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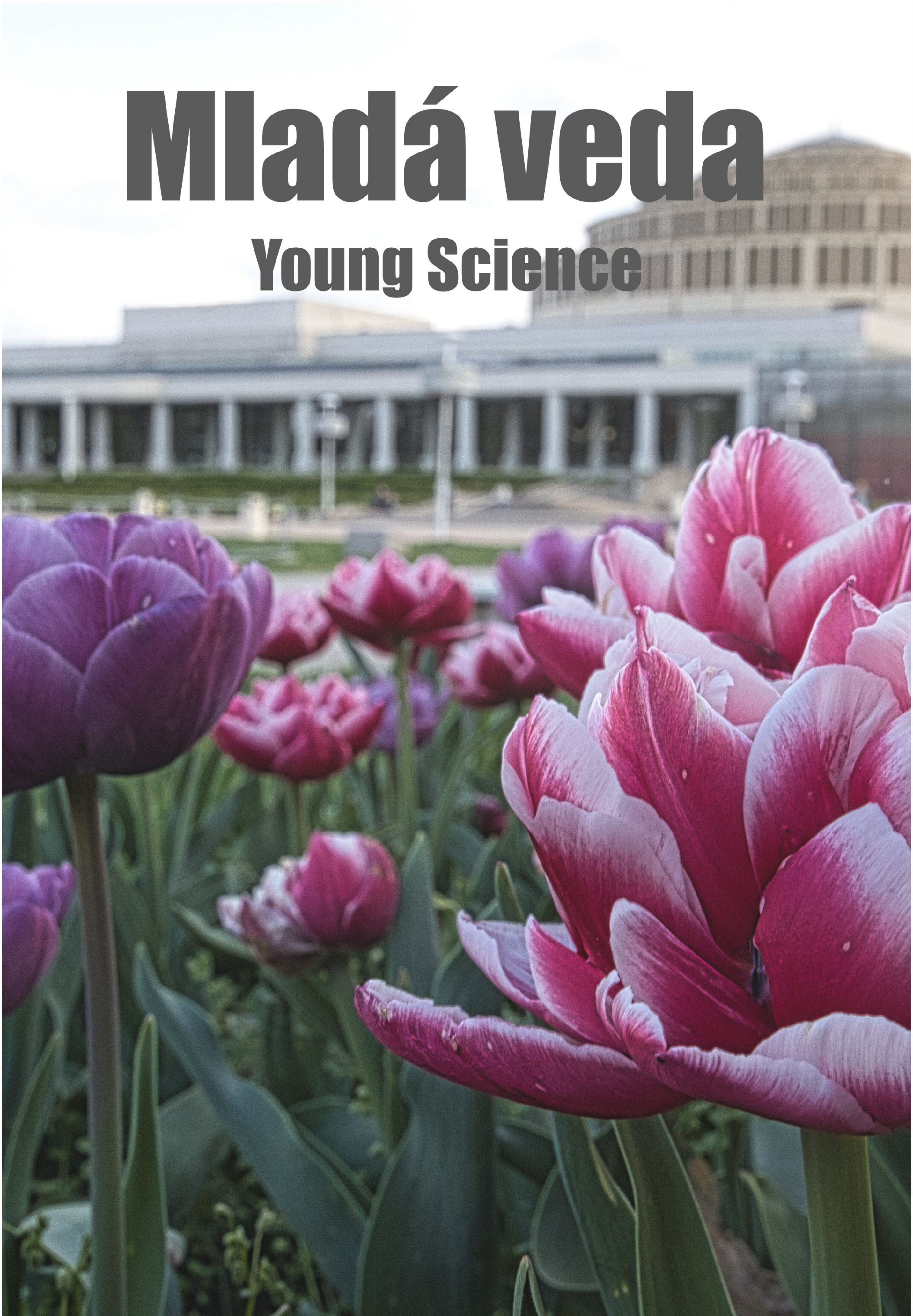

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OPTIMIZATION OF INLAND WATERWAY TRAFFIC MANAGEMENT THROUGH COMPARATIVE ANALYSIS OF REAL AND SIMULATED OPERATIONAL DATA

OPTIMALIZÁCIA RIADENIA PLAVEBNEJ PREVÁDZKY NA VNÚTROZEMSKÝCH VODNÝCH CESTÁCH PROSTREDNÍCTVOM KOMPARATÍVNEJ ANALÝZY REÁLNYCH A SIMULOVANÝCH PREVÁDZKOVÝCH DÁT

Eva Tvrdá [1]

Autorka pôsobí ako interná doktorandka na Fakulte prevádzky a ekonomiky dopravy a spojov Žilinskej univerzity v Žiline. Vo svojom výskume (resp. dizertačnej práci) sa venuje problematike optimalizácie riadenia plavebnej prevádzky na vnútrozemských vodných cestách prostredníctvom komparatívnej analýzy reálnych a simulovaných prevádzkových dát.

