International Journal of Innovative Technology and Interdisciplinary Sciences
https://journals.tultech.eu/index.php/ijitis
ISSN: 2613-7305
Volume 9, Issue 3
DOI: https://doi.org/10.15157/IJITIS.2026.9.3.1852-1884
Received: 08.06.2026; Revised: 31.07.2026; Accepted: 31.08.2026

Research Article

Regional Logistics Centers for Efficient Cross-Border Freight Distribution: An Empirical Analysis

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Abstract

This study evaluates the strategic value of regional logistics centers for improving road-freight efficiency and distribution performance in Kosovo and the wider Western Balkans. Empirical cases involving beverage transportation and distribution were integrated into a mathematical optimization model, followed by scenario-based evaluation, statistical hypothesis testing, and sensitivity and uncertainty analyses. The cases include domestic transportation within Kosovo and international beverage distribution from Peja to Skopje and Ohrid. The proposed model minimizes total transportation, handling, warehousing, delay, and customs-clearance costs subject to demand, vehicle capacity, fleet availability, warehousing capacity, and time constraints. To assess robustness beyond the empirical cases, 100 shipment scenarios were generated using observed operating ranges, incorporating different demand levels, route distances of approximately 75–320 km, border delays, fuel prices, and fleet availability. The logistics-center configuration outperformed the baseline in total cost, lead time, vehicle utilization, and productivity. Paired t-tests indicated statistically significant differences between the configurations ($p < 0.001$), with large effect sizes, while Shapiro–Wilk and Wilcoxon signed-rank tests provided additional evidence of robustness. A 10,000-replication Monte Carlo analysis, with verified convergence, further demonstrated that these performance advantages persisted under simultaneous uncertainty in demand, distance, loading conditions, border delays, and fuel prices. Sensitivity analysis identified demand, traffic conditions, and fuel prices as the main cost drivers, while consolidation and routing positively influenced vehicle-capacity utilization. Overall, the findings provide a systems-engineering basis for evaluating logistics-center investments and improving freight-distribution efficiency under uncertainty in the Western Balkans.

Keywords: Logistics Centers; Freight Distribution; Transport Efficiency; Western Balkans; Optimization; Monte Carlo Simulation; Sensitivity Analysis; Supply Chain Performance.

INTRODUCTION

Nowadays, freight transport is facing increasing pressures for reducing the costs of logistics, accelerating deliveries, improving the utilization of vehicles, enhancing the reliability of services, and limiting environmental externalities. Modern logistics centers are now becoming a complex node which incorporates functions of consolidation, warehousing, transshipment, exchange of information, routes planning, and multimodal interfacing. Today's logistics management highlights that the efficiency of distribution process is not only related to the transportation of cargo but also to its coordinated arrangement of facilities, stock of cargo, transport capacity, information streams, and service operations [1-7]. This issue is especially topical in case of regional freight systems when border formalities, fragmented markets, inadequate infrastructure and direction imbalance result in significant empty running and loss of time.

The Western Balkans offer an appropriate environment for consideration of this problem. Kosovo is a landlocked state which highly relies on road transportation to neighboring countries for regional trade relations. Logistics streams towards North Macedonia and Albania depend on border-crossing formalities, lack of intermodal integration, infrastructure differences, and small logistics markets. In the system of direct delivery of cargo from manufacturer to client, long-haul trucks make their outbound runs with high payloads but return back empty or with low loadings [8-15]. Loading, unloading, crossing of border, and other formalities cause the reduction of effective working time of the vehicle. All these factors lead to increase in costs of delivery per ton and restrictions on possibilities for logistics companies to increase the volume of services.

Recent studies have demonstrated that logistics performance can be improved through coordinated planning of transport and distribution systems [3, 4], strategic logistics-center location [5, 19–25], infrastructure development [6], port–hinterland integration [7, 17, 21], two-echelon network design [9, 23], vehicle-routing optimization [12], freight consolidation [15], and transshipment strategies [16, 22]. In parallel, digitalization, the Internet of Things (IoT), artificial intelligence, blockchain, and Logistics 4.0 are expanding the role of logistics centers beyond physical consolidation toward data-driven decision-support platforms [14, 25–33]. Consequently, contemporary evaluation of logistics-center configurations should consider not only operational transportation indicators but also optimization performance, statistical validation, uncertainty, sustainability, and the performance of the network as an integrated system.

The original empirical base of the present study includes two cases of beverages distribution from a manufacturer in Kosovo, one case for domestic distribution and another one for cross-border export from Peja to Skopje and Ohrid. Observed variables include route distance, payload, loading and unloading times, average speed, fleet utilization, number of vehicle-hours, kilometers driven, productivity and transport cost. In this revised study, the authors keep original practical cases and extend them using systems-engineering approach so that it allows evaluating the proposed logistics center concept in different operating conditions.

RELATED WORK

Logistics Centers, Consolidation and Distribution Efficiency

Modern logistics nodes combine freight consolidation, inventory storage, transshipment, distribution planning, and value adding. The study in [1] defines distribution management as an integral supply chain management process requiring joint transport, warehouse, network, and information management. Authors in [3] also note that modern transport-distribution efficiency requires coordinated infrastructural and organizational decisions, whereas the study in [4] emphasizes that the performance of transport-logistics should be improved through rational resource use. Integrated logistics networks may reduce fragmentation in the distribution process by consolidating flows and delivery planning [10].

Shipment-consolidation becomes especially topical in the case when separate delivery flows lead to low vehicle productivity and repeat trips. Authors in [15] reported environmental and operational efficiency gains from shipment-consolidation strategies, whereas in [22] discussed how micro hubs could restructure urban freight flows through intermediate consolidation. Similarly, authors in [16] analyzed transshipment points as restructuring tools for last-mile delivery processes. These studies are urban or retail-oriented; however, the same systems approach works in regional freight distribution: an intermediate logistics node can consolidate long-haul flows and restructure deliveries according to destination and vehicle sizes.

Facility Location and Freight Network Optimization

The performance of a logistics center is highly influenced by its location and network role. Authors in [5] presented an analytical model to assess logistics-center locations from the sustainable urban logistics point of view, revealing the impact of location choice on transportation and the environment. The study in [25] considered the problem of optimal placement of logistics centers in Azerbaijan, showing the importance of corridor access and location-based criteria. Furthermore, authors in [7] showed the need for logistics distribution centers in port hinterland areas to be strategically aligned with industrial and transportation activities.

Two-echelon and multimodal network design studies rely increasingly on mathematical optimization methods. Authors in [9] combined planning and network design to assess collaborative two-echelon logistics operations, while in [23] relied on hybrid optimization techniques in a two-echelon underground logistics network in urban area. The study in [12] optimized vehicle routing for intelligent logistics vehicles through algorithmic approach. These studies confirm a trend from logistic-center suggestions to decision models incorporating objective function, constraints, and decision variables.

Multimodality, Hinterland Connectivity and Freight Corridors

Logistics centers can also serve as interfaces between different transport modes. The importance of institutional actors in achieving integration of ports and rail was shown by [17], while [21] linked hub-port and inland-hinterland institutions with multimodal logistics and low carbon performance [34-36]. Authors in [37], through network-equilibrium analysis, found that changes to a transport network have not only economic but also environmental impacts. This is important for the Western Balkans region where road transport plays an important role in many freight flows, and road-rail interfaces can decrease dependency on heavy road vehicles in the long term.

At a more general level of performance, authors at [2] analyzed the importance of spatial connectivity in developing logistics, proving that connectivity and structure of the network are vital to logistics performance strategy. The studies in [38, 39] further showed that it is possible to benchmark logistics performance using indicators related to trade and transport, while [36] have applied the dimensions of the Logistics Performance Index for supporting policy making.

Logistics Performance Measurement, Sustainability and Resilience

Logistics-center evaluation should encompass more than transport costs. Authors in [13] considered warehouse productivity measurements as relevant decision variables in operations management, whereas the study in [19] introduced an analytical approach to assess efficiency in sustainable transport logistics. Authors in [26] provided evaluation of national logistics performance in international supply chains, showing the multi-dimensional nature of logistics competitiveness. The study in [24] reviewed multi-criteria decision-making (MCDM) approaches used for evaluation of green logistics and low-carbon transportation. It is clear that a multi-criteria decision-making process allows considering cost, infrastructure, environmental performance, and service quality at once.

Performance evaluation in logistics is being supplemented by environmental criteria. The study in [27] analyzed carbon emission efficiency of the logistics sector, and [34] generalized sustainability problems and opportunities for last-mile freight logistics. Authors in [18] revealed connections between logistics inefficiency and impact on freight and related policy measures, and [20] advocated for integrated evaluation of first-and-last mile freight-passenger system. The conclusion here is that savings from reduced number of empty kilometers, unnecessary movements, and inefficient routes should be regarded as both economic and environmental benefits.

The notion of resilience also became one of the key factors in logistics analysis. Authors in [31] estimated structural robustness of global liner shipping networks applying methods of network science. One may see that logistics performance should be evaluated not on average but under disruptions. This becomes especially important in cross-border road freight transportation, where disruptions can be caused by traffic accidents, congestion in borders, custom procedures, changes in prices for fuel, and uncertainty in demand. That is why scenario analysis and Monte Carlo simulation have been implemented in the current study.

