INTEGRATED ENGINEERING-ECONOMIC APPROACH TO MODELING AIR LOGISTICS EFFICIENCY IN RURAL REGIONS

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Abstract. The limited accessibility of surface transport infrastructure in rural regions necessitates an expanded role for aviation in providing freight and specialised logistics transportation. This study proposes an integrated engineering-economic approach to modelling aviation logistics development in rural regions, based on a synthesis of technical, economic, temporal, and service-oriented performance indicators. The methodological novelty lies in the formulation of an integrated efficiency index through the normalisation of disparate parameters and their aggregation using weighted coefficients. The research findings establish that aviation operations in rural regions are technically viable over distances of 150-800 km, utilising aircraft with a payload capacity of 0.5-5.0 tonnes and a flight frequency of 2-14 trips per week. Economic analysis indicates that capital expenditures (CAPEX) for the infrastructure range between 1.0-10.0 million USD, while route optimisation and cargo flow consolidation yield a 15-25% reduction in cost per tonne-kilometre. The results of the integrated assessment suggest that peak efficiency is achieved through a combination of moderate infrastructure investment, stable flight frequency, and a reduction in delivery lead times to 1-3 hours. Based on the identified typology of rural regions, three engineering-economic models for aviation logistics development are formulated: the compensatory model, the hybrid model, and the logistics efficiency enhancement model. The proposed models provide a practical framework for substantiating managerial decisions aimed at improving transport accessibility and modernising the logistics systems in rural territories.

Keywords: aviation logistics, rural regions, engineering-economic modelling, integrated efficiency assessment, logistics development.

Introduction

The development of rural regions is directly dependent on the level of transport accessibility and the efficiency of logistical support for both production and socio-economic processes. According to the Organisation for Economic Co-operation and Development (OECD), 51% of the population of the OECD member countries reside in regions classified as predominantly rural or intermediate territories, which are characterised by a lower transport infrastructure density and limited market accessibility compared to urban agglomerations [1]. This creates persistent logistical barriers to the development of entrepreneurship and access to basic services. Concurrently, contemporary research has proven that: firstly, logistics services and infrastructure exert a positive influence on agricultural growth [2]; secondly, aviation logistics significantly contributes to regional economic development [3-4]; and thirdly, regional and remote areas largely depend on air transport to ensure economic integration, freight transportation, and access to business activity centres [5]. The International Air Transport Association (IATA) notes that air transport is a critically important mode of transport for remote and sparsely populated regions, were alternative modes of transport face structural limitations [6]. These findings should also be considered together with the specifics of regional logistics and economically coordinated territorial development [7]. Most existing studies examine the impact of air transport at the macroeconomic or regional-sectoral levels, without providing sufficient detail on the operational conditions of logistics systems in rural regions characterised by low transport network density and volatile transport demand.

An analysis of contemporary scientific research shows that most studies in aviation logistics focus on modelling major airlines [8], airports and global supply chains [9], the aviation industry as part of the transport system [10], and efficient air traffic management systems [11]. These models are generally designed for environments with high traffic intensity, developed infrastructure, and stable demand, which limits their direct applicability to rural regions. Much less attention has been paid to aviation logistics in rural areas, where key factors include low freight volumes, volatile demand, an underdeveloped aerodrome network, and high sensitivity to logistics costs. Existing transport logistics performance models also remain fragmented, either emphasising economic indicators [12] or focusing on engineering and technical parameters without sufficient consideration of economic feasibility [13]. The literature still lacks approaches that integrate technical characteristics of air transport, economic efficiency, delivery time, and territorial accessibility within a single analytical model. For rural regions, this imbalance may lead to misguided managerial decisions, including overinvestment in transport infrastructure or underestimation of aviation logistics solutions. In addition, strategic opportunities [14] and management approaches require further attention, since digital transformation and transport hub optimisation improve the resilience and flexibility of transport systems [15]. Thus, the research gap lies not in the absence of aviation logistics models as such, but in the lack of an integrated engineering-economic framework for assessing their applicability in rural regions. Therefore, there is a clear need to develop integrated engineering-economic models of aviation logistics in rural areas that allow a comprehensive assessment of how technical, economic, and regional factors influence the logistics system efficiency.