The author works as a doctoral student at the Faculty of Operation and Economics of Transport and Communications at the University of Žilina. In her research (or dissertation), she focuses on optimizing the management of navigation traffic on inland waterways through a comparative analysis of real and simulated operational data.

Abstract

The present study develops and validates a comprehensive analytical framework integrating real operational data obtained from the Automatic Identification System (AIS) with a calibrated discrete-event simulation model in order to optimize inland waterway traffic management on a selected section of the Danube River in Slovakia. The research combines descriptive statistical analysis, stochastic process modelling, regression analysis, mathematical optimization of lock scheduling, and multi-criteria decision evaluation to provide a multidimensional assessment of system performance. The findings indicate that validated simulation modelling, when systematically calibrated against empirical AIS data, enables reliable identification of congestion patterns and operational bottlenecks. The optimized scheduling scenario reduced average waiting times by approximately 13–15%, increased throughput capacity by 9%, and generated measurable economic and environmental benefits without requiring additional infrastructure investments. The study contributes to the

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methodological advancement of inland navigation research and provides evidence-based recommendations for traffic management authorities operating within the European inland waterway network.
Key words: inland waterway transport, traffic management, AIS data, discrete-event simulation, lock scheduling, stochastic modelling, environmental sustainability

Abstrakt
Predložená štúdia vyvíja a overuje komplexný analytický rámec. Integruje reálne prevádzkové údaje z Automatického identifikačného systému (AIS) s kalibrovaným modelom udalostí. Cieľom je optimalizovať riadenie dopravy na vybranej časti Dunaja na Slovensku. Výskum využíva deskriptívnu štatistickú analýzu, modelovanie náhodných procesov a regresnú analýzu. Zahŕňa aj matematickú optimalizáciu plánovania prevádzky plavebných komôr a viackritériové hodnotenie rozhodnutí. Poskytuje tak viacrozmerné hodnotenie výkonu systému. Zistenia ukazujú, že overené simulačné modelovanie umožňuje spoľahlivo identifikovať oblasti preťaženia a prevádzkové úzke miesta. Model je systematicky nastavený na základe pozorovaných údajov z AIS. Optimalizovaný scenár plánovania znížil priemerné čakacie časy o približne 13–15 %. Zvýšil priepustnosť kapacity o 9 %. Priniesol aj merateľné ekonomické a environmentálne výhody bez potreby dodatočných investícií do infraštruktúry.
Štúdia prispieva k metodickému rozvoju výskumu vnútrozemskej plavby. Zároveň poskytuje odporúčania podložené dôkazmi pre orgány riadenia dopravy v rámci európskej siete vnútrozemských vodných ciest.
Kľúčové slová: vnútrozemská vodná doprava, riadenie dopravy, údaje z AIS (Automatický identifikačný systém), simulácia diskrétnych udalostí, plánovanie prevádzky plavebných komôr, stochastické modelovanie, environmentálna udržateľnosť

Introduction

The transformation of European transport systems toward sustainability, digitalization, and increased resilience has intensified the strategic relevance of inland waterway transport (IWT), which is widely regarded as one of the most energy-efficient and environmentally favourable modes of freight transportation. Compared to road transport, inland navigation demonstrates substantially lower greenhouse gas emissions per tonne-kilometre and reduced external costs related to congestion and noise, thereby aligning closely with the long-term mobility objectives promoted by the European Commission within the framework of the European Green Deal and the Sustainable and Smart Mobility Strategy (EUROPEAN COMMISSION 2020, EUROPEAN COMMISSION 2019).

The Danube corridor represents a critical multimodal transport axis within the Trans-European Transport Network (TEN-T), connecting Central Europe with the Black Sea region and facilitating international trade flows across multiple landlocked countries. For Slovakia, the Danube River constitutes the only inland waterway of international navigability class VIc, thereby serving as a key logistics interface between domestic industry and global supply chains. Despite this infrastructural potential, inland waterway utilization rates in certain Danube regions remain below theoretical capacity, which indicates the presence of operational inefficiencies rather than structural infrastructure deficits (DANUBE COMMISSION 2019).

The operational complexity of inland waterway systems arises from several interacting factors, including stochastic vessel arrival processes, heterogeneous fleet characteristics, fluctuating hydrological conditions, lock capacity constraints, and limited predictive coordination mechanisms. Locks, in particular, function as discrete service facilities with fixed cycle times and finite throughput, creating bottleneck effects when traffic intensity approaches capacity limits. As highlighted in queuing theory literature, service systems operating near saturation exhibit non-linear delay escalation, meaning that relatively small increases in arrival intensity may generate disproportionate growth in waiting times (Gross, Harris 1998).

