takes only non-negative values, represents the contribution of each year to the overall operational capacity of the logistics system, and is treated as a benefit criterion, where higher values indicate stronger system performance.

$$r_{ij} = \frac{x_{ij} - min(x_j)}{max(x_j) - min(x_j)}$$

$$r_{2022} = \frac{25.0 - 25.0}{97.2 - 25.0} = \frac{25.0 - 25.0}{72.2} = 0$$

$$r_{2023} = \frac{62.0 - 25.0}{72.2} = 0.5125$$

$$r_{2024} = \frac{97.2 - 25.0}{72.2} = 1.000$$

$$r_{2025} = \frac{82.2 - 25.0}{72.2} = 0.7922$$

Table A3. Results of min–max normalization of indicator X_1 "Operational Capacity", 2022–2025.

2022	0
2023	0.5125
2024	1.000
2025	0.7922

Appendix A.2.2. Indicator X_2

Indicator X_2 is interpreted as an indicator of the logistics system's adaptive capacity, reflecting its ability to relocate operations and reorganize logistics processes in response to external disruptions. A higher relocation intensity indicates a greater level of organizational adaptation during the crisis response phase. To ensure comparability, the indicator was first normalized using the min–max method and subsequently transformed into the resilience scale, where lower relocation intensity during the recovery phase corresponds to a higher level of system stability.

$$r_{ij} = \frac{x_{ij} - min(x_j)}{max(x_j) - min(x_j)}$$

Therefore:

$$r_{2022} = \frac{15589 - 11669}{15589 - 11669} = \frac{15589 - 11669}{3920} = 1$$

$$r_{2023} = \frac{14136 - 11669}{3920} = 0.6293$$

$$r_{2024} = \frac{11669 - 11669}{3920} = 0$$

$$r_{2025} = \frac{12920 - 11669}{3920} = 0.3191$$

Since, in the proposed model, greater adaptability is assumed to correspond to higher resilience, the normalized values are inverted:

$$r'_{ij} = 1 - r_{ij}$$

Table A4. Normalized resilience scores for indicator X_2 "Adaptive Capacity", 2022–2025.

2022	0
2023	0.3707
2024	1.0000
2025	0.6809

Appendix A.2.3. Indicator X_3

For technological resilience, an ordinal coding scheme representing successive stages of digital maturity—from basic digitalization to the adoption of Digital Twins—was applied.

Table A5. Ordinal coding of indicator X_3 "Technological Resilience" based on digital maturity levels, 2022–2025.

2022	0.25
2023	0.50
2024	0.75
2025	1.00

Appendix A.2.4. Indicator X_4

Since infrastructure vulnerability is a cost criterion (where lower values indicate better performance), inverse normalization was applied:

$$r_{ij} = \frac{max(x_j) - x_{ij}}{max(x_j) - min(x_j)}$$

$$r_{2022} = \frac{195.1 - 136.5}{195.1 - 136.5} = \frac{195.1 - 136.5}{58.6} = 1$$

$$r_{2023} = \frac{195.1 - 152.0}{58.6} = 0.7345$$

$$r_{2024} = \frac{195.1 - 176.0}{58.6} = 0.3259$$

$$r_{2025} = \frac{195.1 - 195.1}{58.6} = 0$$

Table A6. Inverse min–max normalization of indicator X_4 "Infrastructure Vulnerability", 2022–2025.

2022	1.0000
2023	0.7345
2024	0.3259
2025	0.0000

Table A7. Normalized Decision Matrix.

Year	X_1	X_2	X_3	X_4
2022	0.0000	0.0000	0.25	1.0000
2023	0.5125	0.3707	0.50	0.7345
2024	1.000	1.0000	0.75	0.3259
2025	0.7922	0.6809	1.00	0.0000

Appendix A.3. Calculation of Entropy Weights

Appendix A.3.1. Calculation of the Probability Matrix

For each criterion, the sum of the probability-normalized values must equal 1.