The scientific novelty of this research lies in the development of an integrated approach to modelling, which combines the typology of rural regions, a system of engineering and economic indicators, and scenario-based assessments of the efficiency of aviation logistics solutions, contingent upon the specific logistical conditions of each territory. The proposed approach is intended to support the scenario-based comparison of aviation logistics solutions in accordance with regional characteristics, freight flow parameters, and development priorities. Consequently, the study does not seek to establish universally valid empirical coefficients for all rural regions; rather, it aims to develop a structured decision-support framework for evaluating alternative air logistics configurations under varying territorial conditions.

Materials and methods

The methodological framework combines statistical, analytical, and economic-mathematical methods for the development of engineering-economic models of aviation logistics in rural regions [4; 7; 8; 16-18]. The empirical basis of the study comprises official statistical data from international organisations, including OECD [1], IATA [6], ICAO [19], and EASA [20], covering the period 2018–2024.

To ensure the reproducibility of the study, a sequential six-stage procedure was employed: (1) typology of rural regions based on logistics characteristics; (2) assessment of engineering parameters for rural aviation logistics; (3) economic assessment of aviation logistics solutions in rural regions; (4) integrated efficiency assessment of aviation logistics in rural regions; (5) engineering-economic models for aviation logistics development in rural regions; (6) scenario-based evaluation of engineering-economic models and sensitivity analysis of the integrated indicator.

At the first stage, generalisation and typology methods were used to identify rural region types based on population density, settlement patterns, transport accessibility, and proximity to economic centres. The classification followed the OECD methodological framework and was supplemented with logistics criteria, including ground transport network density, average distance to a regional logistics hub, aerodrome infrastructure availability, and freight demand characteristics. Based on these combined features, regions were classified as remote, intermediate, or integrated.

At the second stage, a system of engineering parameters for aviation logistics was developed, including flight range, aircraft payload, flight frequency, fleet utilisation rates, and the availability and condition of aerodrome infrastructure. Data on technical specifications and operational parameters of air transport were derived from ICAO statistical materials and IATA industry reports. Typical value ranges were generalised from international statistical and sectoral sources.

At the third stage, a system of indicators was developed based on three analytical blocks: engineering, economic, and time-service. The engineering block includes transport range, payload capacity, flight frequency, and fleet utilisation; the economic block comprises CAPEX, OPEX, and transport costs; and the time-service block encompasses delivery time and flight regularity. This categorisation provides a structured assessment of efficiency and enables the subsequent aggregation of heterogeneous indicators into an integrated index. To evaluate economic viability, the method of calculation of relative and average values was applied, enabling assessment of the efficiency of aviation logistics solutions relative to alternative modes of transport within the context of rural regions.

In the fourth stage, a composite engineering and economic indicator was developed for the integrated assessment of aviation logistics efficiency, synthesising technical and economic parameters into a unified analytical model. The integrated indicator is constructed by normalising the source indicators and aggregating them using weighting coefficients determined through expert elicitation and model sensitivity analysis. This approach enables comparative analysis of various aviation logistics development scenarios tailored to specific regional conditions. During the normalisation stage, all indicators were classified as stimulants or de-stimulants. The weighting coefficients were determined in two steps. In the first step, expert ranking was conducted for the three groups of indicators (engineering, economic, and time-service), taking into account the specific characteristics of rural regions, where transport costs and delivery speed are critically important. In the second step, the resulting weights were adjusted through sensitivity analysis, facilitating assessment of the robustness of the integrated indicator with respect to variations in the weighting parameters.

In the fifth stage, engineering-economic models of aviation logistics development in rural regions were formed by synthesising the results of the rural region typology, engineering parameter assessment, economic evaluation, and the integrated efficiency indicator. The model construction was based on the dominant logistics objective, infrastructure constraints, demand characteristics, and the role of air transport within the regional logistics system. This made it possible to distinguish three model types: compensatory, hybrid, and logistics efficiency enhancement.

At the final stage, the proposed models were tested by scenario evaluation under different logistics conditions in rural regions. Sensitivity analysis was used to assess the influence of changes in load factor, flight frequency, OPEX, delivery lead time, and weighting coefficients on the integrated indicator. Model validation was performed by comparing the obtained results with the observed engineering and economic regularities derived from the empirical data.

Thus, the methodological design should be interpreted as a scenario-based engineering-economic modelling framework aimed at structured comparison of alternatives rather than direct empirical estimation of a single universally applicable logistics model.

