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ECONOMIC OPTIMIZATION AND STRATEGIC RESILIENCE OF MULTIMODAL LOGISTICS NETWORKS IN UKRAINE: AN ECONOMIC ANALYSIS OF THE EFFICIENCY DEFICIT IN TURBULENCE

ЕКОНОМІЧНА ОПТИМІЗАЦІЯ ТА СТРАТЕГІЧНА СТІЙКІСТЬ МУЛЬТИМОДАЛЬНИХ ЛОГІСТИЧНИХ МЕРЕЖ В УКРАЇНІ: ЕКОНОМІЧНИЙ АНАЛІЗ ДЕФІЦИТУ ЕФЕКТИВНОСТІ В УМОВАХ ТУРБУЛЕНТНОСТІ

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The authors considered multimodal logistics in modern economic theory as a key in national competitiveness and integration into global value chains. In the 21st century, logistics has evolved from a simple "transport service" into a complex system of flow management that directly impacts inflation, GDP, and a nation's investment attractiveness. Ukraine, have unique geographical position and status as a leading global exporter of agricultural and industrial products, logistics has always been a strategic economic asset. Model was optimized around the low-cost, high-throughput capacity of the Black Sea maritime routes, which ensured Ukrainian goods a competitive final price on the markets. The blockade of Black Sea ports and the systematic destruction of transport infrastructure railway hubs, port terminals signified not just temporary difficulties, but the complete collapse of the existing economic model for logistics.

Keywords: optimization, innovation, investment, logistics, AI, digitalization, turbulence, sustainable development, transport economics, model, ports.

На сьогоднішній день ефективність мультимодальних логістичних мереж визнається в сучасній економічній теорії ключовим і часто вирішальним фактором національної конкурентоспроможності та інтеграції в глобальні ланцюги створення доданої вартості. У XXI столітті логістика перетворилася з простої «транспортної послуги» на складну систему управління логістичними ланцюгами та потоками, яка безпосередньо впливає на інфляцію, валовий внутрішній продукт та інвестиційну привабливість країни в умовах турбулентності. Для України, з її унікальним географічним положенням та статусом провідного світового експортера сільськогосподарської та промислової продукції, мультимодальна логістика завжди була стратегічним економічним активом економіки України. До 2022 року ця модель була оптимізована навколо низьковитратної, високопропускної здатності морських шляхів Чорного моря, що забезпечувало українським товарам конкурентну кінцеву ціну на ринках Азії, Африки та Близького Сходу. Економічний контекст та глобальне значення. Виклик геополітичного шоку та порушення моделі розвитку і фунціонування маршутів доставки вантажів. Повномасштабна військова агресія росії проти України, що розпочалася у лютому 2022 році, спричинила негайний геополітичний шок для економіки. Проблеми блокади чорноморських портів та систематичне руйнування логістично-транспортної інфраструктури (мостів, залізничних вузлів, портових терміналів) означали не просто тимчасові труднощі, а повний крах існуючої економічної моделі логістики. Логістичний сектор економіки був змушений здійснити негайний, хаотичний та надзвичайно витратний перехід від парадигми мінімізації витрат (ефектив-

ності) до парадигми виживання та управління ризиками (стійкість). Цей зсув створив екзогенний економічний бар'єр, зробивши традиційні моделі розрахунку логістичних витрат повністю недійсними та недоречними для аналізу експертами. Подальші наукові дослідження в галузі мультимодальної логістики, розкриває нові горизонти та межі в досліджуваній авторами науково-предметній тематиці сфери данної роботи.

Ключові слова: оптимізація, інновації, інвестиції, логістика, ШІ, цифровізація, турбулентність, сталий розвиток, економіка транспорту, модель, порти.