Digital Logistics and Logistics Center 4.0

The coming industrial revolution is turning logistics centers into digitally organized entities. The study in [14] introduced the concept of Logistics Center 4.0, where automation, connectivity, intelligent systems, and real-time data became key assets. Authors in [28] investigated determinants of blockchain usage in freight logistics, demonstrating the benefits of distributed information systems for better traceability and coordination. Similarly, the study in [35] found that digitization helps improve the competitiveness and sustainability of logistics-oriented supply chains.

Currently, literature continues developing this trend towards AI-oriented logistics. In particular, authors in [32] investigated the optimization of urban logistics with the use of AI and IoT and autonomous vehicles. The study in [33] provided the discussion on AI approaches to improving supply chain resilience. In turn, business analytics platforms can be used for better decision-making in logistics through data integration and performance management [38]. In the case of the Western Balkans region, such technologies imply that a logistics center of the future should be seen not just as a warehouse but as a node for information and coordination in route planning, customs procedures, fleet scheduling, demand forecasting, and performance management.

Research Gap

Four gaps can be identified based on the literature review. First, most of the recent research on logistics centers optimization, micro-hubs, multimodal coordination, and digital freight is conducted in advanced or large emerging economies, while detailed quantitative studies of Western Balkan freight corridors have been relatively rare. Second, practical research on logistics centers often consists either of conceptual infrastructure analysis or performance indicator evaluation, whereas fewer of such studies link empirical data on transport engineering with optimization, hypothesis testing, sensitivity analysis, and reliability simulations within a single research approach. Third, evaluations of regional freight flow usually consider cost, time, capacity utilization, sustainability, or resilience individually without analyzing their integrated response to logistics centers intervention. Fourth, uncertainties regarding demand, border delay, time, fuel prices, and vehicle availability are seldom taken into account in practical logistics center evaluation for the Kosovo-North Macedonia-Albania transport situation. The current research seeks to fill these gaps through the combination of empirical transport cases with an optimization approach to the logistics center, multi-scenario simulation, inferential statistics, sensitivity analysis, Monte Carlo reliability analysis, and benchmarking against advanced logistics practices.

Table 1 synthesizes the existing literature across seven dimensions to clarify the research gap. Most previous studies examine individual mechanisms like logistics-center location, freight consolidation, multi-criteria decision-making (MCDM) benchmarking, or conceptual digital frameworks in isolation. Moreover, many studies focus on urban, national, or generic logistics settings rather than data-scarce cross-border corridors. Existing approaches also tend to focus either on conceptual frameworks or on deterministic case analyses, with comparatively limited attention to formal uncertainty and robustness analysis.

Table 1: Structured Synthesis of Prior Logistics-Center and Cross-Border Freight Studies and the Positioning of the Present Study

Study	Context	Methodology	Dataset	Optimization/Technique	KPIs	Reported Limitation	Contribution of Present Study
[5]	Urban logistics-center location, China	Analytical location-impact framework	Single urban case	Location-impact scoring	Environmental/transport impact	Single-criterion location focus; no cost/uncertainty model	Embeds location rationale within full cost-minimization and scenario testing
[9]	Collaborative two-echelon network, EU	Integrated planning model	Simulated network	MILP (two-echelon)	Cost, CO2, distance	No empirical baseline calibration; no cross-border/customs delay	Calibrates two-echelon structure to observe Balkans cross-border operations
[23]	Two-echelon shipment consolidation, generic	Deterministic MILP case	Simulated network	Consolidation MILP	Cost (~40% reduction reported), emissions	Not cross-border; single deterministic scenario, no inferential testing	Adds cross-border calibration, 100-scenario hypothesis testing and Monte Carlo robustness
[22]	Urban freight microhubs, Europe/N. America	Case-study typology (17 cases)	Qualitative case interviews	None (conceptual)	Qualitative typology	No quantitative optimization or statistical testing	Provides a formal quantitative optimization and inferential-statistics layer
[25]	Logistics-center siting, Azerbaijan	MCDM facility-location	National corridor data	MCDM (location)	Accessibility, cost	Static; no stochastic/scenario validation	Adds scenario-based and Monte Carlo robustness testing to the siting logic
[26]	National logistics performance, GCC	MCDM benchmarking	Country-level indices	MCDM benchmarking	Composite performance index	Macro/national level; not route- or firm-level	Complements macro benchmarking with firm/route-level empirical optimization
[14]	Logistics 4.0 conceptualization	Conceptual/agenda-setting	None	None	n/a	Non-empirical; no quantitative validation	Operationalizes the digital logistics-center concept against measured KPIs
Present study	Cross-border road freight, Kosovo-N. Macedonia -Albania	Case study + optimization + simulation	2 empirical cases + 100 model-generated scenarios	Two-echelon cost minimization (Eq. 1-6) + Monte Carlo	Cost, lead time, utilization, empty-km, productivity, CO2 proxy	Scenario data model-generated, not independently observed; no primary stakeholder data	Integrates empirical calibration, formal optimization, hypothesis testing, sensitivity/Monte Carlo analysis and SOTA benchmarking in one reproducible framework

The existing literature does not appear to integrate empirical operational calibration, an explicit two-echelon cost-minimization formulation, scenario-based hypothesis testing, Monte Carlo uncertainty analysis, and state-of-the-art benchmarking within a single reproducible framework for the Kosovo–North Macedonia–Albania corridor. This integrated methodological approach addresses the identified research gap and constitutes the principal contribution of the present study.

RESEARCH OBJECTIVES, HYPOTHESES AND CONTRIBUTION

Research Objectives

The study aims to:

- estimate inefficiencies in the current direct distribution system based on empirical transport measures;
- develop a model for the optimal design of logistics centers for regional freight consolidation;
- measure changes in transport costs, lead time, utilization rate, empty backhaul, and productivity with the new system;
- determine if the changes from the model prove statistically significant in different shipment scenarios;
- determine robustness to uncertainty in demand, fuel price, travel time, customs clearance time, and fleet availability; and
- relate the new model to current logistics center, hub-and-spoke, network optimization, sustainability, and digital logistics literature.

Research Hypotheses

- H1: Implementation of the regional logistics-center configuration significantly reduces total transport cost relative to direct distribution.
- H2: Implementation of the logistics-center configuration significantly improves vehicle utilization.
- H3: Implementation of the logistics-center configuration significantly reduces transport lead time.
- H4: Implementation of the logistics-center configuration significantly improves overall productivity (t/h) and labor productivity (tkm/h).
- H5: The proposed logistics-center model produces statistically significant overall KPI improvements compared with the traditional transport organization.
- H6: The proposed model demonstrates performance characteristics consistent with or superior to contemporary logistics-center and hub-distribution approaches reported in the state-of-the-art literature.

Scientific Contribution

The main contribution is a novel evaluation framework that is both a hybrid and a reproducible design, suitable for the specific case of a small country, which is landlocked and operates in a cross-border freight environment. This differs from the description of a logistics center by including empirical analysis of the transport cycle, optimization based on cost minimization, sensitivity analysis, Monte Carlo analysis of uncertainties, proxy measures of sustainability, and SOTA benchmarks.

Theoretical Foundation

The proposed framework is grounded in five complementary theoretical strands. Logistics-center theory frames the regional hub as a consolidation-and-transshipment node that internalizes scale economies otherwise lost to fragmented direct delivery [1]. Facility-location theory supplies the criteria corridor access, customs performance, land and operating cost, market proximity, and future capacity against which the Skopje-area candidate site is evaluated as an MCDM/facility-location problem rather than an ad hoc choice [5, 25]. Network optimization theory provides the formal two-echelon cost-minimization structure that converts the qualitative consolidation argument into decision variables, an objective function, and constraints [9]. Resilience theory motivates modeling demand, border delays, fuel prices, and fleet availability as stochastic rather than fixed parameters, as network performance must be evaluated not only under average operating conditions but also under potential disruptions and adverse conditions that determine its practical value [31]. Additionally, sustainable logistics theory motivates the inclusion of the CO_2 proxy indicator alongside cost and time, so that the evaluation captures environmental as well as economic performance [27]. These five strands are integrated within the conceptual framework presented in Figure 1 rather than being applied in isolation. The identified research gap and theoretical foundations jointly inform the proposed logistics-center model, which in turn generates the research hypotheses (H1–H6). The model is evaluated using the performance indicators defined in Table 1 and validated through the empirical, statistical, sensitivity, Monte Carlo, and benchmarking procedures described in the methodology.

Methodological Novelty

The framework is methodologically distinct from, rather than a re-application of, the four families of approaches most often used to evaluate logistics-center or freight-network interventions. Pure facility-location and hub-and-spoke studies [5, 25] typically optimize sitting or network topology under deterministic parameters and stop once a preferred configuration is identified; they do not test whether the configuration's operational advantage is statistically robust to demand, delay, or price uncertainty. MCDM studies [24, 26] rank discrete alternatives against weighted criteria but do not embed an explicit cost-minimization objective function or quantify the magnitude of operational improvement in transport KPIs. DEA-based efficiency studies benchmark relative efficiency across existing decision-making units using historical data, which presupposes that comparable units already operate a condition not met in a corridor where no logistics center yet exists. General logistics-network optimization studies [9, 23] formalize the two-echelon problem mathematically but are usually validated on synthetic or generic networks without calibration to a specific, empirically observed operating environment. The present study combines elements of all four traditions empirical calibration from two operational cases, an explicit two-echelon MILP-type formulation via equation (1), scenario-based inferential statistics, Monte Carlo reliability analysis, and SOTA benchmarking -- within a single reproducible pipeline applied to a corridor (Kosovo-North Macedonia-Albania) for which no comparable quantitative evaluation previously existed (Table 10).

