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Mechanism for balancing freight flows between international road border crossing points under conditions of uneven border infrastructure utilisation

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Abstract. The structural transformation of international transport flows after 2022 resulted in a disproportionate distribution of transport demand across Ukraine's international road border crossing points (IRBCPs), leading to congestion at certain crossing points and prolonged queues. The aim of this article was to substantiate a mechanism for balancing freight flows between international road border crossing points in order to improve the efficiency of international freight transport under conditions of uneven utilisation of border infrastructure. The methodological framework of the study was based on queueing theory (a multi-channel M/G/s system with the Allen-Cunneen approximation), combined with scenario analysis and normalised multi-criteria assessment methods. To ensure the reproducibility of the results, a separate methodological section was included to justify the procedure for determining all key model parameters (λ, μ, s, c_a, c_s). The article investigated the problem of uneven utilisation of Ukraine's international road border crossing points under conditions of the structural transformation of international transport flows. It has been established that changes in the geography of foreign trade routes have led to an imbalance in the utilisation of border infrastructure, resulting in the systematic overloading of certain border crossing points. An adaptive mechanism for balancing freight flows between IRBCPs based on an integral efficiency criterion has been developed. A dedicated methodology section has been introduced to justify the procedure for obtaining the model parameters. The results of the scenario modelling confirmed the effectiveness of the proposed approach, reducing the utilisation factor (ρ) of the Krakovets-Korczowa IRBCP from 1.05 to 0.63-0.74 and decreasing the average queue waiting time (W_q) from more than 72 hours to 2.3-7.2 hours. The proposed mechanism enables the prompt redistribution of freight flows between IRBCPs without requiring capital investment in border infrastructure, thereby significantly reducing the economic losses incurred by freight carriers as a result of prolonged delays at the border

Keywords: transport and technological process; M/G/s; queueing theory; logistics; e-Queue; digitalisation

Introduction

Following 2022, Ukraine's international freight transport system underwent a substantial transformation driven by changes in the structure of foreign trade flows, the reorientation of logistics routes, and a sharp increase in the utilisation of international road border crossing points (IRBCPs). According to The State Border Guard Service (2024) and Solidarity Lanes: Latest Figures (2025a), restrictions on the capacity of maritime and rail transport corridors resulted in a significant proportion of export and import freight being redirected to road transport, leading to a systematic increase in traffic intensity at Ukraine's western border crossings. According to Solidarity Lanes: Latest Figures (2025b), the Polish corridor experienced the highest level of demand, accounting for approximately 48%

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of Ukraine's international road freight transport in 2025. This asymmetry in freight flows resulted in the persistent overloading of several IRBCPs, particularly Krakovets-Korczowa, Rava-Ruska-Hrebenne, and Yahodyn-Dorohusk, while the Hungarian and Slovak corridors retained substantial spare capacity. During peak periods, the average waiting time for vehicles at certain IRBCPs exceeds 60-72 hours, with maximum waiting times surpassing 240 hours (Solidarity Lanes: Latest Figures, 2025b). As noted by the European Commission (2025) and K. Prytula *et al.* (2022), conventional approaches to alleviating congestion at IRBCPs, such as reconstructing border infrastructure or increasing the number of service channels, require considerable capital investment and long implementation periods of five to ten years. Consequently, the development of a freight flow balancing mechanism between IRBCPs using digital decision-support systems has become particularly relevant.

Numerous contemporary studies have examined the operation of international transport and technological systems and the management of transport flows under conditions of congested border infrastructure. In particular, the studies by M. Golnar & B. Beškovnik (2022), and B. Stewart *et al.* (2023), explored the application of queueing theory and multi-criteria decision-making methods to evaluate the performance of border crossing points. A.K. Jain *et al.* (2023) analysed approaches to optimising multimodal transport networks under conditions of stochastic demand, the digital transformation of supply chains, inter-organisational integration of information systems, enhancing the resilience of transport and logistics networks to external disruptions, developing intermodal freight transport between Ukraine and Poland, forecasting waiting times at border crossings using machine learning techniques, and modelling and optimising border service systems using a simulation-based multi-criteria decision analysis approach. D. Ivanov & A. Dolgui (2021) introduced the concept of the ripple effect, explaining how congestion at a single IRBCP propagates disruption throughout the entire transport corridor. The freight flow balancing mechanism proposed in this study effectively implements the principle of structural resilience through route diversification, consistent with the recommendations of these authors. Its distinguishing feature lies in adapting this concept to the specific characteristics of border logistics, where traffic redistribution is constrained by the fixed geographical distribution of IRBCPs and customs regulations. The study by I. Jacyna-Gołda *et al.* (2024) confirmed that the development of intermodal transport routes between Ukraine and Poland is essential for reducing the utilisation of road border crossing points. The integration of a border logistics hub proposed in the present study represents a specific organisational and technological mechanism for implementing this approach, complementing the strategic recommendations of that research with an operational decision-making framework.