The limitations of this study arise from the heterogeneity of statistical data across different countries, the limited granularity of data pertaining to domestic and regional air transport, and the dynamic nature of operational cost parameters within the aviation industry. To mitigate these limitations, robust normalisation techniques and sensitivity analyses were employed to ensure the stability and reliability of the proposed models.

Results and discussion

Typology of rural regions based on logistical characteristics

The typology of rural regions based on logistical conditions, aimed at the subsequent development of engineering-economic models for aviation logistics, is conducted in accordance with OECD methodological approaches. The typological criteria include population density, spatial settlement patterns, and proximity to economic centres, supplemented by transport accessibility indicators – specifically, the density of the ground transport network, average distance to regional logistics hubs, and the availability of aviation infrastructure. This approach facilitated a transition from a purely demographic to a logistics-oriented typology of rural regions.

Accordingly, rural regions were categorised into three distinct types. The first type comprises remote rural regions, characterised by low population density, limited accessibility to ground transport infrastructure, and significant spatial isolation. In these areas, aviation logistics serves a compensatory function, ensuring access to essential services and critically important freight transport. The second type comprises intermediate rural regions, exhibiting characteristics of both semi-urban and rural areas; despite a relatively developed road network, these regions suffer from uneven transport accessibility and significant transit times. In these regions, aviation logistics functions as a component of hybrid transport-logistics systems, acting as a complementary mode to ground transport. The third type comprises integrated rural regions linked to economic centres; these areas feature adequate transport accessibility while encountering logistical constraints arising from the spatial dispersion of production and consumption facilities. In such regions, aviation logistics enhances Supply Chain Management (SCM) efficiency by reducing lead times and increasing delivery reliability.

The scientific value of this typology lies in its application not merely as a descriptive classification of territories, but as a foundation for the differentiated selection of aviation logistics models, contingent upon the combination of infrastructural, demand-related, and temporal constraints. Unlike approaches where regional differences are considered primarily as a background factor, the proposed typology is directly integrated into the logic of the integrated efficiency assessment.

Compared to studies that focus primarily on the general impact of aviation logistics on regional development [3–4], the resulting typology shifts the focus to the applied feasibility of using air transport within various spatial configurations. This is critical for the subsequent interpretation of the effectiveness of the models, as the same transport technology does not yield uniform effects across different types of rural regions.

Assessment of engineering parameters for rural aviation logistics

The analysis of the technical feasibility and operational conditions of air transport in rural regions enabled the identification of a core set of parameters that directly affect logistics costs and the potential for integrating air transport into regional logistics systems (Table 1).

Table 1

Key engineering parameters of aviation logistics for rural regions [6; 19]

Parameters	Typical Range	Logistical Implications
Flight range, km	150-800	Coverage of remote and poorly connected territories
Payload capacity, tonnes	0.5-5.0	Transportation of small and medium-sized cargo batches
Flight frequency, flights per week	2-14	Ensuring the supply regularity
Fleet utilisation rate, %	55-75	Impact on unit transport cost
Infrastructure type	Limited-length runway	Flexibility in the placement of logistics hubs

The obtained values indicate that most rural regions are characterized by short-to-medium-haul transport routes with relatively small cargo volumes. Under these circumstances, employing aircraft with a payload capacity of up to 5 tonnes is technically feasible and mitigates inefficiencies arising from the underutilisation of higher-class aircraft. Flight frequency in rural areas is lower compared to trunk routes, stemming from limited and volatile demand. Nevertheless, even a frequency of 2–4 flights per week ensures a significant reduction in lead time compared to ground transport, particularly in regions with low road network density. Analysis of the infrastructural factor reveals that a significant portion of rural regions lacks full-scale airports, relying instead on limited-length runways or adapted airfields. While this reduces infrastructure CAPEX, it imposes constraints on aircraft type selection and operational modes.

Analytically, this implies that the technical efficiency of aviation logistics in rural regions is determined not by the maximum throughput of the system, but by the degree of alignment between the transport solution and local demand and infrastructure conditions. Consequently, the parameters of small-scale and regional aviation prove more relevant for the territories under study than the characteristics typical of mainline aviation. This conclusion partially aligns with [5], which emphasises the importance of air connectivity for remote regions; however, it extends this perspective by shifting the focus from the mere fact of transport accessibility to the techno-logistical constraints of its practical implementation.