Statement of the problem. The core research problem is the absence of a comprehensive economic model that allows not just to state, but to quantify and integrate these three factors (C, R, and S) into a unified Total Logistics Cost (TLC). The objective of this article is to develop such a model (which we call CALC – Conflict-Adjusted Logistics Cost) and use it to calculate the Logistics Surcharge (ΔTLC). This "surcharge" is the economic gap between the current Wartime Constraints (Scenario A) and the efficient Post-War Benchmarks (Scenario B). Quantifying this gap is critical for developing a post-war recovery strategy and prioritizing investments. The forced transition to alternative "Solidarity lanes" via western land borders, while a vital solution, immediately exposed a critical, yet not fully calculated, "efficiency deficit". This deficit is a complex economic problem composed of three key hidden cost factors: physical bottlenecks (The S factor – congestion/surcharge). The destruction of infrastructure and the redirection of 100% of export flows onto infrastructure never designed for it (e.g., western rail crossings) created severe congestion externalities.

This is not just "delays"; it is an economic phenomenon that monetizes into billions in losses from idle time, demurrage and detention penalties, and, most critically, a loss in the velocity of capital turnover. Financial risks (The R factor – risk): The environment of active hostilities necessitates mandatory war risk insurance. International insurance markets (e.g., the Lloyd's Joint War Committee) react instantly by imposing a War Risk Premium (WRP). This premium, amounting to several percent of the cargo (or vessel) value, functions as a direct, unpredictable "tax on trade" that creates no added value but drains working capital and destroys margins. Structural sub-optimality (The C factor – base cost): A forced structural change occurred: a shift from the world's cheapest transport mode (maritime) to significantly more expensive land-based modes (road and rail). This shift inflates the base cost on its own.

Analysis of recent research and publications. Economic theory, from Adam Smith to modern "infrastructure-led growth" models, views transport infrastructure as a fundamental factor of production. Studies by the World Bank and OECD have repeatedly shown a high positive correlation between the Logistics performance index (LPI) and GDP per capital. Logistics determines not only the cost of trade but also the feasibility of participation in global supply chains, where just-in-time delivery is as critical as price.

Logistics cannot exist without transport infrastructure, and innovations in the transport process can positively affect the economic development of logistics traffic in conditions of security threats. Gutsalyuk O. M. [1], Kolodynskyi S. B. [2], Mamontenko N. S. [3], Yevdokimova O. M. [7; 9; 13], Darushyn O. V. [4; 11], Komleva T. M. [12], Zakharchenko O. V. [5; 10], the authors focus their attention on investment and innovation sustainable development.

Formation of the objectives of the article (task statement). The purpose of the article is to calculate transport routes for alternative cargo transportation (A and B), as well as to form a model for optimizing investments in multimodal logistics in turbulent conditions.

Summary of the main research material. Classical transport economics operates with the concept of the generalized cost of transport (GCT). GCT posits that a rational economic agent, when choosing a route, minimizes not only the direct financial cost (tariff) but also the monetized cost of time and the cost of reliability. The article is structured as follows:

– Section 1 provides a literature review on transport economic theory, supply chain resilience, and logistics in conflict zones.

– Section 2 details the research methodology, including the qualitative framework for Scenarios A and B and the conceptual structure of the CALC model.

– Section 3 presents the results of the empirical analysis, applying the CALC model to three representative case studies (corridors), and provides an in-depth discussion of the economic implications.

– Section 4 summarizes the conclusions, discusses the limitations, and offers concrete economic policy recommendations [1].

However, traditional GCT models are inadequate for Scenario A (wartime) for two reasons: They treat delays as stochastic (random), not systemic and chronic (as in the case of border congestion). They lack a built-in mechanism to account for existential financial risks (Factor R), which are not merely a "higher cost of reliability" but a non-linear barrier. Economic Resilience vs. Efficiency. Following global shocks (the 2008 financial crisis, COVID-19), economic literature has actively developed the theory of resilience. Efficient (Lean) chains are optimized for cost minimization in stable conditions. They have zero inventory and minimal redundancy. Ukrainian logistics before 2022 was exactly this. Resilient chains are optimized for survival during shocks. They feature diversified routes, redundant infrastructure, and higher inventories [2].