Nevertheless, the majority of existing studies focus primarily on the local optimisation of individual transport nodes without comprehensively addressing the asymmetry of international freight flows between border corridors. Adaptive freight flow balancing between alternative IRBCPs, taking into account an integral efficiency criterion for the transport and technological process, remains insufficiently investigated, thereby highlighting the relevance of the present research. The aim of this study was to develop a mechanism for balancing freight flows between international road border crossing points under conditions of uneven utilisation of border infrastructure in order to improve the efficiency of the transport and technological process of international freight transport. To achieve this aim, the following objectives were defined: (1) to analyse the current operation of Ukraine's IRBCPs under conditions of structural asymmetry in transport flows; (2) to formalise and parameterise a mathematical model of an IRBCP as a multi-channel M/G/s queueing system, including the procedure for obtaining the required input data; and (3) to develop and validate an adaptive freight flow balancing mechanism between IRBCPs using an integral efficiency criterion for the transport and technological process.

Materials and Methods

The study was conducted as an applied modelling investigation of transport and logistics systems. The methodological framework was based on queueing theory, specifically the theory of multi-channel M/G/s systems and the Allen-Cunneen approximation for estimating the average waiting time. In addition, scenario analysis and normalised multi-criteria assessment methods were employed to evaluate alternative transport routes. The object of the study was the operational system of Ukraine's international road border crossing points. The subject of the study was an adaptive mechanism for balancing freight flows between IRBCPs under conditions of uneven utilisation of border infrastructure. The empirical basis comprised data provided by the Ministry for Development of Communities and Territories of Ukraine (n.d.) on traffic intensity at IRBCPs during 2024-2025, together with analytical materials published by the United Nations Economic Commission for Europe (2025). Data sources were selected according to the following criteria: (a) timeliness, covering the period 2024-2025; (b) reliability, including only official governmental and scientific sources; and (c) relevance, with direct applicability to IRBCPs located on the Ukrainian-Polish and Ukrainian-Hungarian border corridors.

The vehicle arrival rate (λ) was determined as the average number of freight vehicles per hour during peak operating hours (07:00-19:00) based on data from the State Border Guard Service of Ukraine for 2024-2025; for the Krakovets-Korczowa IRBCP, $\lambda = 22.6$ vehicles/h. The service rate (μ) was calculated as the reciprocal of the average service time per vehicle, taking into account customs and border control procedures; the baseline value was $\mu = 2.15$ vehicles/h/channel. The number of service channels ($s = 10$) corresponded to the number of operational inspection lanes at the IRBCP during the study period. The coefficients of variation for the arrival process (c_a)

and service time (c_s) were determined from statistical data describing the variability of inter-arrival intervals and service times. IRBCPs were classified according to threshold values of the utilisation factor (ρ): $\rho > 1$ indicated an overloaded operating regime (donor IRBCP); $0.85 \leq \rho \leq 1$ indicated a critically loaded regime; and $\rho < 0.85$ indicated a stable operating regime with reserve service capacity (recipient IRBCP). The critical threshold value of $\rho_{crit} = 0.85$ was selected to preserve sufficient spare capacity for compensating stochastic fluctuations in the arrival rate. The average waiting time for vehicles in the M/G/s system was estimated using the following relationship (Allen-Cunneen approximation):

$$W_q \approx [\rho^s / (s!(1 - \rho))] \cdot [(c_a^2 + c_s^2)/2] \cdot (1/\mu), \qquad (1)$$

where W_q – the average vehicle waiting time in the queue; ρ – the system utilisation factor; c_a – the coefficient of variation of the inter-arrival times; c_s – the coefficient of variation of the service times; s – the number of service channels; μ – the service rate of a single channel.