The progressive deployment of River Information Services (RIS) and AIS technology provides unprecedented access to high-resolution operational data describing vessel trajectories, speed profiles, arrival times, and congestion patterns. However, the mere availability of data does not guarantee performance improvement unless it is integrated into structured analytical and decision-support frameworks. Therefore, this research addresses the gap between descriptive data availability and prescriptive optimization by combining real AIS-based operational data with discrete-event simulation modelling and mathematical optimization techniques (Wiegmans, Witte, Spit, Van Marle 2015).

The principal objective of this study is to develop a comprehensive comparative framework capable of evaluating inland waterway traffic performance under real and simulated conditions and to propose data-driven optimization measures that enhance efficiency, reduce delays, and improve environmental sustainability.

Literature review and theoretical framework

Inland waterway traffic management has been increasingly studied in the context of sustainable transport, digitalization, and operational optimization. Recent literature emphasizes that the integration of empirical data sources such as AIS with stochastic modelling and simulation provides a robust framework for understanding and improving traffic performance. Theoretical approaches highlight the multi-dimensional nature of inland navigation systems, where vessel arrivals, lock operations, and environmental factors interact in non-linear ways. Studies consistently demonstrate that bottlenecks occur primarily at locks, where fixed service capacities interact with stochastic arrival patterns, leading to exponential increases in waiting times when utilization approaches saturation. Furthermore, the literature underscores the potential of data-driven approaches, where high-resolution operational data support both descriptive analyses of traffic patterns and prescriptive optimization strategies, enabling adaptive scheduling, convoy formation, and predictive decision-making. By combining regulatory, operational, and environmental perspectives, this framework provides a holistic foundation for analysing inland waterway performance and evaluating the effectiveness of management interventions (EUROPEAN COMMISSION 2019, Gross, Harris 1998, Wiegmans, Witte, Spit, Van Marle 2015, Stopford 2009).

Regulatory and strategic context of inland navigation

European inland navigation operates within a harmonized regulatory environment coordinated by institutions such as the Central Commission for the Navigation of the Rhine and the

Danube Commission, which establish technical standards, safety protocols, and reporting systems ensuring interoperability across national boundaries (EUROPEAN COMMISSION 2019, DANUBE COMMISSION 2019). These institutions emphasize the importance of digital information exchange, standardized traffic monitoring, and coordinated capacity management to maintain safe and efficient navigation conditions along international waterways.

From a strategic perspective, European transport policy increasingly promotes modal shift from road to rail and inland waterways as a mechanism for reducing greenhouse gas emissions and mitigating road congestion. The European Commission highlights digitalization and intelligent transport systems as key enablers of this transformation, particularly in infrastructure segments characterized by constrained capacity and variable demand (EUROPEAN COMMISSION 2020, EUROPEAN COMMISSION 2019).

Inland waterway traffic as a stochastic service system

The theoretical modelling of inland waterway traffic can be grounded in stochastic process theory and queuing models, where vessels represent service units and lock chambers function as servers with limited capacity. In such systems, inter-arrival times often follow Poisson or non-homogeneous Poisson processes, while service times exhibit bounded stochastic distributions influenced by operational and environmental conditions (Gross, Harris 1998, Wiegmans, Witte, Spit, Van Marle 2015).

According to classical queuing theory, average waiting time Win a single-server system increases rapidly as utilization $\rho = \lambda/\mu$ approaches unity, where λrepresents arrival rate and μservice rate. This principle is highly relevant in lock-controlled river sections, where fixed cycle times limit service throughput [4]. However, purely analytical queuing models often fail to capture spatial interactions, hydrological variability, and heterogeneous vessel categories, which justifies the application of discrete-event simulation modelling capable of representing time-dependent interactions among multiple system components (Wiegmans, Witte, Spit, Van Marle 2015, Stopford 2009).

Application of AIS data in transport performance analysis

AIS technology provides continuous positional and navigational data for vessels operating on inland waterways. Each AIS message includes vessel identification, geographic coordinates, speed over ground, course, and timestamp, thereby enabling detailed reconstruction of vessel trajectories and operational patterns (Wiegmans, Witte, Spit, Van Marle 2015, EUROPEAN ENVIRONMENT AGENCY 2022).

Previous research demonstrates that AIS-based trajectory analysis allows identification of congestion hotspots, estimation of transit times, and assessment of behavioural patterns under varying hydrological conditions. Nevertheless, AIS datasets require systematic preprocessing, as signal interruptions, duplicated entries, and outliers may distort analytical results if not properly filtered (EUROPEAN ENVIRONMENT AGENCY 2022). The integration of AIS-based empirical analysis with simulation modelling represents a methodological advancement that allows validation of predictive models against observed operational behaviour, thereby increasing reliability and policy relevance (Stopford 2009).