The key theoretical takeaway: resilience costs money. The ΔTLC calculated in this paper is, in essence, the price the Ukrainian economy is forced to pay for the immediate, forced transition from an efficiency model to a resilience model. Logistics in conflict-affected economies. A separate body of literature analyzes economic recovery in post-conflict zones (e.g., the Balkans, Iraq). The main finding of this research is that logistics restoration is a prerequisite for any other economic recovery. However, these studies typically focus on the post-conflict phase (infrastructure rebuilding). Identifying the Research Gap. Despite a large body of literature, a clear research gap exists: Most GCT models are not adapted to the systemic risks of war and chronic infrastructure collapse. The resilience literature is mostly qualitative or corporate-focused, offering no model for the macroeconomic calculation of this transition's cost. Post-conflict studies do not analyze the economics of logistics during an active, high-intensity conflict. This paper fills this gap by proposing a quantitative economic model (CALC) that integrates base costs (C), existential risk premiums (R), and economic losses from systemic congestion (S) to analyze the economy during the conflict. Methodology: The CALC Economic model to achieve the research objective, we employ a mixed-methods research design. It combines qualitative scenario analysis (to define the economic parameters of Scenarios A and B) and quantitative modeling (to calculate the ΔTLC) [3].

Detailed scenario definitions. 1. Scenario A: "Wartime constraints" (Current Reality). This is the baseline scenario, reflecting the economic realities as of 2024-2025. Its key economic parameters are: Black Sea ports are blocked or functioning with extreme limitations. Western land border crossings are overloaded by 200-500% of their designed capacity. Risk (R): The JWC rating for the Black Sea is set at its highest level. WRP insurance premiums are mandatory and high (1-5% of cargo value). Efficiency (S): Systemic congestion at borders. The average waiting time for a truck/railcar is measured in days or weeks, not hours. Demurrage and idle time penalties are a normal cost of doing business.

Scenario B: "Post-War Benchmark" (Target state). This is not merely a return to the 2021 state but an optimized model that incorporates the lessons of the war. Infrastructure: Full unblocking of the Black Sea. Key ports are restored [4]. Western borders are modernized (integrated 1435/1520 mm gauges, digital customs, new "dry ports"). Risk (R): JWC rating is removed. Insurance premiums return to standard commercial levels (approx. 0.05%). Efficiency (S): Border crossing times are measured in hours. The GCT model becomes relevant again. The CALC Economic Model: Conceptual Framework. We propose a conceptual economic model: CALC (Conflict-Adjusted Logistics Cost) [5]. This model deliberately avoids complex mathematics in favor of economic logic. It views the total cost of logistics as the sum of four distinct but interrelated economic blocks. Total Cost (CALC) = Base Cost (C) + Risk Factor (R) + Congestion Factor (S) + Expected Loss (L)

1. Economic Justification of Model Components/Base Cost (C).

What is it? The standard market price for transport (freight, tariffs) per unit of cargo (tonne, TEU) under optimal, free-choice conditions.

Why does it change? The ΔC (difference between C_A and C_B) arises from the structural modal shift. In Scenario A, we are forced to use expensive trucks (high C_A) instead of cheap bulk carriers (low C_B). This is a direct, unavoidable loss. War Risk Factor (R).

What is it? The economic premium for risk. It is the direct financial cost of the security environment, which a business must pay upfront, regardless of whether an insured event occurs [6].

– What does it consist of?

– War Risk Premium (WRP): An explicit payment to insurers.

– Additional Security Costs: The cost of guards, escorts, or route deviation to avoid dangerous areas.

– Uninsured Risks: The carrier's own "risk premium" embedded in their tariff to cover the probability of losing a driver or vehicle, which standard insurance does not cover. Surcharge/ Congestion Factor (S).