System utilisation factor:

$$\rho = \lambda / (s \cdot \mu), \qquad (2)$$

where, for $\rho < 1$, the system operates under stable conditions. As $\rho \to 1$ a nonlinear increase in W_q is observed, whereas for $\rho \leq 1$ the system enters an overloaded regime characterised by unlimited queue growth.

Results and Discussion

The operation of IRBCPs was modelled as a multi-channel M/G/s queueing system. Based on the analysis of materials published by the Ministry for Development of Communities and Territories of Ukraine (n.d.) concerning the operation of international transport corridors, it was established that the Polish corridor experienced the most critical level of utilisation during 2024-2025. At the Krakovets-Korczowa IRBCP, the system utilisation factor reached a value corresponding to an overloaded operating regime:

$$\rho_{\text{Krakovets}} = \frac{22{,}6}{10 \cdot 2.15} \approx 1.05.$$

Figure 1 illustrates the relationship between W_q and ρ for an M/G/s system with parameters $c_a = 1.0$ and $c_s = 0.6$.

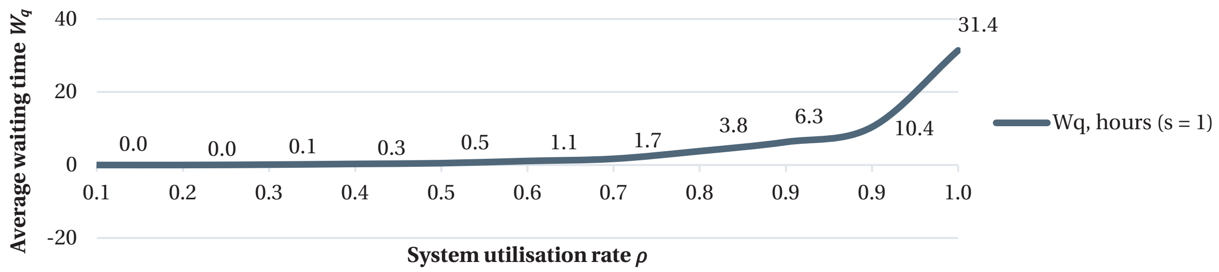

Figure 1. Relationship between the average waiting time for vehicles and the system utilisation factor M/G/s
Source: compiled by the author

Analysis of Figure 1 demonstrates the nonlinear nature of this relationship. Within the range $\rho < 0.7$, the average waiting time does not exceed 2 hours and increases gradually. In the interval $0.7 \leq \rho < 0.9$, queue accumulation accelerates significantly, while as $\rho \to 1$ W_q tends towards infinity. The practical region of stable system operation corresponds to $\rho \leq 0.85$, which justifies selecting this value as the threshold for activating the freight flow balancing mechanism. Practical evidence supporting this theoretical relationship is provided by the operation of the e-Queue system. At most IRBCPs, digital slot allocation reduced W_q by 24-70% through a reduction in service time variability (c_s) (Ministry for Development of Communities and Territories of Ukraine, 2025). However, no substantial improvement was observed at the Krakovets-Korczowa IRBCP. When $\rho < 1$, even a considerable reduction in service time variability cannot stabilise the system because the arrival rate exceeds the total service capacity. This finding is consistent with the conclusions of I. Badi *et al.* (2026), who argued that the digitalisation of border procedures is a necessary but insufficient condition for resolving congestion problems. Within the framework of this study, an adaptive mechanism for balancing freight flows between IRBCPs is proposed. A continuous monitoring system records the current values of λ, μ, and s and calculates the utilisation factor (ρ) for each IRBCP in real time. When the critical threshold $\rho_{crit} = 0.85$ is reached or when $\rho > 1$, the decision-support module initiates the balancing procedure by assessing the available capacity of recipient IRBCPs and generating a recommendation to redirect part of the freight traffic. The criterion for initiating freight flow balancing is:

$$\rho \geq \rho_{crit} = 0.85.$$

Figure 2 shows a structural diagram of the proposed mechanism.

The proposed framework comprises four functional modules: a monitoring module (collecting real-time data on λ, μ, and ρ from all IRBCPs), an analysis module (classifying IRBCPs according to threshold values of ρ and identifying donor and recipient IRBCPs), a decision-support module (calculating the integral efficiency indicator, , for each alternative route and selecting the optimal option), and an implementation module (generating recommendations for freight carriers through integration with the e-Queue system and logistics platforms). Feedback between the implementation module and the monitoring module enables the effects of traffic redirection to be monitored continuously and recommendations to be adjusted promptly as operating conditions change. The optimal route is selected on the basis of the integral efficiency indicator of the transport and technological process:

$$I_e = w_1 \cdot T_n + w_2 \cdot C_n + w3 \cdot R + w_4 \cdot S + w_5 \cdot E, \quad (3)$$

where T_n – the normalised delivery time indicator; C_n – the normalised transport cost indicator; R – the delivery reliability indicator; S – the service quality indicator; E – the environmental indicator; w_i – the weighting coefficients ($\Sigma w_i = 1$).