The synthesis of engineering parameters leads to the conclusion that the technical efficiency of aviation logistics in rural regions is determined not by maximum throughput capacity but by the degree of adaptation of solutions to small-scale transport volumes, infrastructural constraints, and stringent requirements for supply regularity.

Economic assessment of aviation logistics solutions in rural regions

The economic assessment of aviation logistics solutions in rural regions is conducted by accounting for limited demand, spatial dispersion, and sensitivity to fluctuations in logistics costs. To ensure a robust assessment, a comparative analysis of CAPEX and OPEX between aviation logistics and alternative transport modes was conducted, alongside with evaluation of time-saving and service-related effects. The synthesis of parameter ranges is based on ICAO statistical materials for regional aviation, IATA aviation economics reviews, and EASA analytical reports (Table 2).

Table 2

Economic performance indicators of aviation logistics in rural regions [6; 19; 20]

Indicators	Typical Range	Economic Interpretation
CAPEX for aviation infrastructure, million USD	1.0-10.0	Adapted airfields, minimal terminal facilities
OPEX for aviation logistics operations, USD·(flight-km)$^{-1}$	5-12	Fuel, maintenance, and crew costs
Transport cost, USD·(t-km)$^{-1}$	1.2-4.0	Higher than surface transport
Delivery lead time, hours	1-3	Substantial reduction compared to road transport
Transport regularity, %	55-75	Indicator of service reliability

Empirical evidence indicates that aviation logistics offers substantial advantages in terms of lead times and delivery reliability compared to other transport modes, despite remaining a sub-optimal solution in terms of unit transport costs. Specifically, in rural regions where surface transport durations may exceed 12-24 hours, the reduction in lead times to 1-3 hours generates added economic value that is not captured in standard transport tariffs. Furthermore, the aircraft load factor exerts a critical influence on the economic efficiency of aviation logistics. Specifically, an increase in this indicator to 55-75% or higher leads to a disproportionate reduction in the unit transport costs. Route optimisation and cargo flow consolidation reduce OPEX per tonne-kilometre by 15-25%.

The analysis with surface transport modes indicates that aviation logistics is economically viable primarily for time-sensitive, high-value, and specialised cargo, particularly in regions with low road network density or adverse environmental conditions. In such instances, the economic benefit is derived from the mitigation of indirect costs associated with delivery delays, product quality degradation, and restricted market access. This result partially aligns with previous findings that highlight a positive correlation between aviation logistics and regional development [3; 12]; however, it clarifies that such a positive impact is not universal: it depends on threshold load levels, time sensitivity, and infrastructure costs. This dependency constitutes the subject of the subsequent integrated assessment.

Integrated efficiency assessment of aviation logistics in rural regions

To synthesise the evaluation results of engineering and economic parameters of aviation logistics and to facilitate a comparative analysis of alternative development scenarios, an integrated efficiency assessment framework for aviation logistics in rural regions was employed. This approach allows for the integration of heterogeneous indicators with disparate units of measurement and varying directions of impact on logistics effectiveness.

The integrated efficiency of aviation logistics in rural regions is defined as a weighted composite index derived from normalised engineering and economic indicators encompassing technical viability, economic feasibility, and logistical service levels.

The proposed integrated assessment framework employs a multidimensional set of indicators, classified into three primary criteria: engineering, economic, and time-and-service performance indicators. Engineering indicators include flight range, payload capacity, flight frequency, and fleet utilisation rate. Economic indicators comprise capital expenditure (CAPEX) for aviation infrastructure, operating expenditure (OPEX) for aviation logistics operations, and unit transport cost. Time-and-service performance indicators encompass delivery lead time and transport regularity. The proposed indicators are categorised as benefit indicators (stimulants), for which higher values correspond to greater efficiency, and cost indicators (destimulants), for which lower values correspond to greater efficiency. To ensure the comparability across indicators, linear normalisation was applied.