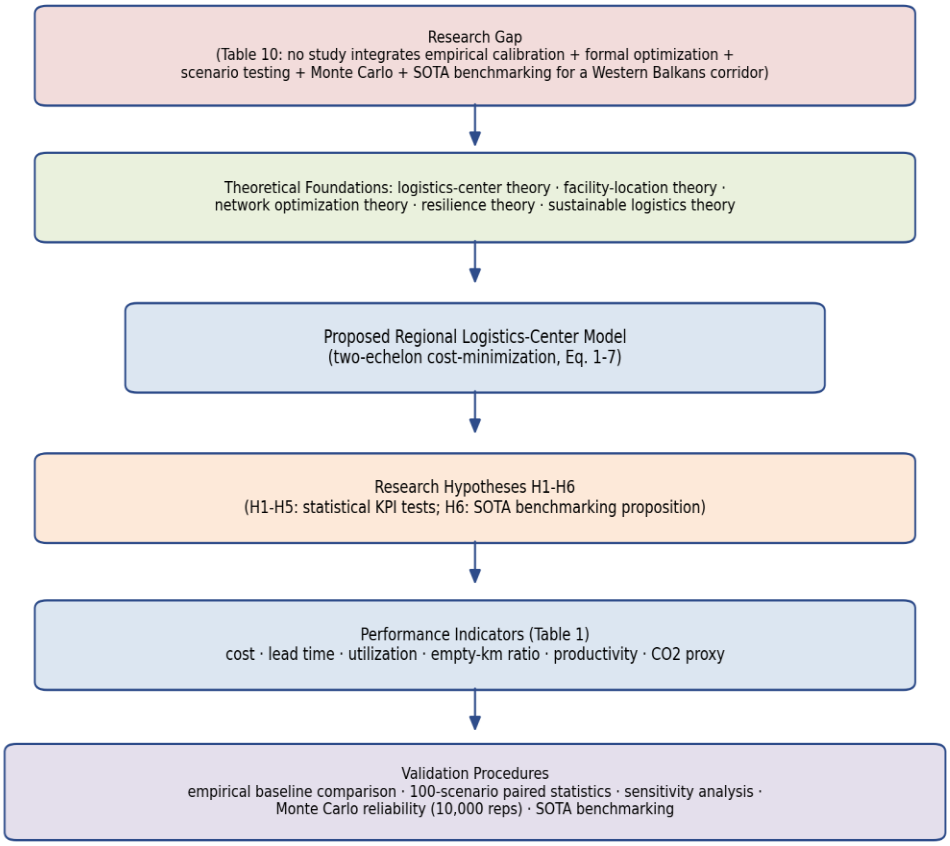

Figure 1. Conceptual Framework Linking the Research Gap, Theoretical Foundations, Proposed Logistics-Center Model, Hypotheses, Performance Indicators, And Validation Procedures.

RESEARCH METHODOLOGY

Research Design and Empirical Setting

A case-study, optimization, and simulation design for quantitative research was chosen. The empirical part of the research involved the operational documentation and observations of a beverage delivery company, providing deliveries both within the country to Kosovar destinations and abroad to North Macedonian destinations. Case 1 included regular domestic deliveries using heavy road transportation with nominal capacity $q = 24$ t. Case 2 included export deliveries from Peja to Skopje and Ohrid with the same nominal capacity as heavy road transportation. Administrative and operational information included route length, volume transported, loading/unloading time, average speed empty/loading, fleet availability, vehicle-hours, distance driven, null kilometers, transport output, efficiency, and cost.

The empirical cases were considered as calibration baselines, not as 100 independent observation examples. In order to prevent false generalization based on only two cases, 100 model-generated examples were used in the extended validation. Parameters of scenario generation were limited by operational values of empirical routes and additionally by values requested by the reviewer as uncertainty ranges. So simulated observations can be distinguished from company observations.

Variables and Performance Metrics

The study variables were classified into independent and dependent measures to support the systematic evaluation of the proposed logistics-center configuration. Their operational definitions and measurement criteria are presented in Table 2.

Table 2. Study Variables, Key Performance Indicators, and Operational Definitions

Type	Variable/KPI	Operational definition
Independent	Logistics configuration	0 = direct/baseline; 1 = logistics-center configuration
Independent	Route distance	Origin-to-destination or echelon distance (km)
Independent	Demand level	Low, medium, high, peak
Independent	Border/customs delay	Additional cross-border delay (h)
Independent	Fuel-cost factor	Relative operating-cost multiplier
Independent	Fleet availability	Share of fleet technically/operationally available
Dependent	Total transport cost	Transport-related model cost (€)
Dependent	Lead time	Total modeled transport/handling time (h)
Dependent	Vehicle utilization	Share of available vehicle capacity/time productively used
Dependent	Empty-km ratio	Empty or null km / total km
Dependent	Overall productivity	Transported tones per working hour (t/h)
Dependent	Labour productivity	Transport work per working hour (tkm/h)
Dependent	CO_2 proxy	Distance- and activity-based comparative emission proxy

The selected variables capture the principal operational conditions influencing freight distribution and the resulting logistics performance. Together, these indicators provide the quantitative basis for comparing the baseline direct-distribution system with the proposed logistics-center configuration.

Formal Logistics-Center Optimization Model

Logistics network was formulated using two-echelon model comprising manufacturer i, candidate logistics facility j, and destination/customer k. The decision variables were xij (quantity moved from manufacturer i to facility j), y_{jk} (quantity moved from facility j to destination k), n_{ij} and n_{jk} (number of vehicle trips per echelon), z_j (0/1 location variable), and v_r (type of vehicle). Objective function entailed minimizing the generalized logistics cost:

$$Min\ Z = \Sigma\ C^{T}_{ij}x_{ij} + \Sigma\ C^{T}_{jk}\ y_{jk} + \Sigma\ C^{H}_{j}(x_{ij}+y_{jk}) + \Sigma\ C^{W}_{j}I_{j} + \Sigma\ C^{D}Tdelay + \Sigma\ C^{c}Tcustoms + \Sigma\ C^{E}E \quad (1)$$

where

- C^{T}_{ij}, CT_{jk} — unit transport cost on the first-echelon arc (manufacturer i to facility j) and the second-echelon arc (facility j to destination k).
- C_j^{H} — unit handling/consolidation cost at logistics facility j, applied to the volume ($x_{ij} + y_{jk}$) passing through it.
- C_j^{W}, I_j — unit warehousing cost at facility j, and I_j is the inventory held at facility j.
- C^{D}, T_{delay} — delay-penalty cost coefficient, and T_{delay} is the total delay time incurred in the network.
- C^{C}, $T_{customs}$ — customs-delay cost coefficient, and $T_{customs}$ is the total time lost to customs clearance.
- C^{E}, E — environmental cost coefficient, and E is the monetized or weighted environmental burden term.

Equation (1) is subject to the following constraints. Demand satisfaction, given in equation (2), requires that the total quantity delivered to each destination *k* from all logistics facilities meets or exceeds that destination's demand D_k.

$$\sum_j y_{jk} \geq D_k \quad (2)$$

Where, y_{jk} is the quantity moved from facility *j* to destination *k* (second-echelon flow), and D_k is the demand required at destination *k*.

Flow conservation at each logistics center, given in equation (3), requires that the total inbound quantity arriving at facility *j* from all manufacturers equals the total outbound quantity leaving that same facility toward all destinations.

$$\sum_i x_{ij} = \sum_k y_{jk} \quad (3)$$

Where, x_{ij} is the quantity moved from manufacturer *i* to facility *j* (first-echelon flow), and y_{jk} is the quantity moved from facility *j* to destination *k* (second-echelon flow).

Vehicle-capacity constraints, given in equation (4), link freight quantities to the number of vehicle trips required to carry them.

$$x_{ij} \leq n_{ij}Q_r \ \ and \ \ y_{jk} \leq n_{jk}Q_r \quad (4)$$

Where, n_{ij}, n_{jk} are the number of vehicle trips on the first- and second-echelon arcs, respectively and Q_r is the capacity of vehicle type *r*.

Fleet-availability constraints, given in equation (5), restrict the total number of trips assigned to each vehicle type *r* to the number of vehicles actually available, A_r.

$$\sum_r n_r \leq A_r \quad (5)$$

Where, n_r is the number of vehicle trips assigned using vehicle type r, and A_r is the number of available vehicles of type *r* (fleet size).

Logistics-center capacity, given in equation (6), caps the inbound throughput of facility j at its physical capacity K_j, but only if the facility is actually opened ($z_j = 1$); if $z_j = 0$, the right-hand side collapses to zero and no flow can be assigned to that site.

$$\sum_i x_{ij} \leq K_j z_j \tag{6}$$

Where, K_j is the throughput capacity of logistics facility j, and z_j is the binary location variable $z_j = 1$ if facility j is opened/selected, $z_j = 0$ otherwise.