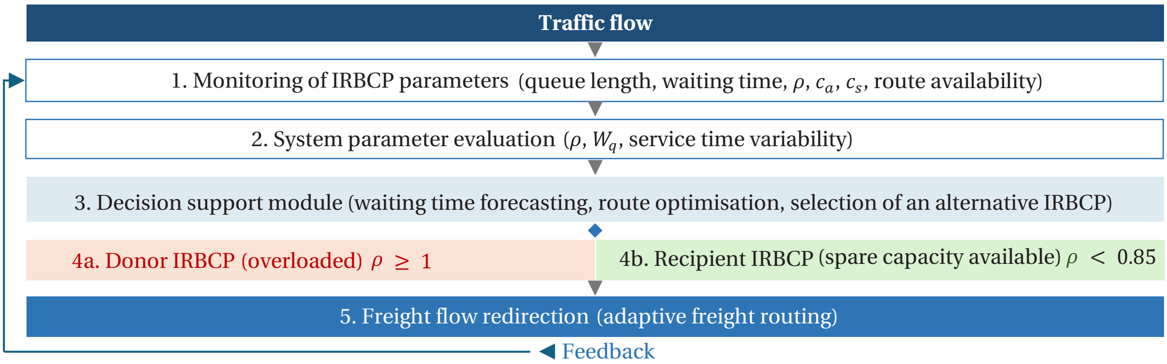

Figure 2. Structural diagram of the adaptive freight flow balancing mechanism between international road border crossing points

Source: developed by the author

Normalisation is performed using linear scaling within the range [0, 1]. The weighting coefficients are determined using the AHP, taking into account the priorities of the individual freight carrier. To evaluate the effectiveness of the proposed mechanism, three scenarios were considered: S0 (baseline scenario – no freight flow balancing), S1 (conservative scenario – partial traffic redirection combined with digital slot allocation), and S2 (optimistic scenario – full adaptive freight flow balancing supported by a border logistics hub). Table 1 presents a comparison of the baseline, conservative, and optimistic scenarios for the operation of the Krakovets-Korczowa IRBCP in terms of arrival rate, service channel utilisation, and average vehicle waiting time.

Table 1. Impact of the freight flow balancing mechanism on the operational parameters of the Krakovets-Korczowa IRBCP

Parameter	Baseline scenario	Conservative scenario	Optimistic scenario
Arrival rate, λ (vehicles/h)	22.6	18.9	15.9
Number of service channels, s	10	10	10
Service rate, μ (vehicles/h/channel)	2.15	2.54	2.54
Service time coefficient of variation, c_s	0.60	0.25	0.25
Arrival process coefficient of variation, c_a	1.00	0.35	0.30
Utilisation factor, ρ (–)	1.05	0.74	0.63
Average waiting time, W_q (h)	≥ 72	4.8-7.2	2.3-4.1

Source: compiled by the author based on Ministry for Development of Communities and Territories of Ukraine (n.d.)

Analysis of Table 1 reveals several fundamentally important patterns. In the conservative scenario (S1), reducing the λ from 22.6 to 18.9 vehicles/h is achieved by redirecting approximately 16% of the freight traffic to alternative IRBCPs (Rava-Ruska-Hrebenne and Yahodyn-Dorohusk). With the number of service channels remaining unchanged ($s = 10$), this reduces the utilisation factor (ρ) from an overloaded operating regime (1.05) to a stable level (0.74). At the same time, the increase in the service rate (μ) to 2.54 vehicles/h/channel results from the introduction of digital slot allocation, which standardises vehicle arrival intervals and reduces organisational delays. The reduction in the coefficients of variation (c_s from 0.60 to 0.25 and c_a from 1.00 to 0.35) reflects the positive effect of the digitalisation of border service procedures. Consequently, decreases to 4.8-7.2 hours, representing a ten- to fifteen-fold reduction compared with the baseline scenario. In the optimistic scenario (S2), the further reduction of the arrival rate (λ) to 15.9 vehicles/h is achieved through the active use of a border logistics hub and intermodal transport routes, reducing the ρ to 0.63 and the to 2.3-4.1 hours. The difference between the baseline scenario (S0) and the conservative scenario (S1) exceeds 65 hours, corresponding to a reduction of more than 90%, thereby confirming the practical effectiveness of the proposed mechanism. Table 2 specifies the application of the proposed mechanism to actual international road border crossing points.