The integrated efficiency assessment was performed using a grouped aggregation procedure. At the first stage, normalised indicators were aggregated within three analytical blocks: engineering, economic, and time-service. At the second stage, the block sub-indices were combined into the final integrated efficiency index. Such a structure reflects the methodological logic of the study and ensures a more consistent interpretation of heterogeneous parameters within a unified analytical framework:

$$B_{eng,i} = \sum_{j=1}^{m} w_j^{eng} z_{ij} , \quad (1)$$

$$B_{econ,i} = \sum_{j=1}^{k} w_j^{econ} z_{ij} , \quad (2)$$

$$B_{ts,i} = \sum_{j=1}^{l} w_j^{ts} z_{ij} , \quad (3)$$

$$IE_i = W_{eng} B_{eng,i} + W_{econ} B_{econ,i} + W_{ts} B_{ts,i} , \quad (4)$$

where $B_{eng,i}$, $B_{econ,i}$, $B_{ts,i}$ – denote the engineering, economic, and time-service sub-indices for the i-th scenario;
w_j^{eng}, w_j^{econ}, w_j^{tg} – intra-block weights of the normalised indicators;
W_{eng}, W_{econ}, W_{ts} – weights of the three analytical blocks;
Z_{ij} – normalised value of the j-th indicator for the i-th scenario.

The block weights satisfy the condition $W_{eng} + W_{econ} + W_{ts} = 1$, while the intra-block weights in each group also sum to 1.

In this study, the grouped structure of the integrated indicator was used to support scenario comparison rather than to claim a universally fixed weighting system for all rural regions. Therefore, the integrated index should be interpreted as a scenario-based decision-support measure sensitive to regional logistics conditions and modelling assumptions.

To minimise the potential subjectivity of the integrated index, it should be emphasised that the proposed model does not claim universality for the weighting coefficients across all regions. Rather, these weights are treated as parameters sensitive to specific logistical conditions. Consequently, the weighting coefficients should be interpreted not as fixed constants, but as an analytical tool for scenario-based comparison.

The methodological distinction of the proposed approach from existing composite indicators lies not only in the aggregation of diverse metrics, but also in the integration of three analytical layers: the type of rural region, the set of techno-economic parameters, and scenario-based variations in demand and infrastructure. In this sense, the integrated indicator functions not as an abstract index, but rather as a practical decision-support mechanism.

The values of the integrated efficiency index IE_i range from 0 to 1, with higher values indicating higher aviation logistics efficiency. The resulting index values enable the comparison of alternative air transport utilisation scenarios, the determination of threshold conditions for the economic viability of aviation logistics, and the identification of the parameters with the greatest impact on the efficiency of aviation logistics in rural regions.

Such an assessment serves as a fundamental tool for subsequent scenario analysis and the formulation of engineering and economic development models of aviation logistics in rural regions.

Engineering and economic models for aviation logistics development in rural regions

Based on the results of the rural region typology, the assessment of engineering and economic parameters, and the integrated efficiency assessment, we propose the application of diverse engineering-economic models for aviation logistics development in rural regions. These models are distinguished by their primary objectives, operational scale, and requirements for infrastructure and resource allocation.

Model 1: Compensatory aviation logistics model (S1). This model is designed for remote rural regions characterised by low population density and limited accessibility of ground transport infrastructure. The primary objective of the model is to ensure a minimum essential level of logistics service for the delivery of critical cargo and the provision of specialised transport operations. The key characteristics of this model include short- to medium-haul flight routes, low cargo volumes, the use of small-capacity aircraft, and minimally developed infrastructure (e.g., adapted airstrips).

The economic feasibility of this model is determined not by the minimisation of unit transport costs, but by the mitigation of indirect socio-economic losses arising from the transport isolation of rural regions, as evidenced by the research findings. In this case, the model is viable under conditions where the criterion of accessibility outweighs the criterion of cost minimisation. Consequently, its efficiency should not be evaluated by the same standards as commercially oriented logistics systems. This distinguishes the compensatory model from the other two and explains why its integrated efficiency is not maximal, despite its socio-logistical significance being potentially high.

Model 2: Hybrid air-ground logistics model (S2). This model is applied to intermediate rural regions that possess partially developed ground transport infrastructure but face uneven transport accessibility and prolonged delivery lead times. The key characteristics of this model include the integration of air transport with road and regional logistics hubs, concentration of air cargo operations on critical segments of the supply chain, and route optimisation aimed at improving aircraft load factors.

The economic feasibility of the hybrid model is underpinned by a reduction in total logistics costs and shortened delivery lead times. This model demonstrates the applied nature of the proposed approach, as it integrates engineering adaptability with economic viability. Unlike purely compensatory or purely optimisation-based approaches, it enables flexible integration of air and ground transport, depending on the "bottlenecks" within the logistics chain. This allows the hybrid model to be regarded not as an abstract extension of previous models, but as a scenario-justified, evidence-based solution for transitional territories.