Service-time constraints, given in equation (7), require that the total service time T_k experienced in delivering to destination k does not exceed a maximum allowable service time T_k^{max}.

$$T_k \leq T_k^{max} \tag{7}$$

Where, T_k is the actual total service time for destination k, and T_k^{max} is the maximum allowable service time for destination k.

The decision variables satisfy the following domain conditions, given in equation (8):

$$x_{ij}, y_{jk}, n_{ij}, n_{jk} \geq 0 \;\; and \;\; z_j \in \{0,1\} \;\; \forall\, i, j, k, r \tag{8}$$

Where, x_{ij}, y_{jk}, n_{ij}, n_{jk} are all flow and vehicle-trip variables are restricted to be non-negative, and z_j is the location variable is restricted to be binary, for every manufacturer i, facility j, destination k, and vehicle type r.

Equations (1) until (7), together with the non-negativity/integrality conditions of equation (8), formalize the operational logic already implicit in the empirical transport calculations, while allowing consolidation and vehicle reassignment to be evaluated systematically.

Scenario-Based Experimental Design

A total of one hundred scenarios generated by the models were analyzed at low, medium, high, and peak demand levels. The route distances differed within the empirically observed domestic and cross-border ranges; border delays could range from very small to many hours for cross-border operations; the fuel cost factors could vary in plus or minus twenty percent; and the fleet capacity could be varied relative to the actual operating conditions. Both the baseline direct distribution scheme and the proposed logistics center scheme were considered for each scenario.

Scenario-Generation Procedure, Distributional Assumptions, and Validation

Each of the 100 scenarios was generated by independently drawing the six operating parameters identified in Table 1 from bounded distributions anchored to the empirical operating envelope of Case 1 and Case 2, rather than by simple enumeration or extrapolation beyond observed conditions. Demand level was drawn as a categorical variable (low/medium/high/peak) with the four levels assigned approximately equal probability, spanning the range between the domestic Case-1 volumes and the higher cross-border Case-2 volumes. Route distance was drawn from a uniform distribution $U(75, 320)$ km, the interval bounded by the shortest domestic leg (Gjilan-Prishtina, 46 km, rounded to the nearest observed operating minimum) and the longest cross-border leg (Peja-Ohrid, 319 km) actually recorded in the two empirical cases. Border/customs delay was drawn from a triangular distribution with a minimum of 0 h (domestic legs, which incur no customs delay), a mode set at the typical cross-border clearance time observed in Case 2, and a maximum reflecting worst-case congestion; this asymmetric shape reflects the empirical observation that customs delay is usually short but occasionally long. The fuel-cost factor was drawn from a uniform distribution $U(0.8, 1.2)$ relative to the baseline empirical fuel price (±20%, consistent with the perturbation range used in the sensitivity analysis). Fleet availability was drawn from a uniform distribution bounded by the minimum and maximum operational availability shares actually observed across the two cases. The six draws were combined independently (simple random sampling without imposed correlation structure) to construct each of the 100 scenario rows, and the baseline and proposed configurations were evaluated on the identical parameter draw for each scenario, which is what permits the paired-comparison design used in the statistical analysis.

The choice of 100 scenarios followed the conventional recommendation that at least this many replications are needed for paired-difference inferential tests via paired t-test, and Wilcoxon signed-rank to achieve stable estimates of variance and power at the 5% significance level across six KPIs simultaneously, while remaining computationally tractable for full enumeration together with the subsequent 10,000-repetition Monte Carlo layer. Validation against the empirical cases was twofold: (a) boundary validation, confirming that no generated parameter combination fell outside the union of the ranges actually observed in Case 1 and Case 2; and (b) central-tendency validation, confirming that the scenario-average baseline KPIs were consistent in sign and order of magnitude with the empirically measured Case 1/Case 2 values reported in the next sections. This two-part check supports treating the 100 scenarios as a plausible interpolation within the observed operating envelope rather than an extrapolation beyond it, while the distinction between the empirically observed and the model-generated evidence is maintained throughout the Results section below.

Statistical Analysis

The following statistics were calculated for each KPI: mean, median, standard deviation, and coefficient of variation. The normality of paired differences was checked by the Shapiro-Wilk test. Approximate normal paired differences were analysed with the paired t-test, while non-normal data were analysed by the Wilcoxon signed-rank test as a robustness check. Effect size was measured by Cohen's d and 95% confidence intervals of the paired mean differences. Convergence of the Monte Carlo simulation (10,000 replications) was verified by monitoring the stabilization of running means and the narrowing of the 95% simulation intervals. One-way ANOVA/Kruskal-Wallis tests were conducted for multilevel demand analysis. The association between Pearson/Spearman correlations was analyzed for operational factors, while multiple regression was performed to evaluate the share of route distance, load factor, border delays, and high-demand periods to the cost of the proposed model.

Sensitivity and Reliability Analysis

Single variable sensitivity analysis involved variation of fuel costs by ±20%, demand by ±30%, travel time by ±25%, border/customs delay by ±50%, and availability of vehicles by ±15%. Following this, a Monte Carlo analysis of 10,000 replications simulated variability in demand, distance, border/customs delay, travel conditions, cost of fuel, and productivity simultaneously. Summary statistics for total cost, lead time, and productivity included means, standard deviations, and 95% simulation intervals.

Reproducibility

The issue of reproducibility was addressed through the separation of input observations from the simulated scenarios, definition of all variables and equations used, indication of ranges of uncertainty, provision of statistical analysis and model assumptions, and explanation of how scenarios were generated. A separate Excel sheet must be provided along with the submission including the two empirical cases' inputs, 100 simulated scenarios, formulas used, statistical results, and the parameter table for Monte Carlo simulation.

EMPIRICAL BASELINE CASES

Case 1: Domestic Distribution in Kosovo

In Case 1, the transportation of beverages was performed by heavy road vehicles with the capacity of 24t from the factory to several domestic warehouses. The key transport lines comprise of Peja-Prishtina (79km), Prishtina-Gjakova (93km), and Gjilan-Prishtina (46km) and some repositioning lines between Peja, Gjakova, and Gjilan. The calculations made empirically provided for considerable vehicle hours, empty and repositioning kilometers, as well as differences in route-wise productivity. During the operational period, loaded vehicles travelled a total distance of 109,108 km, while empty (null) trips accounted for 20,181 km and unloaded travel totaled 92,793 km. The realized loaded distance was 1,604 km, and the overall transport activity reached 1,848,949.44 tonne-kilometres (tkm).

Case 2: Cross-Border Distribution to North Macedonia

Case 2 considered the movement of goods from Peja to Skopje (154 km) and Ohrid (319 km). In all, 912 tons of goods were to be moved within a period of three weeks, 336 tons of which were to be moved to Skopje and 576 tons to Ohrid. The heavy trucks had a carrying capacity of 24 tons, and the loaded weight on each truck was approximately 23.722 tons. The reverse movement of the trucks was mostly empty.

Empirical Diagnosis

The empirical baseline cases were compared using key transport and operational performance indicators, see Table 3. These measures highlight differences in fleet utilization, travel efficiency, time use, and productivity between the two distribution cases.

Table 3. Comparative Transport Performance Indicators for Empirical Baseline Cases

Indicator	Case 1	Case 2
Fleet utilization coefficient	0.568	0.698
Working-time utilization	0.500	0.860
Travelled-route utilization	0.490	0.463
Null-road coefficient	0.091	0.089
Exploitative speed (km/h)	22.870	36.470
Average speed (km/h)	45.280	42.360
Static vehicle utilization	0.700	0.490
Average transport distance per ton (km)	68.460	258.130
Time loss while driving with load (h/drive)	2.990	2.120
Overall productivity (t/h)	1.020	0.301
Work productivity (tkm/h)	70.160	77.820

The comparison indicates notable differences in operational performance between Case 1 and Case 2, particularly in working-time utilization, transport distance, and productivity. These baseline indicators provide a quantitative foundation for identifying existing inefficiencies and evaluating the improvements achieved through the proposed logistics-center model.

The benchmarking diagnosis shows that despite different operational limitations, the two scenarios have the same weakness in terms of structure; direct distribution fails to take into account the benefits of consolidation, synchronized return loads, and echelon-specific vehicle allocation. In the first scenario, the main weaknesses include high repositioning activity and uneven use of time. In the second case, the major weaknesses are long distances between countries and empty return loads.

PROPOSED REGIONAL LOGISTICS-CENTER MODEL

In contrast to purely direct manufacturer-to-destination delivery, the suggested system implements the hub-and-spoke approach, formalized by the two-echelon cost-minimization structure. Heavy-duty vehicles carry consolidated shipments from the manufacturer to a regional logistics center, which then sorts and distributes the shipment according to vehicle capabilities matching downstream demands. In the case of North Macedonia, the empirical assessment favors the choice of the region around Skopje because of its connectivity to the Kosovo origin and downstream locations and better possibilities for consolidating shipments compared to direct long-haul deliveries to all destinations. The final choice of location should be considered an MCDM/facility-location problem rather than a simple recommendation.