Table 2. Classification of IRBCP by service system utilisation level

IRBCP category	Characteristics	Value ρ	Recommended action
Donor IRBCP (overloaded)	Exceeds service capacity; persistent growth in vehicle queues and waiting times	$\rho > 1$	Redirection of part of the freight flow to reserve IRBCPs
Critically loaded	High utilisation level; close to critical operating conditions; periodic congestion and delays may occur	$0.85 \leq \rho \leq 1$	Partial balancing of freight flows and stricter monitoring
Recipient IRBCP (reserve)	Available reserve service capacity; capable of accommodating additional traffic flow without the risk of congestion	$\rho < 0.85$	Acceptance of additional freight flow

Source: compiled by the author based on Solidarity lanes: Latest figures… (2025a; 2025b; 2025c), Ministry for Development of Communities and Territories of Ukraine (n.d.)

Table 2 presents the classification of IRBCPs according to the level of service system utilisation, establishing threshold values of the utilisation factor (ρ), the characteristics of each category of border crossing point, and the corresponding management measures: redirecting part of the freight flow to reserve IRBCPs, partial freight flow balancing with enhanced monitoring, or accommodating additional freight traffic. The Krakovets-Korczowa IRBCP, with $\rho \approx 1.05$, represents the highest priority for traffic redistribution. The Rava-Ruska-Hrebenne and Yahodyn-Dorohusk IRBCPs operate within the critically loaded range ($\rho \approx 0.88$-0.95). For these crossing points, enhanced monitoring involves increasing the frequency of data updates to once per hour and automatically generating an alert for the traffic management centre whenever ρ increases by 0.05 compared with the previous measurement. The recipient IRBCPs on the Hungarian corridor – Luzhanka-Beregsurány, Chop-Záhony, and Uzhhorod-Vyšné Nemecké – operated with average utilisation factors of approximately $\rho \approx 0.55$-0.70, indicating substantial reserve service capacity for accommodating redirected freight flows. A comparison of the principal system performance indicators under the three scenarios (S0, S1, and S2) is presented in Figure 3.