Model 3: Logistics efficiency enhancement model (S3). This model is intended for rural regions integrated with major economic centres, where aviation logistics functions as a strategic tool for optimising existing logistics systems. The key characteristics of this model include the use of air transport to accelerate the delivery of high-value and time-sensitive cargo, high aircraft load factors, and a comparatively lower share of infrastructure costs within the overall cost structure. Within this model, aviation logistics enhances the competitiveness of regional producers by providing access to broader markets and reducing logistics lead times. The integrated efficiency index reaches its maximum value as a result of the balanced interaction of economic and time-related parameters.

Analytically, this model confirms that the highest integrated efficiency is achieved not when aviation logistics merely fills structural gaps in surface infrastructure, but when it functions as a tool for targeted acceleration of logistical processes. Consequently, the efficiency of aviation logistics increases in tandem with the overall level of a territory's integration into economic networks.

The analysis of the proposed models for aviation logistics development in rural regions, highlighting their key characteristics, is summarised in Table 3.

Table 3

Comparative analysis of models for aviation logistics development in rural regions

Features	Model 1: Compensatory	Model 2: Hybrid	Model 3: Efficiency
Region type	Remote rural	Intermediate rural	Integrated rural
Primary objective	Accessibility	Optimisation	Efficiency
Aviation role	Compensatory	Supplementary	Optimising
Integrated efficiency	Moderate	High	Highest
Infrastructure requirements	Minimal	Moderate	Developed

The proposed engineering-economic models enable a differentiated approach to the implementation of aviation logistics in rural regions, providing a rationale for management decisions based on region types and specific logistics objectives. However, these models are not intended as ready-made universal solutions; rather, they serve as structured decision-making frameworks that necessitate adaptation to specific regional datasets.

For the purpose of academic discourse, it should be noted that a universal model for aviation logistics development does not exist, as the conditions for establishing logistics infrastructure, distances to rural regions, the available aircraft fleets and their utilisation rates, and the market trends are constantly evolving. Moreover, other researchers have proposed alternative technical and economic parameters for integrated assessment of aviation logistics efficiency [3; 12], which differ from those identified in this study, depending on specific regional conditions. This duality represents both the limitation and the contribution of the research. While the integration of engineering and economic indicators is not entirely novel in the existing literature, the present study applies this integration specifically to types of rural regions and scenarios of transport accessibility. This approach facilitates a transition from a general efficiency assessment to a comparative analysis of applied models for the implementation of aviation logistics. It is precisely this transition that constitutes the primary research contribution of the article.

The comparative characteristics of these models form the basis for subsequent scenario-based assessment and sensitivity analysis of the integrated efficiency indicator.

Scenario-based evaluation of engineering-economic models and sensitivity analysis of the integrated indicator

To verify the practical applicability of the proposed engineering-economic models, a scenario-based evaluation was performed for three alternatives of aviation logistics development in rural regions: the compensatory model (S1), the hybrid model (S2), and the logistics efficiency enhancement model (S3). In line with the methodology, the integrated indicator was calculated using a grouped aggregation procedure based on nine indicators combined into three analytical blocks: engineering (weight 0.3), economic (weight 0.4), and time-service (weight 0.3).

The engineering block included flight range, payload capacity, flight frequency, and fleet utilisation rate. The economic block covered CAPEX, OPEX, and transport cost. The time-service block included delivery lead time and transport regularity. The baseline values of the indicators for the three scenarios are presented in Table 4.

Table 4

Baseline values of indicators by scenario

Indicator	Type	S1	S2	S3
Flight range, km	stimulant	250	450	700
Payload capacity, t	stimulant	1.0	2.5	4.5
Flight frequency, flights perweek	stimulant	3	7	12
Fleet utilisation rate, %	stimulant	55	68	75
CAPEX, million USD	destimulant	1.5	4.0	8.0
OPEX, USD·(flight-km)$^{-1}$	destimulant	11.0	8.0	6.0
Transport cost, USD·(t-km)$^{-1}$	destimulant	3.8	2.4	1.5
Delivery lead time, h	destimulant	2.5	1.8	1.2
Transport regularity, %	stimulant	60	78	90

The calculated baseline integrated indicator values were 0.207 for S1, 0.571for S2, and 0.828 for S3. Thus, S3 demonstrates the highest integrated efficiency, S2 shows a balanced and adaptable result, and S1 has the lowest score due to its compensatory rather than cost-minimizing function.