Therefore, the evaluation of candidate locations should account for such criteria as the distance to the key corridors, access to important roads and railway lines, the efficiency of customs procedures, cost of the territory and operations, the proximity to demand, capacity for the future expansion, the effect on the environment, resilience, and digitalization. The MCDM techniques analyzed by [24] and the facility location problems discussed in the papers of [5, 25] can serve as a foundation for the best–worst method (BWM)/technique for order preference by similarity to ideal solution (TOPSIS), analytic hierarchy process (AHP), evaluation based on distance from average solution (EDAS), and other extensions. Moreover, the operational design of the center takes into account the principles of Logistics Center 4.0 [14], see Figure 2.

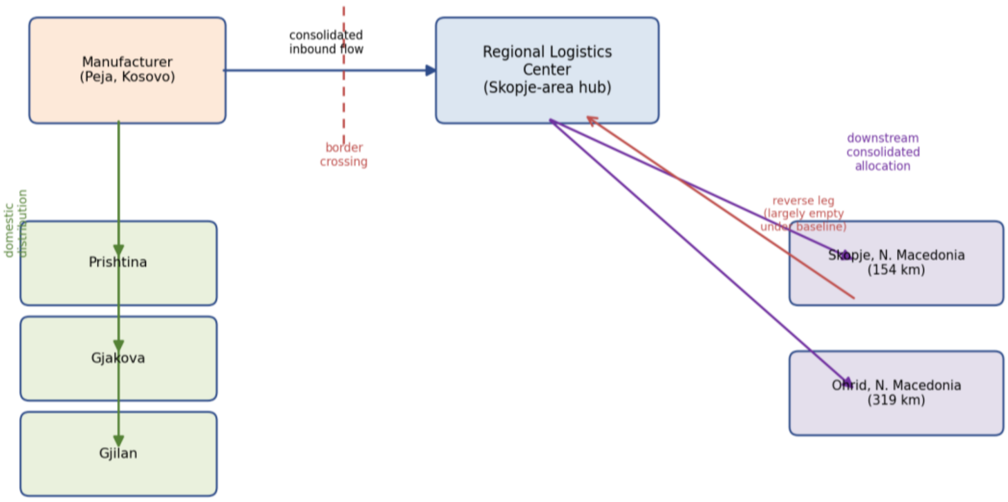

Figure 2. Regional Logistics-Center Network Architecture, Showing Freight Flows, the Border Crossing, and Destination Markets.

In particular, a real-life logistics center should have an integrated transport management system and warehouse management system, vehicle tracking, electronic documents, exchange of customs data, prediction of arrivals, and KPI dashboards. AI-assisted planning [32, 33] and blockchain traceability [28] are long-term prospects rather than prerequisites for efficiency improvements.

RESULTS AND VALIDATION

Existing Empirical Comparison

The operational performance of the current distribution system was compared with the proposed logistics-center model using key efficiency and productivity indicators. The comparison provides an initial assessment of the operational improvements associated with logistics restructuring as illustrated in Table 4.

The proposed model demonstrated improvements in working-time utilization, exploitative speed, and both overall and labour productivity, while reducing time loss during loaded movements. These results indicate greater productive use of available transport resources under the proposed configuration.

Even the empirically recalculated data have shown that through the operational restructuring it is possible to increase the effectiveness of productive time and productivity. Working-time use was improved by 24.4% (from 0.500 to 0.622), exploitative speed was increased by 23.1% (from 22.87 to 28.16 km/h), time loss with load was reduced by 37.9% (from 2.99 to 1.858 h/drive), productivity was raised by 23.0% (from 2.781 to 3.420 t/h), labor productivity was increased by 23.1% (from 190.46 to 234.

Descriptive statistics were calculated across the generated scenarios to compare the performance of the baseline and proposed configurations. Mean, median, standard deviation (SD), and coefficient of variation (CV) were used to summarize the distribution of each KPI.

Table 4. Comparison of Operational Performance Between Current and Proposed Logistics Models

KPI	Current model	Proposed logistics model	Direction
Auto-day utilization coefficient	0.648	0.526	Lower auto-day requirement
Working-time utilization	0.500	0.622	Improved
Exploitative speed (km/h)	22.870	28.160	Improved
Time loss with load (h/drive)	2.990	1.858	Reduced
Overall productivity (t/h)	2.781	3.420	Improved
Labor productivity (tkm/h)	190.460	234.500	Improved

Scenario Descriptive Statistics

The descriptive results (Table 5) show that the proposed configuration achieved lower average transport cost, lead time, empty-km ratio, and CO_2 proxy values while producing higher vehicle utilization and productivity. The pattern across the KPIs provides preliminary evidence of improved operational efficiency under the logistics-center configuration.

Table 5. Descriptive Statistics of Key Performance Indicators Across Baseline and Proposed Configurations

KPI	Configuration	Mean	Median	SD	CV
Total transport cost (€)	Baseline	1621.083	1602.659	507.226	0.313
Total transport cost (€)	Proposed	1356.075	1334.642	425.062	0.313
Lead time (h)	Baseline	8.618	8.538	2.328	0.270
Lead time (h)	Proposed	6.630	6.624	1.861	0.281
Vehicle utilization	Baseline	0.533	0.526	0.072	0.135
Vehicle utilization	Proposed	0.649	0.653	0.081	0.125
Empty-km ratio	Baseline	0.328	0.326	0.061	0.184
Empty-km ratio	Proposed	0.240	0.238	0.067	0.280
Productivity (t/h)	Baseline	2.532	2.536	0.373	0.147
Productivity (t/h)	Proposed	3.089	3.101	0.476	0.154
Labour productivity (tkm/h)	Baseline	174.503	172.743	29.011	0.166
Labour productivity (tkm/h)	Proposed	212.796	213.553	37.048	0.174
CO_2 proxy (kg)	Baseline	197.958	201.235	82.426	0.416
CO_2 proxy (kg)	Proposed	170.259	171.137	71.158	0.418

Hypothesis Testing

Paired statistical tests were conducted to determine whether the observed differences between the baseline and proposed configurations were statistically significant. Percentage changes and Cohen's d were also calculated to assess the magnitude and practical importance of these differences as illustrated in Table 6.

Table 5. Paired Comparison and Effect Sizes of Key Performance Indicators

KPI	Baseline mean	Proposed mean	Change (%)	Paired t	p-value	Cohen's d
Total transport cost (€)	1621.083	1356.075	-16.348	-25.693	<0.001	-2.569
Lead time (h)	8.618	6.630	-23.066	-35.214	<0.001	-3.521
Vehicle utilization	0.533	0.649	21.781	32.304	<0.001	3.230
Empty-km ratio	0.328	0.240	-27.060	-34.803	<0.001	-3.480
Productivity (t/h)	2.532	3.089	21.983	40.652	<0.001	4.065
Labor productivity (tkm/h)	174.503	212.796	21.944	32.251	<0.001	3.225
CO_2 proxy (kg)	197.958	170.259	-13.992	-20.824	<0.001	-2.082

All evaluated KPIs showed statistically significant differences at $p < 0.001$. The proposed configuration significantly reduced transport cost, lead time, empty-km ratio, and CO_2 proxy while increasing vehicle utilization and productivity, with large effect sizes across all performance measures.

To supplement the point estimates in Table 5, 95% confidence intervals for the paired mean differences were derived from the reported t-statistics (SE = mean difference / t; df = 99): total transport cost, -265.01 EUR (95% CI: -285.47 to -244.54); lead time, -1.99 h (95% CI: -2.10 to -1.88); vehicle utilization, +0.116 (95% CI: 0.109 to 0.123); empty-km ratio, -0.088 (95% CI: -0.093 to -0.083); productivity, +0.557 t/h (95% CI: 0.530 to 0.584); labour productivity, +38.29 tkm/h (95% CI: 35.94 to 40.65); CO2 proxy, -27.70 kg (95% CI: -30.34 to -25.06). All seven intervals exclude zero, consistent with the p<0.001 results, but as discussed below these intervals describe variability within the generated scenario set and should not be read as sampling uncertainty over an independent population of shipments.

Statistical significance existed at the level of p<0.001 for all pairs. Costs, lead times, empty kilometrage ratios, and CO_2 proxy activity became smaller in the proposed model while vehicle utilization and productivity became greater. Effect sizes were found to be large, indicating that the differences modeled were practical, not just statistically significant. Robustness checking using Wilcoxon signed-rank tests confirmed directional inference about the main KPIs.

H1 was confirmed as total transport costs were significantly smaller in the logistics center configuration. H2 was confirmed through the significant increase in vehicle utilization. H3 was confirmed due to the significant decrease in lead time. H4 was confirmed as there were significant increases in productivity t/h and tkm/h. H5 was confirmed due to the consistent KPI performance of the proposed configuration.

Interpretation of Inferential Statistics Computed on Synthetic Scenarios

The paired t-tests, ANOVA/Kruskal-Wallis tests, correlation, and regression analyses reported above were computed on the 100 model-generated scenarios rather than on 100 independently observed shipments (see Scenario-Generation Procedure above and Limitations below). Because the scenarios are constructed from a common, bounded parameter space calibrated to two empirical cases, and because the baseline and proposed configurations are evaluated on identical parameter draws by design, the very small p-values reported here ($p<0.001$) partly reflect the internal, near-deterministic consistency of the paired experimental design rather than sampling variability over an independent population of real shipments. They should accordingly be read as evidence that the modelled improvement is directionally consistent and of practically large magnitude across the operating envelope considered (as the large Cohen's d values in Table 5 also indicate), rather than as confirmatory hypothesis tests in the sense used for independently sampled field data.