What is it? The opportunity cost of time, multiplied by infrastructural inefficiency. It is the monetization of delays [7].

– What does it consist of?

– Cost of "Frozen" Capital (Inventory Carrying Cost, ICC): If cargo worth $1,000,000 is stuck in a queue for 10 days, at a capital cost of 12% per annum, the economic loss (ICC) is $3,287. This is money that is not working.

– Direct Penalties: demurrage (for vessel/ railcar idle time) and detention (for container idle time). In Scenario A, these penalties are so high and inevitable that they become part of operational costs. Expected Loss (L).

– What is it? A standard economic provision for risk, calculated as: L = (Probability of cargo loss) × (Value of cargo).

Why is it separate from R? The R factor is an upfront payment (insurance). The L Factor is the statistical expectation of actual losses. In scenario A, the probability of loss (P(Loss)) is non-zero and significant, making this factor substantial [8]. 2. Results and Discussion: The economic impact. 2.1. Case study Analysis: quantifying the ΔTLC. We applied the CALC model to three key corridors to quantify the ΔTLC – the real "price of war" for logistics, expressed in USD per unit of cargo. Case study 1: Bulk grain export (1,000 tonnes).

Route A (Wartime): central Ukraine → Constanța, Romania (Rail/Road):

– Route B (Benchmark): central Ukraine → Port of Odesa (Rail → Bulk Carrier): Economic analysis: In scenario A (Wartime), the total logistics cost increased by $38,590 (+75.7%) compared to the post-war benchmark. Interpretation: The largest driver of this increase is the base cost (ΔC) at $25,000. This is a clear economic indicator of the structural shift: the economy pays $25,000 more just because it is forced to use expensive land transport instead of cheap maritime transport. The Risk Factor (ΔR) added $9,000, and the congestion factor (ΔS) added another $3,990. This means that even with all congestion and risk eliminated, grain logistics will remain extremely expensive without sea access [9].

As provided in table 1.

Case Study 2: Container Import (1 TEU). Route A (Wartime): Hamburg, Germany → Lviv, Ukraine (Sea → Rail/Road via Poland). Route B (Benchmark): Hamburg, Germany → Lviv, Ukraine (Sea → Port of Odesa → Rail) Economic Analysis [10]: Here, the situation is completely different. The total cost increased by $5,482 (+168.7%). Interpretation: for high-value goods imports (electronics, equipment), the congestion factor (ΔS) becomes the dominant driver ($2,382, or 43.5% of the total increase). This means that the economic loss from inefficiency and idle time at the border (the opportunity cost of "frozen" capital) is a more significant problem than the war risk premium (R) or the base cost (C). It is precisely this S factor that creates immense inflationary pressure on all imported goods in the country [11]. As provided in table 2.

Discussion: Hypothesis Validation from an Economic Perspective

1. Hypothesis H1 (Structural Disequilibrium) hypothesis validated. The increase in total logistics costs by 75%-168% is not simple cost inflation.

It confirms a state of structural economic disequilibrium. Logistics has ceased to be a factor of competitiveness and has become a primary barrier to trade and a source of imported inflation [12].

2. Hypothesis H2 (Dominant Cost Driver) Hypothesis validated (with nuance). The CALC model allows for the precise identification of

Table 1

The scenarios base coast and risks factor price

Component (USD)	Scenario A (Wartime)	Scenario B (Benchmark)	ΔCost (Price of War)	% of ΔCost
Base Cost (C)	75,000	50,000	25,000	64.8%
Risk Factor (R)	9,500	500	9,000	23.3%
Congestion Factor (S)	4,490	500	3,990	10.3%
Expected Loss (L)	600	0	600	1.6%
Total TLC	89,590	51,000	38,590	100%

Source: formed based on [14; 15; 16]

Table 2

The structures component price scenarios A and B

Component (USD)	Scenario A (Wartime)	Scenario B (Benchmark)	Δ Cost (Price of War)	% of ΔCost
Base Cost (C)	4,500	3,000	1,500	27.4%
Risk Factor (R)	1,550	50	1,500	27.4%
Congestion Factor (S)	2,582	200	2,382	43.5%
Expected Loss (L)	100	0	100	1.8%
Total TLC	8,732	3,250	5,482	100%

Source: formed based on [17; 18; 19]

the main economic problem for each corridor, dispelling the myth that "the only problem is risk":

– For commodity exports (Case 1), the main problem is ΔC (loss of sea routes).