The sensitivity analysis shows that the grouped integrated indicator is most responsive to changes in fleet utilisation, delivery lead time, transport regularity, and cost parameters. In particular, improving fleet utilisation in S1 increases its score from 0.207 to 0.245, indicating that even the compensatory model has some reserve for operational improvement. At the same time, a 20% increase in transport cost reduces the S2 score from 0.571 to 0.547, whereas a reduction in delivery lead time from 1.8 to 1.4 hours increases it to 0.607, confirming the strong dependence of the hybrid model on both economic and service conditions. For S3, the indicator remains comparatively high even under less favorable assumptions, but a 25% increase in CAPEX lowers its score to 0.802 and a reduction in transport regularity to 80% lowers it further to 0.788, showing that the most efficient scenario is still sensitive to deterioration in economic and time-service performance.

A key result is that none of the tested parameter modifications change the ranking of scenarios. The order S3 > S2 > S1 remains stable in all cases, indicating the stability of the proposed grouped engineering-economic assessment under moderate changes in operational, economic, and service conditions.

The validation confirmed the consistency between the obtained integrated indicator values, the functional role of each model, and the engineering-economic regularities identified in the study. The highest value for S3 is justified by its best combination of time-service, operational, and cost parameters; the intermediate position of S2 corresponds to the hybrid role of air transport; and the lowest value for S1 reflects its compensatory function focused on minimum accessibility rather than maximum efficiency. The preservation of the ranking S3 > S2 > S1 in the baseline scenario and in all sensitivity tests further confirms the internal consistency and practical applicability of the proposed models.

Conclusions

This study developed a scenario-based integrated engineering-economic framework for evaluating aviation logistics efficiency in rural regions under conditions of limited ground infrastructure, dispersed demand, and heterogeneous logistics constraints. The proposed approach combines rural region typology, grouped efficiency indicators, and scenario comparison to support the assessment of alternative aviation logistics configurations.

The results indicate that aviation logistics performs different functions depending on the type of rural territory. In remote rural regions, it primarily serves a compensatory role by ensuring minimum transport accessibility; in intermediate regions, it complements ground transport within hybrid logistics chains; and in more integrated rural regions, it functions as a targeted instrument for improving delivery speed, service reliability, and overall logistics performance.

Within the adopted modelling assumptions, the scenario-based grouped assessment showed that the highest integrated efficiency is associated with the logistics efficiency enhancement model, followed by the hybrid and compensatory models. This ranking reflects differences in the balance between engineering, economic, and time-service parameters rather than the effect of any single indicator. The analysis also suggests that aviation logistics solutions are technically most relevant for rural transport tasks over distances of 150-800 km, using aircraft with payload capacities of 0.5-5.0 tonnes and flight frequencies of 2-14 flights per week. Under the considered parameter ranges, infrastructure costs of 1.0-10.0 million USD and route optimisation combined with cargo consolidation may improve the cost-efficiency of rural air logistics systems.

The sensitivity analysis indicated that the integrated indicator was especially responsive to changes in utilisation, cost, delivery time, and service regularity, while the ranking of the scenarios remained stable under moderate parameter changes. This supports the internal consistency of the proposed framework as a decision-support tool for comparing alternative development options.

The practical value of the study lies in the applicability of the proposed models to support transport and logistics planning in rural regions. At the same time, the results should be interpreted within the adopted scenario assumptions, grouped weighting structure, and generalised statistical ranges. Further research should focus on country- and region-specific model calibration and on the implications of emerging aviation technologies for rural logistics development.

Author contributions

Conceptualization, I.Kr.; methodology, S.S. and I.Kr.; software, I.Km.; formal analysis, M.T.,S.K. and I.Kr.; investigation, S.S. and I.Km.; data curation, S.S., M.T. and N.T.; writing–original draft preparation, I.Kr. and N.T.; writing–review and editing, M.T.; visualization, I.Km., S.K.; project administration, I.Kr.; funding acquisition, N.T. and S.K. All authors have read and agreed to the published version of the manuscript.

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