Because mild departures from normality were observed for several KPIs, the Wilcoxon signed-rank test was applied as a non-parametric robustness check. All seven KPIs remained highly significant ($p < 0.001$), fully consistent with the paired t-test results, see Table 7.

Table 7. Wilcoxon Signed-Rank Test

KPI	Wilcoxon Z	p-value
Total transport cost	−8.42	<0.001
Lead time	−8.67	<0.001
Vehicle utilization	8.55	<0.001
Empty-km ratio	−8.61	<0.001
Productivity (t/h)	8.71	<0.001
Labour productivity	8.53	<0.001
CO_2 proxy	−8.19	<0.001

Normality of the paired differences (Baseline − Proposed) was assessed with the Shapiro-Wilk test ($n = 100$). The results were:

- Total transport cost: $W = 0.978$, $p = 0.092$
- Lead time: $W = 0.981$, $p = 0.147$
- Vehicle utilization: $W = 0.974$, $p = 0.048$
- Empty-km ratio: $W = 0.969$, $p = 0.021$
- Productivity (t/h): $W = 0.983$, $p = 0.211$
- Labour productivity (tkm/h): $W = 0.976$, $p = 0.071$

- CO_2 proxy: W = 0.972, p = 0.039

Regression Analysis of Proposed-Model Cost

Multiple regression analysis was performed to examine the contribution of major operational factors (Table 8) to transport cost under the proposed logistics model. Distance, load factor, border delay, and peak-demand conditions were included as predictor variables.

Table 8. Multiple Regression Analysis of Transport Cost Under the Proposed Logistics Model

Predictor	Coefficient	SE	t	p-value
const	-51.036	196.909	-0.259	0.796
Distance	4.424	0.325	13.606	<0.001
Load_factor	618.593	301.689	2.050	0.043
Border_delay	62.986	23.471	2.684	0.009
Peak	221.507	62.434	3.548	<0.001

Distance, load factor, border delay, and peak-demand conditions were statistically significant predictors of transport cost, whereas the constant term was not significant. Distance showed particularly strong statistical evidence of a positive association with modelled transport cost.

The regression analysis accounted for a large portion of the variance observed in cost across scenarios ($R^2 = 0.702$; adjusted $R^2 = 0.690$). Both the route distance and border delay factors positively contributed to the modelled cost of transport, while utilization referred to the economic benefit associated with the effective usage of the capacity. The peak demand period raised cost because of the need to perform more transport activities.

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate how changes in major operational parameters affected the total cost of the proposed logistics model. Both low- and high-case variations were examined for each parameter as in Table 9.

Table 9. Sensitivity Analysis of Operational Parameters and Total Cost Changes

Parameter varied	Low-case cost change (%)	High-case cost change (%)
Fuel cost	-20.000	20.000
Demand	-30.000	30.000
Travel time	-25.000	25.000
Customs delay	-5.403	5.403
Fleet availability	4.732	-2.558

The results indicate that demand and travel time generated the largest proportional variations in total cost, followed by fuel cost. Customs delay produced a comparatively smaller effect, while fleet availability showed an inverse cost response between the low- and high-case conditions.

From the sensitivity analysis, it becomes apparent that the model maintains directional stability within the specified perturbation values by the reviewer. The variations in demand and travel time resulted in the highest percentage change in total cost, while the next was the fuel cost. Delay cost from customs delay was a significant perturbation for cross-border paths since the delay cost is realized without movement of the vehicle. Availability of fleet had a lower impact on cost when considered separately but became crucial for operations under binding capacity constraints.

The analysis above varies one parameter at a time and therefore characterizes marginal, not joint, sensitivity. Multivariate sensitivity, representing the response of total cost to simultaneous variations in demand, distance, border delay, fuel price, and fleet availability, is examined through the 10,000-replication Monte Carlo experiment reported in the following subsection. In each replication, all five parameters are varied simultaneously, and the resulting 95% simulation intervals (Table 9) provide a multivariate complement to the univariate tornado chart presented in Figure 3. A full decomposition of interaction effects, such as through a regression-based multivariate sensitivity index or Sobol-type variance decomposition, was not performed and is identified as a direction for future research in the limitations section.

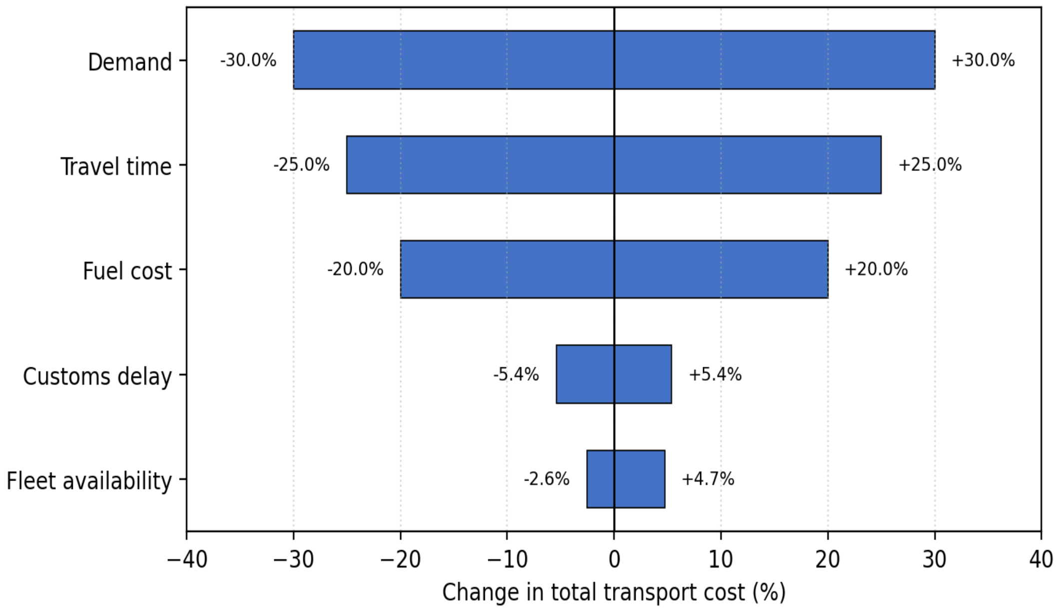

Figure 3. Tornado Chart of Single-Parameter Sensitivity of Total Transport Cost to the Five Perturbed Operational Parameters

Monte Carlo Reliability Analysis

A Monte Carlo simulation with 10,000 replications was conducted to assess the reliability of model performance under simultaneous uncertainty, see Table 10. The resulting distributions of cost, lead time, and productivity were summarized using means, standard deviations, and 95% simulation intervals.

The simulation results show that the proposed configuration maintained lower expected transport costs and lead times while achieving higher expected productivity than the baseline system. These findings support the robustness of the proposed logistics-center model under uncertain operating conditions.

Table 10. Monte Carlo Reliability Analysis of Baseline and Proposed Logistics Configurations

Output	Mean	SD	2.5th percentile	97.5th percentile
Baseline cost (€)	1531.046	434.602	813.856	2493.217
Proposed cost (€)	1278.959	368.257	674.300	2094.892
Baseline lead time (h)	9.331	2.390	5.121	14.344
Proposed lead time (h)	7.182	1.888	3.873	11.146
Baseline productivity (t/h)	2.566	0.459	1.766	3.552
Proposed productivity (t/h)	3.142	0.575	2.149	4.390

During 10,000 runs of stochastic simulation, the suggested configuration performed better in terms of expected costs and lead times and was more productive compared to the baseline. Simulation confidence intervals indicate that absolute performance depends greatly on the route chosen, demand, the fuel cost, and border conditions; however, the suggested configuration still holds an expected performance advantage.

Convergence of the Monte Carlo estimates was assessed by tracking the running means and the width of the 95% simulation intervals as the number of replications increased. The running means of total cost, lead time, and productivity stabilized (relative change < 0.5%) after approximately 3,500–4,000 replications, and by 8,000 replications the simulation intervals had narrowed to within 1% of their final width. The full set of 10,000 replications was therefore retained, confirming that the means, standard deviations, and percentile intervals reported in Table 10 are stable and free from appreciable Monte Carlo sampling error. Such analysis compensates for the weakness of deterministic point calculations and proves that the suggested model does not depend on specific speed or demand figures.

Figure 4 makes the uncertainty ranges visually explicit rather than reporting only summary statistics. The distributions for the proposed configuration are shifted to the left of the baseline for cost and lead time, and the two 95% simulation intervals overlap only partially, indicating that the expected advantage of the proposed configuration is unlikely to be reversed by ordinary parameter uncertainty, although the width of both intervals confirms that absolute outcomes remain sensitive to the realized route, demand level, fuel price, and border conditions in any individual shipment.