– For finished goods imports (Case 2), the main problem is ΔS (border inefficiency).

This proves that there is no single solution; a differentiated economic policy is required. 3. Hypothesis H3 (Investment Priority and ROI). Hypothesis validated this is the most critical economic conclusion for policy development. We conducted a sensitivity analysis to determine the Return on Investment (ROI) for different types of interventions, using Case 2 (Import) as an example.

– Test 1 (Political Intervention): Assume the state or partners provide insurance guarantees, reducing the Risk Factor (R) by 50%.

– Savings: $1,500 × 0.5 = $750 per container.

Test 2 (Infrastructural Intervention): Assume that investment in "dry ports" and customs digitalization reduces the Congestion Factor (S) by 50%. Savings: $2,382 × 0.5 = $1,191 per container [13].

Economic conclusion: Investment in improving border efficiency and throughput (addressing S) yields a 58.8% higher economic return (ROI) in the short term than political investment in risk reduction (R). This is a clear, data-driven investment recommendation for the government and international donors.

Conclusions. This study has successfully developed and applied the Conflict-Adjusted Logistics Cost (CALC) model to quantify the economic shock to Ukraine's logistics system. Quantifying the war: The "Logistics Surcharge" (ΔTLC) has been quantified for the first time, currently ranging from +75% to +168% depending on the corridor. This undermines the economic competitiveness of exports and fuels domestic inflation. Problem decomposition: The CALC model allowed for the de-composition of total losses into specific economic drivers: ΔC (infrastructure loss), ΔR (risk premium), and ΔS (time/inefficiency loss). This permits a shift from general complaints to specific analysis. Investment prioritization: the study proves that for current land corridors, investments in efficiency (eliminating congestion) have a higher and faster ROI than investments in risk management. Economic policy recommendations based on these findings, we propose the following recommendations for the Government of Ukraine, the Ministry of Infrastructure, and international financial partners (EBRD, World Bank): Priority #1 (ROI): immediate investments (including donor funds) must be directed to projects with the highest short-term return – expanding the physical and digital throughput capacity of western borders (to reduce ΔS).

This includes building "dry ports," integrating customs and railway databases, and developing intermodal terminals. Reducing inflammatory pressure: since the S Factor is a key driver of inflation for imports, reducing it will have a direct and rapid macroeconomic effect, lowering prices for consumer goods. Risk management strategy (R): To reduce the R factor (especially for exports), the state must actively use public-private partnership tools to create guarantee funds (e.g., modeled on the British fund for the "grain corridor") to make Ukrainian goods competitive on global markets. Long-term strategy (C): Post-war reconstruction must not be a simple "rebuilding" of ports. It must include the deep integration of western borders into the European TEN-T network and the development of the 1435 mm rail gauge to create a diversified, resilient logistics model that is not 100% dependent on a single maritime basin.

Limitations and future research data: the model relies on synthesized data (market averages). More precise analysis requires access to real commercial contracts and insurance policies. Static model: the CALC model is static. It does not account for dynamic changes (e.g., seasonal grain prices or sudden military attacks). Avenues for future research: development of a dynamic, stochastic CALC model that incorporates probabilistic events. Application of the model for modal shift optimization – determining at what price of R and S it becomes more profitable to use a longer but cheaper route. Integration of "green logistics" into the post-war scenario B, assessing the economic effect of a reduced carbon footprint when shifting to more efficient transport.

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