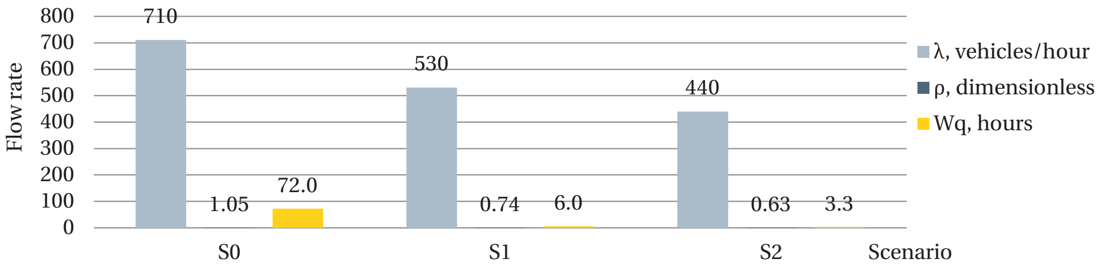

Figure 3. Graphical comparison of key performance indicators for the IRBCPs

Source: compiled by the author

Figure 3 demonstrates that freight flow balancing reduces traffic intensity from 710 to 530 and 440 vehicles/h under scenarios S1 and S2, respectively. This is accompanied by a reduction in the utilisation factor from 1.05 to 0.74 and 0.63, together with a decrease in the average waiting time from 72.0 hours to 6.0 and 3.3 hours, indicating a substantial improvement in the operational stability of IRBCPs. The practical implementation of the proposed balancing mechanism involves integrating digital traffic monitoring systems, the e-Queue system, the e-CMR electronic consignment note system, and a decision-support module into a unified information and analytical platform for managing international freight transport (Regulation (EU) 2020/1056, 2020; United Nations Economic Commission for Europe, 2025). The border logistics hub represents the key organisational and technological component of the proposed mechanism. Rather than constructing a new dedicated facility, the concept involves the functional repurposing of existing infrastructure, including warehouse complexes, customs terminals, and temporary storage facilities located within 20-50 km of an IRBCP. The adaptive vehicle redirection algorithm implemented at the logistics hub operates as follows. Upon vehicle arrival, the system retrieves the current ρ for all available IRBCPs, calculates the for each alternative route, and provides the driver with a recommendation specifying the optimal IRBCP, the estimated average , and the recommended route. Synchronisation of border-crossing time slots is achieved through integration between the logistics hub and the e-Queue system, allowing vehicles to receive a confirmed crossing slot at the selected IRBCP while still at the hub, thereby eliminating unproductive waiting near the border. The intermodal capability of the hub is ensured through the availability of railway sidings or the organisation of road-to-rail transhipment operations for freight that can be redirected to rail border crossings with lower utilisation levels (Solidarity Lanes: Latest Figures, 2025c; Ministry for Development of Communities and Territories of Ukraine, n.d.). A practical example is the rerouting of freight from the Krakovets-Korczowa crossing to the Luzhanka-Beregsurány IRBCP. The additional detour cost is approximately EUR 216, corresponding to more than 300 km of additional travel. The economic benefit of freight flow balancing is:

$$\Delta E_b = C_{delay} - C_{detour}, \quad (4)$$

where ΔE_b – the economic benefit of balancing, EUR; C_{delay} – the cost of vehicle delay while queuing; C_{detour} – the additional cost incurred when travelling via an alternative IRBCP.

With the average daily cost of freight vehicle downtime estimated at EUR 400-600 and $W_q \geq 72$ hours, the total losses associated with vehicle delays amount to EUR 1,200-1,800, which is five to eight times greater than the additional detour costs. A similar effect is observed for the Rava-Ruska-Yahodyn and Uzhhorod-Chop routes. These findings should be considered in the context of related research in order to assess the contribution of the proposed mechanism and identify promising directions for further development. The approach proposed in this study is conceptually consistent with the work of I. Badi *et al.* (2026), in which queueing theory is combined with MCDM to optimise border crossing operations. The principal distinction is that the cited study focuses on the static evaluation of the configuration of a single border crossing point, whereas the mechanism proposed here provides dynamic, real-time management of a system of interconnected IRBCPs. R.S. Sakhare *et al.* (2024) proposed a methodology for monitoring delays at road border crossing points using connected vehicle data, enabling the estimation of waiting times, the ranking of IRBCPs according to their utilisation levels, and the support of operational decision-making for border traffic management. The application of the , rather than relying solely on the minimisation of travel time, makes it possible to incorporate economic, reliability, and environmental considerations that are particularly relevant to international freight transport. The results of the scenario analysis, which reduced from more than 72 hours to 2.3-7.2 hours, are comparable with the benefits of adaptive optimisation in hub-and-spoke transport networks reported by M. Karimi-Mamaghan *et al.* (2020), M.H. Akyüz *et al.* (2023), and J. Zhang *et al.* (2024). However, as noted by W. Xu *et al.* (2021) and J. Wu *et al.* (2023), the specific characteristics of border service systems, where ρ may exceed 1 and the system therefore operates beyond the assumptions of conventional optimisation models, require the application of queueing theory. This constitutes a methodological advantage of the present study over approaches based exclusively on optimisation techniques. The findings concerning digitalisation, specifically the reduction of the service time coefficient of variation (c_s) from 0.60 to 0.25 in Scenario S1, are consistent with the conclusions of H.S. Sternberg *et al.* (2021), who emphasised the critical role of inter-organisational integration. Their research demonstrated that digital solutions achieve maximum effectiveness only when customs authorities, freight carriers, and IRBCP operators are fully synchronised. The practical experience of the e-Queue system fully supports this conclusion: its limited effectiveness at the Krakovets-Korczowa IRBCP is attributable primarily to insufficient organisational integration rather than to technical limitations of the digital platform itself (Ministry for Development of Communities and Territories of Ukraine, n.d.). The results regarding carriers' willingness to use alternative routes when the economic benefit ranges from EUR 550 to EUR 1,600 (the difference between C_{delay} and C_{detour}) are consistent with the findings of S. Sharma *et al.* (2021) and G. Cole *et al.* (2023). Forecasting W_q, provided by the decision-support module, is precisely the tool that enables freight carriers to make informed routing decisions before commencing their journey, as highlighted by these authors. Consequently, the proposed mechanism not only addresses the local problem of congestion at individual IRBCPs but also implements a system-wide approach to managing freight flows across border infrastructure, consistent with current trends in the development of adaptive logistics systems reported in the contemporary scientific literature.