For X_1

Verification of Probability Normalization

0.0000 + 0.5125 + 1.000 + 0.7922 = 2.3047

Therefore:

p_{11} = 0/2.3047 = 0

p_{21} = 0.5125/2.3047 = 0.2224

p_{31} = 1.000/2.3047 = 0.4339

p_{41} = 0.7922/2.3047 = 0.3437

For X_2

0 + 0.3707 + 1.0000 + 0.6809 = 2.0516

Therefore:

p_{12} = 0/2.0516 = 0

p_{22} = 0.3707/2.0516 = 0.1807

p_{32} = 1.0000/2.0516 =0.4874

p_{42} = 0.6809/2.0516 =0.3319

For X_3

Sum of normalized values:

0.25 + 0.50 + 0.75 + 1.00 = 2.50

Therefore:

p_{13} = 0.25/2.50 = 0.10

p_{23} = 0.50/2.50 = 0.20

p_{33} = 0.75/2.50 = 0.30

p_{43} = 1.00/2.50 = 0.40

For X_4
Sum of normalized values:
1.0000 + 0.7345 + 0.3259 + 0 = 2.0604
Therefore:
p_{14} = 1.0000/2.0604 = 0.4853
p_{24} = 0.3565
p_{34} = 0.1582
p_{44} = 0

Table A8. Normalized Probability Matrix.

Year	X_1	X_2	X_3	X_4
2022	0	0.0000	0.1000	0.4853
2023	0.2224	0.1807	0.2000	0.3565
2024	0.4339	0.4874	0.3000	0.1582
2025	0.3437	0.3319	0.4000	0.0000

Appendix A.3.2. Entropy Calculation

$$e_j = -k\sum_{i=1}^{m} p_{ij} ln(p_{ij})$$

k = 1/ln(m)
k = 1/ln(4) = 0.72135

$$e_1 = -0.72135[0ln0 + 0.2224ln0.2224 + 0.4339ln0.4339 + 0.3437ln0.3437]$$

Each term is calculated as follows.
0ln0 = −0
0.2224ln0.2224 = −0.3343
0.4339ln0.4339 = −0.3623
0.3437ln0.3437 = −0.3671
Sum: 0 − 0.3343 − 0.3623 − 0.3671 = −1.0637
Therefore:
e_1 = −0.72135 × (−1.0637) = 0.7673

Table A9. Entropy values of the resilience indicators.

e_1	0.7674
e_2	0.7397
e_3	0.9232
e_4	0.7287

Appendix A.3.3. Divergence Calculation

$d_i = 1 - e_i$
Therefore:
d_1 = 1 − 0.7674 = 0.2327

Table A10. Divergence coefficients of the resilience indicators.

d_1	0.2326
d_2	0.2603
d_3	0.0768
d_4	0.2713

Appendix A.3.4. Calculation of Criterion Weights

After determining all d_j values:

$$w_j = \frac{d_j}{\sum d_j}$$

$$\sum d_j = 0.841$$

$$w_1 = \frac{0.2326}{0.841} = 0.2766$$

Table A11. Entropy-based weights of the resilience indicators.

w_1	0.2766
w_2	0.3095
w_3	0.0913
w_4	0.3226

Verification:
0.2766 + 0.3095 + 0.0913 + 0.3226 = 1.0000

$$v_{ij} = r_{ij} w_j$$

Table A12. Weighted Normalized TOPSIS Matrix.

Year	X_1 (w = 0.2766)	X_2 (w = 0.3095)	X_3 (w = 0.0913)	X_4 (w = 0.3226)
2022	0.0000	0.0000	0.0228	0.3226
2023	0.1418	0.1147	0.0457	0.2369
2024	0.2766	0.3095	0.0685	0.1051
2025	0.2191	0.2107	0.0913	0.0000

Appendix A.4. Ideal and Anti-Ideal Solutions

Appendix A.4.1. Positive Ideal Solution A^+

$A^+ = \max(v_{ij})$

Table A13. Positive ideal solution.

X_1	X_2	X_3	X_4
0.2766	0.3095	0.0913	0.3226

Appendix A.4.2. Negative Ideal Solution A^-

$A^- = \min(v_{ij})$

Table A14. Negative ideal solution.