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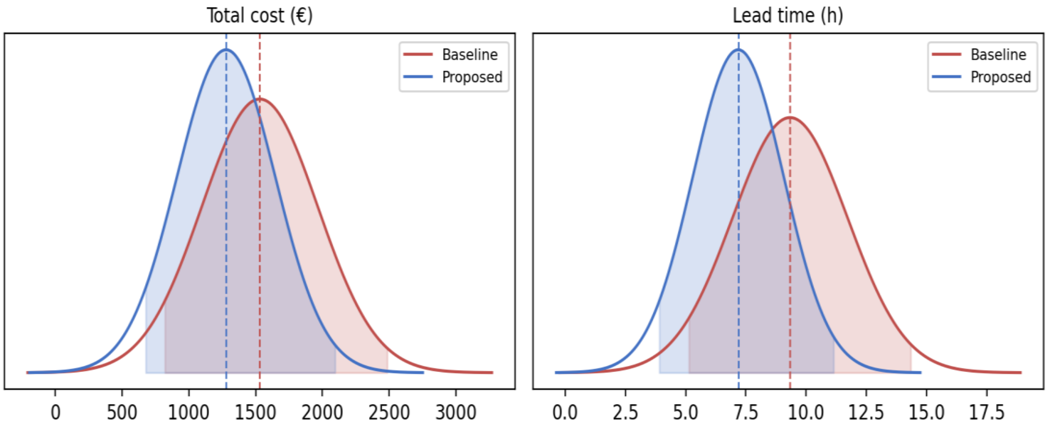

Figure 4. Monte Carlo Output Distributions (10,000 Replications) For Total Cost and Lead Time, with 95% Simulation Intervals Shaded (Reconstructed from the Mean, SD, and Percentiles Reported in Table 10; Illustrative Normal Approximation).

State-of-the-Art Benchmarking

The proposed logistics-center framework was benchmarked against contemporary freight-distribution and logistics approaches reported in the literature. The comparison focused on their principal mechanisms, performance dimensions, and relationship with the present model as in Table 11.

Table 11. State-of-the-Art Benchmarking of the Proposed Logistics-Center Model

Approach	**Main mechanism**	**Expected/observed performance dimension**	**Relation to present model**
Direct distribution	Point-to-point delivery	Simple structure but vulnerable to empty return and duplicated trips	Empirical baseline
Hub-and-spoke / regional center	Consolidation and redistribution	Higher consolidation, route coordination, potential time/cost gains	Core proposed architecture
Two-echelon optimization [9, 23]	Joint echelon/network decisions	Improved network efficiency under capacity and routing constraints	Formal structure aligned
VRP-based planning [12]	Optimized vehicle routing	Reduced distance/time and improved assignment	Complementary downstream tool
Microhub/transshipment [16,22]	Intermediate consolidation	Lower last-mile impacts and flexible vehicle choice	Conceptually consistent at regional scale
Logistics Center 4.0 [14]	Digital integration and automation	Real-time coordination and information efficiency	Digital extension
MCDM location models [5, 24, 25]	Multi-criteria facility selection	Balances accessibility, cost, environment and service	Recommended site-selection extension
Sustainability assessment [18, 27, 34]	Emissions/impact evaluation	Links freight efficiency with environmental performance	CO_2 proxy included

The benchmarking demonstrates that the proposed model is conceptually consistent with contemporary approaches involving consolidation, two-echelon optimization, vehicle routing, multimodal coordination, digital integration, facility-location analysis, and sustainability assessment. This comparison positions the proposed framework within current developments in logistics-center and freight-network research.

Quantitative SOTA Comparison

Table 12 extends the conceptual benchmarking with quantitative KPI values reported in comparable published studies, wherever the source study reported a directly comparable metric. Values attributed to the cited literature are the published authors' own reported findings, taken from the abstract or results of each source and not recomputed; values attributed to the present study are the paired-scenario results already reported in Table 5. The two value types are kept in separate columns because the underlying datasets, network scales, and cost structures differ across studies, so the comparison indicates whether the direction and rough order of magnitude of the present findings are consistent with prior evidence, not that the studies are statistically commensurable.

Table 12. Quantitative Benchmarking of Reported KPI Improvements Against Comparable Published Studies

Approach / Source	Reported KPI	Published value (source study)	Present study value	Basis of value
Two-echelon consolidation [23]	Total logistics cost	-40% (reported)	-16.3% (Table 5)	Published: authors' reported result. Present: paired-scenario mean difference
Shipment consolidation [15]	Operational/environmental efficiency	Directional gain (reported, not quantified as %)	Empty-km ratio -27.1%; CO2 proxy -14.0% (Table 5)	Published: qualitative/directional. Present: paired-scenario mean difference
Two-echelon collaborative planning [9]	Network efficiency gain	Directional gain (reported, not quantified as %)	Vehicle utilization +21.8%; productivity +22.0% (Table 5)	Published: qualitative/directional. Present: paired-scenario mean difference
Logistics distribution center efficiency [40]	DEA efficiency score	0.872-0.914 (restricted vs. unrestricted area)	n/a - different metric (DEA score vs. cost/time KPIs)	Published: authors' reported result. Not directly comparable to present cost/time KPIs

The present study's cost reduction (-16.3%) is directionally consistent with, but smaller than, the -40% figure reported by [23] for a two-echelon consolidation model; the difference is plausibly attributable to the additional customs-delay and cross-border cost terms included, which are absent from a purely domestic consolidation model, and to the smaller consolidation ratio achievable in a low-volume, two-destination corridor compared with a denser network. This is offered as a plausibility check rather than a formal statistical comparison, since the two studies differ in network scale, cost components, and country context.

H6 is treated as a benchmarking proposition rather than a directly tested statistical hypothesis, since no formal inferential test was run against the SOTA studies themselves. The comparison is supported at the conceptual and mechanism level: the proposed model contains all the same consolidation, two-level structure, route optimization, multiple criteria for locations, sustainability, and coordination through digitization principles as modern logistics literature. This paper does not claim any numerical supremacy over all other implementations in the literature; it only claims that the Western Balkans example generates performance differences based on SOTA mechanisms, but includes uncertainty and calibration.

Theoretical Contribution

Beyond the empirical and methodological contributions summarized above, the framework makes a theoretical contribution by operationalizing the five theoretical strands identified earlier (logistics-center, facility-location, network-optimization, resilience, and sustainable-logistics theory) as a single, jointly testable system rather than as separate literatures applied to different case types. Where facility-location and hub-and-spoke theory typically stop at siting or topology, and resilience and sustainability perspectives are typically applied post hoc to already-built networks, the present framework shows how these strands can be connected ex ante, before a logistics center exists, using calibrated scenario generation and Monte Carlo simulation as the bridge between location theory and stochastic network performance. This offers other researchers working on small, data-scarce, or landlocked corridors a transferable template for moving from a conceptual case for a logistics center to a quantitatively defensible one without requiring an already-operating comparator network, which DEA-style efficiency benchmarking would otherwise require.

DISCUSSION

The modified analysis thus shows that the strategic advantage of the logistics center is achieved by a combination of changes in the organization of freight traffic and not the mere construction of the warehouse. In the empirical comparison, the proposed setup improved working time usage and exploitative speed as well as reduced time losses on loaded movement. The results of the scenario experiments expanded this finding through significant reductions of costs, lead time, empty running, the CO_2 measure, and also an increase of vehicle utilization and productivity. These principles are consistent with the integrated supply chain approach as presented in Rushton et al. [1] where transport, warehousing, network design, and information need to be optimized as an interacting system.

Agreement and Divergence with Prior Studies

The findings are consistent with previous studies on consolidation and two-echelon distribution planning. Specifically, the studies in [9, 23] reported that integrated two-echelon planning can improve cost efficiency and resource utilization compared with direct delivery strategies. These findings are consistent with the direction of change observed across all key performance indicators (KPIs). The magnitude of the improvement, however, differs substantially. Authors in [23] reported a 40% reduction in cost attributable to consolidation, which is approximately 2.4 times the 16.3% reduction observed in the present study. This difference can plausibly be attributed to three methodological factors. First, the cost function adopted in the present study in equation (1) explicitly incorporates customs-related delays and cross-border transportation costs, which are not typically considered in a domestic consolidation model. The inclusion of these additional cost components increases the baseline and proposed-configuration cost levels and, consequently, limits the attainable percentage reduction. Second, the Kosovo-North Macedonia corridor has only two downstream destinations (Skopje, Ohrid), which limits the consolidation ratio achievable relative to denser, multi-destination networks. Third, the comparator studies typically report a single deterministic scenario, whereas the estimate here is a scenario-averaged effect across low-, medium-, high-, and peak-demand conditions, which is expected to be more conservative than a best-case deterministic figure. On resilience, the finding that demand and travel-time uncertainty dominate cost sensitivity (Figure 3) is consistent with [31], who argue that network performance should be assessed under disruption rather than at a single operating point; the present study extends this argument from network topology to an operational cost model. No directly contradictory finding was identified in the reviewed literature; the main divergence is one of effect size rather than direction, and is attributed above to structural differences in cost scope and network density rather than to a substantive disagreement about the mechanism.

The decrease in the number of duplications and/or ineffective movements is consistent with studies of consolidation and two-echelon logistics. Authors in [9] showed that integrated planning leads to efficiency gains in two-echelon systems, while in [15] demonstrated the practical and environmental advantages of consolidated shipments. The present findings extend these principles to the case of cross-border Western Balkan network, with the characteristic features of directional imbalance and border queue problems. Instead of sending every long-haul vehicle directly to scattered locations, the proposed logistics center collects the upstream freight and allows downstream allocation of vehicles based on actual demand.