Conclusions

As a result of the study, it was established that one of the principal causes of congestion at Ukraine's IRBCPs is the uneven distribution of freight flows across international transport corridors, causing queueing systems to enter an unstable operating regime. The operation of IRBCPs was formalised as multi-channel M/G/s queueing systems, and the influence of the utilisation factor ρ, arrival rate, and service time variability on the average queue waiting time (W_q) was substantiated. It was found that when $\rho \geq 1$, even the digitalisation of border crossing procedures is insufficient to stabilise traffic flow. An adaptive freight flow balancing mechanism between IRBCPs was developed, based on continuous monitoring of ρ, forecasting of W_q, digital decision-support systems, and adaptive traffic redirection using an integral efficiency criterion (I_e) that incorporates time, economic, reliability, service quality, and environmental delivery parameters. The results of the scenario modelling confirmed the effectiveness of the proposed mechanism, reducing the utilisation factor (ρ) of the Krakovets-Korczowa IRBCP from 1.05 to 0.63-0.74 and decreasing W_q from more than 72 hours to 2.3-7.2 hours, depending on the scenario. The economic benefits of traffic redirection exceed the additional detour costs by a factor of five to eight under the current level of congestion. Practical implementation through the establishment of a border logistics hub and adaptive routing does not require large-scale infrastructure reconstruction and could be implemented within 12-18 months. Future research should focus on the development of a dynamic model for forecasting the arrival rate (λ) using machine learning techniques to improve the accuracy of preventive freight flow balancing and to assess the risk of overloading recipient IRBCPs following traffic redistribution. Particular attention should also be given to investigating the behavioural factors influencing carriers' decisions when selecting alternative routes, as well as to developing regulatory mechanisms that encourage the voluntary redistribution of transport flows between alternative corridors.

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Conflict of Interest

None.

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Механізм балансування вантажопотоків між міжнародними автомобільними пунктами пропуску в умовах нерівномірного навантаження прикордонної інфраструктури

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Анотація. Структурна трансформація міжнародних транспортних потоків після 2022 року зумовила диспропорційний розподіл транспортного навантаження на міжнародні автомобільні пункти пропуску (МАПП) України, наслідком чого стали перевантаження окремих пунктів пропуску та тривалі черги. Метою статті стало обґрунтування механізму балансування вантажопотоків між міжнародними автомобільними пунктами пропуску з метою підвищення ефективності міжнародної доставки вантажів за умов нерівномірного навантаження прикордонної інфраструктури. Методологічну основу дослідження складав апарат теорії масового обслуговування (багатоканальна система типу M/G/s з апроксимацією Аллена-Куніна) у поєднанні з методами сценарного аналізу та нормалізованої багатокритеріальної оцінки, причому для забезпечення відтворюваності результатів введено окремий розділ з обґрунтуванням порядку отримання всіх ключових параметрів моделі (λ, μ, s, c_a, c_s). У статті досліджено проблему нерівномірного навантаження міжнародних автомобільних пунктів пропуску України в умовах структурної трансформації міжнародних транспортних потоків. Встановлено, що зміна географії зовнішньоторговельних маршрутів призвела до дисбалансу у використанні прикордонної інфраструктури, наслідком чого стало систематичне перевантаження окремих пунктів пропуску. Розроблено механізм адаптивного балансування вантажопотоків між МАПП на основі інтегрального критерію ефективності. Введено окремий розділ методології з обґрунтуванням порядку отримання параметрів моделі. Результати сценарного моделювання підтвердили ефективність: зниження ρ МАПП Краківець-Корчова з 1,05 до 0,63-0,74 та скорочення W_q із понад 72 до 2,3-7,2 години. Розроблений механізм дає змогу оперативно перерозподіляти вантажопотоки між МАПП без капітальних інвестицій в інфраструктуру, що суттєво знижує економічні втрати перевізників від тривалих простоїв на кордоні

Ключові слова: транспортно-технологічний процес; M/G/s; теорія масового обслуговування; логістика; єЧерга; цифровізація