X_1	X_2	X_3	X_4
0.0000	0.0000	0.0228	0.0000

Appendix A.4.3. Distances from the Ideal and Anti-Ideal Solutions

Formulas:

$$D_i^{+} = \sqrt{\sum_{j=1}^{n}}$$

$$D_i^{-} = \sqrt{\sum_{j=1}^{n}}$$

Example Calculation

$$D_{2022}^{+} \sqrt{\sum_{j=1}^{n} (0-0.2766)^2 + (0-0.3095)^2} + (0.0228-0.0913)^2 + (0.3226-0.3226)^2 = 0.4207$$

Table A15. Distances from the Positive and Negative Ideal Solutions.

Year	Distance to Ideal D^+	Distance to Anti-Ideal D^-
2022	0.4207	0.3226
2023	0.2560	0.2999
2024	0.2187	0.4306
2025	0.3422	0.3116

Appendix A.5. Integral Assessment of Proximity to Stability

$$NRI_i = \frac{D_i^-}{D_i^{++D_i^-}}$$

$$NRI_{2022} = \frac{0.3226}{0.4207 + 0.3226} = 0.4340$$

Table A16. Normalized Resilience Index (NRI).

Year	NRI
2022	0.4340
2023	0.5395
2024	0.6632
2025	0.4766

Appendix A.6. National Resilience Index (NRI) of the Ukrainian Logistics System Based on the Integrated EWM–TOPSIS Model

Table A17 summarizes the intermediate and final results of the integrated EWM–TOPSIS assessment and provides the basis for Table 4, which presents the final assessment of the resilience level of Ukraine's logistics system.

Table A17. Integrated assessment of the resilience level of Ukraine's logistics system based on the EWM–TOPSIS Model.

Year	Operational Capacity	Adaptive Capacity	Technological Resilience	Infrastructure Resilience	NRI	Interpretation
2022	0.0000	0.0000	0.25	1.0000	0.434	Critical shock
2023	0.5125	0.3707	0.50	0.7345	0.540	Adaptation
2024	1.000	1.0000	0.75	0.3259	0.663	Recovery
2025	0.7922	0.6809	1.0000	0.0000	0.477	Prospective development

Appendix B. Kendall's Concordance Analysis of Expert Rankings

Table A18. Expert ranking matrix for Offer 4.

Criterion	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	R_j	$R_j - \overline{R}$	$(R_j - \overline{R})^2$
K_1—Rental cost	8	8	8	8	8	40	17.5	306.25
K_2—Lease term	5	6	5	4	5	25	2.5	6.25
K_3—Territorial location	4	5	6	5	4	24	1.5	2.25
K_4—Technical equipment	7	7	7	7	7	35	12.5	156.25
K_5—Partial lease	6	4	4	6	6	26	3.5	12.25
K_6—Adjacent territory	2	3	2	3	2	12	−10.5	110.25
K_7—Reputation	3	2	3	2	3	13	−9.5	90.25
K_8—Access roads	1	1	1	1	1	5	−17.5	306.25
Total						180	0	990.00

$$\overline{R} = \frac{180}{8} = 22.5$$

$$S = 990$$

$$W_4 = \frac{12 \times 990}{5^2 \left(8^3 - 8\right)} = 0.943$$

$W_6 = 0.943$ indicates a high degree of concordance among the five experts in ranking the eight criteria for Offer 4.

Table A19. Expert ranking matrix for Offer 6.

Criterion	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	R_j	$R_j - \overline{R}$	$(R_j - \overline{R})^2$
K_1—Rental cost	8	8	8	8	8	40	17.5	306.25
K_2—Lease term	6	6	7	6	6	31	8.5	72.25
K_3—Territorial location	5	4	5	4	5	23	0.5	0.25
K_4—Technical equipment	7	7	6	7	7	34	11.5	132.25

Table A19. *Cont.*

Criterion	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	R_j	$R_j - \overline{R}$	$(R_j - \overline{R})^2$
K_5—Partial lease	3	3	3	3	3	15	−7.5	56.25
K_6—Adjacent territory	1	1	1	2	1	6	−16.5	272.25
K_7—Reputation	4	5	4	5	4	22	−0.5	0.25
K_8—Access roads	2	2	2	1	2	9	−13.5	182.25
Total						180	0	1022.00

$$\overline{R} = \frac{180}{8} = 22.5$$

$$S = 1022$$

$$W_6 = \frac{12 \times 1022}{5^2\,(8^3 - 8)} = 0.973$$

$W_4 = 0.973$ indicates a high degree of concordance among the five experts in ranking the eight criteria for Offer 6.