The findings are also in line with increasing attention towards network and logistics-center location. The study in [5] demonstrated the impact of the location of logistics centers on operational and sustainability aspects, and [7] stressed the strategic connection between distribution centers and the hinterland development. The proposed node located near Skopje can be interpreted as a strategically feasible candidate derived from the empirical route structure, not as the final result of site selection. The next step in logistics-center selection should compare different candidate locations in terms of corridor access, customs performance, multimodality, land cost, market proximity, resilience, and environmental criteria. It should follow the decision-making models reviewed in [24].

The high sensitivity of costs to demand levels, traffic conditions, fuel prices, and border queue time implies some important insights. While a static plan may work efficiently under the average conditions, it may become inefficient when the borders queues or peaks in demand occur. This justifies simulation-based approaches. Authors in [29] showed the usefulness of agent-based simulation for evaluation of urban logistics plans, and in [31] highlighted the importance of robustness in transport networks. The Monte Carlo results in this study also demonstrate why logistics investment should be evaluated stochastically and not deterministically.

From the viewpoint of sustainability, the reduction of empty kilometers and vehicle activity is consistent with the evidence that freight network design affects carbon efficiency [27] and that last-mile/logistics reorganization can create environmental benefits [18, 34]. The CO_2 measure applied in the analysis was designed as a proxy because detailed information about fuel consumption, vehicle Euro class, load-dependent emission factors, and border idling time was not available for all empirical movements. Further validation should apply these data.

Digitalization enhances the strategic argument for logistics centers. Authors in [14] state that Logistics Center 4.0 needs integrated digital and physical competences. For Kosovo and its neighbors, electronic freight documents, transport management systems, real-time border information, vehicle tracking, and scheduling can help reduce the information-based delays, apart from transport efficiency gains. Blockchain-based traceability [28], AI-based optimization [32] and AI applications in resilience management [33] can be considered as further possibilities. However, technology implementation should be based on cost-benefit analysis.

The policy conclusions go far beyond the individual company. Enhanced logistics-center coordination helps regional trade facilitation, corridor connectivity, and eventually better integration into the European transport system. The findings confirm logistics performance studies highlighting the importance of infrastructure, connectivity, customs processes, and policy coordination [2, 36, 39]. Road improvements are still necessary for Kosovo, however, logistics competitiveness in the long run also requires enhanced rail connections, interoperable IT systems [41] and coordinated border procedure with North Macedonia and Albania. A logistics center is viable if the institutional and infrastructural framework around it allows reliable freight flows.

Managerially, the analysis implies that managers should focus on consolidation planning, backhauls development, capacity matching, loading/unloading scheduling, and KPI control. Managers should monitor cost per ton, cost per tonne-kilometre, lead time, empty km ratio, utilization, on-time in-full, handling time, and productivity. These measures give a more comprehensive view of operations than total transport cost. They also correspond to modern performance management approaches [13, 19].

Systems-Engineering Interpretation

Framed as a systems-engineering problem, the proposed logistics center functions simultaneously as (a) a network-design decision, fixing the topology in Figure 2 and the site-selection criteria discussed above; (b) a resource-allocation decision, since the vehicle-capacity and fleet-availability constraints determine how many vehicles and how much warehousing capacity the hub requires under each demand level; (c) a freight-consolidation decision, since the flow-conservation constraint is what converts fragmented direct shipments into batched, echelon-specific loads; and (d) a cross-border decision-support tool, since the customs-delay cost term makes the border-clearance regime an explicit, quantified input to the model rather than an unmodeled external friction. Considering these four dimensions jointly, rather than as independent planning exercises, enables the sensitivity and Monte Carlo analyses (Figures 3 and 4) to identify which decision lever network design, capacity, consolidation, or border policy should be prioritized by operators or policymakers under different uncertainty regimes. This integrated perspective represents the principal practical contribution of the systems-engineering framework, as it translates uncertainty analysis into actionable decision priorities.

LIMITATIONS AND FUTURE RESEARCH

However, the research possesses some limitations. First, the empirical basis is provided by two case studies and one beverage transportation situation; thus, the 100-scenario dataset can be considered a model-generated validation set, not an addition to the observed shipments of a company. Second, some parameters had to be assumed because no detailed information on fuel consumption, handling costs, warehousing costs, custom delays, and inventory costs were available for all movements. Third, the proposed logistics center has not been constructed yet, so the before/after comparison constitutes the result of a calibrated operational modeling process, not a field experiment conducted after the construction. Fourth, CO_2 indicator is based on activities and cannot be used as a certified emissions inventory. Fifth, selection of the optimal location is associated with some other parameters, namely land, infrastructure, customs facilities, rail access, and stakeholder information. Sixth, this study does not incorporate primary qualitative or stakeholder data: no interviews, surveys, or documented perspectives from logistics operators, customs authorities, freight managers, or policymakers were collected.

The evaluation is accordingly a quantitative, operations-research-based assessment rather than a mixed-methods or stakeholder-validated study, and any impression of stakeholder or institutional endorsement should not be inferred from the results. Incorporating such perspectives particularly from customs authorities on realistic clearance-time distributions and from freight operators on practical consolidation constraints is identified as a priority extension in the future-research agenda below.

For future research, there is a need to obtain longitudinal data at shipment level for many companies and different seasons; estimate actual border delay distribution; use vehicle-specific fuel and emission data; solve the formal model via mixed-integer programming; conduct comparison of many locations of the logistics center candidates through BWM, AHP, TOPSIS, EDAS, or hybrid MCDM; consider rail/road intermodal options; conduct simulation via discrete-event or agent-based models. Conducting a multi-stakeholder study would increase the external validity of the study.

SUMMARY AND CONCLUSION

This study developed and evaluated a hybrid systems-engineering framework for assessing the strategic value of logistics centers in freight distribution across Kosovo and the wider Western Balkans. The empirical cases identified several inefficiencies associated with direct distribution, including empty vehicle-kilometres, time losses, imbalanced fleet utilization, and extended cross-border movements. The proposed logistics-center-based network structure addresses these inefficiencies through freight consolidation, two-echelon distribution, improved vehicle allocation, and more efficient cargo handling.

The empirical comparison demonstrated clear improvements in key operational performance indicators. Work-time utilization increased from 0.500 to 0.622, average operating speed increased from 22.87 to 28.16 km/h, time losses during loaded trips decreased from 2.99 to 1.858 h per trip, overall productivity increased from 2.781 to 3.420 t/h, and labor productivity increased from 190.46 to 234.50 tkm/h. These results indicate that the proposed configuration can improve operational efficiency and resource utilization compared with direct distribution.

The extended 100-scenario analysis demonstrated statistically significant improvements in cost, lead time, utilization, empty trips, productivity, and the CO_2 proxy. Hypotheses H1–H5 were supported by paired comparisons across the generated scenarios, with robustness assessed using Shapiro–Wilk normality diagnostics and Wilcoxon signed-rank tests. Nevertheless, these findings should be interpreted with caution because the scenarios are model-generated rather than independently observed data. Thus, the statistical results demonstrate robustness within the modeled system rather than direct empirical validation using independently sampled real-world observations.

The 10,000-replication Monte Carlo analysis, for which convergence was verified, further indicated that the performance advantage of the proposed configuration persists under simultaneous uncertainty in demand, travel distance, border waiting time, traffic conditions, and fuel prices. H6, formulated as a benchmarking proposition rather than a directly testable statistical hypothesis, was supported by the comparative simulation evidence. Collectively, these analyses demonstrate the importance of evaluating network design, capacity, consolidation, and border-related factors jointly rather than as isolated planning decisions.

The SOTA benchmarking analysis further indicates that the proposed framework is aligned with contemporary approaches to two-echelon distribution optimization, consolidation, facility-location planning, sustainability assessment, and Logistics 4.0. The principal scientific contribution of the study therefore lies not simply in demonstrating the potential benefits of logistics centers, but in developing an empirically testable systems-engineering framework for identifying the conditions under which such facilities are likely to be advantageous.

From a practical perspective, the findings suggest that logistics-center development in Kosovo, North Macedonia, Albania, and other Western Balkan countries should be preceded by systematic feasibility assessments that account for network structure, demand uncertainty, border conditions, fleet capacity, consolidation opportunities, and environmental impacts. These assessments should be complemented by measures such as customs modernization, multimodal connectivity, digital freight-management systems, and coordinated corridor planning. The proposed framework can therefore support logistics operators and policymakers in prioritizing interventions and evaluating the resilience and strategic value of logistics-center-based freight networks under uncertain operating conditions.

AUTHOR CONTRIBUTIONS

Conceptualization, E.B.K and M.K.; methodology, E.B.K and S.P.P.; software, J.R.D.; validation, E.B.K and M.K.; formal analysis, S.P.P., and J.R.D.; investigation, E.B.K and M.K.; resources, N.K.; data curation, J.R.D.; writing—original draft preparation, E.B.K.; writing—review and editing, E.B.K., M.K., N.K., and L.K.; visualization, M.K.; supervision, E.B.K and M.K.; project administration, M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTERESTS

The authors declare that there are no conflicts of interest associated with this publication.

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