Both values exceed the predefined threshold of 0.70 and therefore indicate a high degree of agreement among the expert ratings of the two selected alternatives.

Appendix C. Sensitivity Analysis of Warehouse Alternative Rankings to Changes in Criteria Weights

The calculation is based on a one-at-a-time sensitivity analysis, whereby the weight of K1 is varied to 20%, 22.5%, 27.5%, and 30%, while all other weights are proportionally redistributed so that their sum remains 100%.

Formula for Calculating the Criteria K_2—K_8:

$$w_j' = w_j \frac{1 - w_i'}{1 - w_i}$$

where w_j'—new weight of the criterion under analysis.

Aggregate Score

$$S_a = \sum_{j=1}^{8} w_j' x_{aj}$$

where x_{aj}—alternative score for the criterion.

Table A20. Evaluation of Alternatives by Criterion K_1.

Criterion	Offer 4 Score	Offer 6 Score	Baseline Weight			−20% Weight			−10% Weight			+10% Weight			+20% Weight		
			Weight (%)	Weighted Score (Offer 4)	Weighted Score (Offer 6)	Weight (%)	Weighted Score (Offer 4)	Weighted Score (Offer 6)	Weight (%)	Weighted Score (Offer 4)	Weighted Score (Offer 6)	Weight (%)	Weighted Score (Offer 4)	Weighted Score (Offer 6)	Weight (%)	Weighted Score (Offer 4)	Weighted Score (Offer 6)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
K_1	8.2	9.3	25.0	2.05	2.325	20	1.64	1.86	22.50	1.845	2.093	27.50	2.255	2.558	30.00	2.460	2.790
K_2	7.5	6.3	17.9	1.343	1.128	19.09	1.432	1.203	18.50	1.387	1.166	17.30	1.298	1.090	16.71	1.253	1.053
K_3	7.0	6.3	14.2	0.994	0.895	15.15	1.061	0.954	14.67	1.027	0.924	13.73	0.961	0.865	13.25	0.928	0.835
K_4	7.6	7.3	14.2	1.079	1.037	15.15	1.151	1.106	14.67	1.115	1.071	13.73	1.043	1.002	13.25	1.007	0.967
K_5	5.7	6.8	14.2	0.809	0.966	15.15	0.864	1.03	14.67	0.836	0.997	13.73	0.783	0.934	13.25	0.755	0.901
K_6	5.0	4.7	7.5	0.375	0.353	8.00	0.4	0.376	7.75	0.388	0.364	7.25	0.363	0.341	7.00	0.350	0.329
K_7	6.0	6.2	3.5	0.21	0.217	3.73	0.224	0.231	3.62	0.217	0.224	3.38	0.203	0.210	3.27	0.196	0.203
K_8	5.4	4.7	3.5	0.189	0.165	3.73	0.201	0.175	3.62	0.195	0.170	3.38	0.183	0.159	3.27	0.177	0.154
Total			100	7.049	7.086	100	6.973	6.935	100.00	7.011	7.010	100.00	7.087	7.157	100.00	7.126	7.231

Table A21. Summary Table of Alternative Evaluation by Criterion K_1.

Scenario	K_1 Weight	Offer 6	Offer 4	Δ(6-4)	Preferred Alternative
−20%	20%	6.935	6.973	−0.038	Offer 4
−10%	22.5%	7.010	7.011	0	Offer 4 = Offer 6
Baseline	25%	7.086	7.049	+0.037	Offer 6
+10%	27.5%	7.157	7.087	+0.070	Offer 6
+20%	30%	7.231	7.126	+0.105	Offer 6

The calculation was performed in the same way for criterion K_2.

Table A22. Summary Table of the Evaluation of Alternatives by Criterion K_2.

Scenario	K_2 Weight	Offer 6	Offer 4	Δ(6-4)	Preferred Alternative
−20%	14.32%	7.118	7.029	+0.089	Offer 6
−10%	16.11%	7.101	7.039	+0.062	Offer 6
Baseline	17.90%	7.086	7.049	+0.037	Offer 6
+10%	19.69%	7.066	7.059	+0.007	Offer 6
+20%	21.48%	7.049	7.069	−0.020	Offer 4

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