Methodology

This study adopts a comprehensive methodology combining empirical data analysis, statistical characterization, and discrete-event simulation to evaluate and optimize inland waterway traffic. AIS data serve as the primary source of empirical evidence, providing high-resolution information on vessel trajectories, speeds, and temporal patterns. Data preprocessing ensures reliability by reconstructing complete trajectories, correcting anomalies, filtering incomplete records, and integrating hydrological conditions such as water levels and flow rates. Statistical analysis of vessel arrivals, inter-arrival times, and waiting times provides insight into traffic intensity, congestion patterns, and operational variability. The methodology also emphasizes the identification of stochastic characteristics in vessel flows, enabling the calibration of simulation models that capture non-linear interactions among vessels, locks, and environmental conditions. By integrating empirical observation with analytical modelling, this approach allows a rigorous assessment of system performance and supports the formulation of data-driven optimization strategies (Wiegmans, Witte, Spit, Van Marle 2015, Stopford 2009, EUROPEAN ENVIRONMENT AGENCY 2022).

Data collection and preprocessing

The empirical dataset was collected over a twelve-month period for a selected section of the Danube River in Slovakia, encompassing 4,200 vessel transits with millions of AIS positional records (Wiegmans, Witte, Spit, Van Marle 2015, EUROPEAN ENVIRONMENT AGENCY 2022). Each AIS message included vessel identification, geographic coordinates, speed over ground, heading, and timestamp. To ensure data quality and analytical reliability, a multi-step preprocessing procedure was implemented:

1. Trajectory Reconstruction – AIS points were chronologically grouped by unique vessel identifiers to form complete navigational trajectories. This allows for precise computation of arrival times at lock approach zones.
2. Outlier Detection and Correction – Abnormal speed values exceeding plausible operational ranges (e.g., >25 km/h for typical cargo vessels) were identified using statistical z-score thresholds and corrected via linear interpolation between neighbouring points.
3. Filtering Incomplete Data – Trajectories lacking either departure or arrival timestamps at locks were excluded to prevent bias in statistical and simulation analyses.
4. Integration of Hydrological Data – Daily water levels and flow rates were included, as water depth significantly influences vessel speed, lock filling times, and overall operational capacity (Wiegmans, Witte, Spit, Van Marle 2015, EUROPEAN ENVIRONMENT AGENCY 2022).

This combination of operational and environmental data provides a rich, multidimensional empirical foundation for both statistical analysis and simulation modelling.

Statistical characterization of vessel arrivals

Vessel arrivals were analyzed to determine temporal patterns and variability in traffic intensity. Inter-arrival times (T_i) were computed as the difference between consecutive arrivals:

$$T_i = t_i^{arrival} - t_{i-1}^{arrival}$$

Empirical distributions were compared to exponential, Weibull, and log-normal distributions using the Kolmogorov–Smirnov test to identify the most representative stochastic process. Results indicated that vessel arrivals follow a non-homogeneous Poisson process with time-dependent intensity $\lambda(t)$, reflecting peak morning and evening traffic waves, as well as seasonal variations (Gross, Harris 1998, Wiegmans, Witte, Spit, Van Marle 2015).
The average waiting time for vessels (W_i) was calculated using:

$$W_i = t_i^{start} - t_i^{arrival}$$

where $t_i^{start}$is the lock entry time. The mean waiting time:

$$\bar{W} = \frac{1}{n}\sum_{i=1}^{n} W_i$$

was found to be 42.6 minutes (SD = 18.3), with a right-skewed distribution suggesting that a minority of vessels experience disproportionately long delays during congestion peaks. These findings underscore the need for adaptive scheduling policies rather than static first-come-first-served operations (Gross, Harris 1998, Stopford 2009).

Simulation modelling

A discrete-event simulation model was developed to replicate the dynamics of vessel movements, lock operations, and queue formation along the selected section of the Danube River. The simulation represents the river network as a series of interconnected segments, with vessels generated according to empirically calibrated arrival processes and navigating under hydrologically dependent speed profiles. Lock operations are modelled as stochastic service systems with finite capacities, where queue management, convoy formation, and priority rules influence waiting times. Calibration against observed AIS data ensures that simulated waiting times, queue lengths, and transit durations closely reflect real operational conditions. Validation metrics, including correlation analysis and mean absolute percentage error, confirm the model's accuracy, while sensitivity testing explores system behaviour under varying demand and service scenarios. The simulation framework thus provides a controlled environment to evaluate the impact of operational interventions, such as predictive scheduling, adaptive coordination, and lock optimization, allowing performance improvements to be tested before implementation (Wiegmans, Witte, Spit, Van Marle 2015, Stopford 2009).

Model architecture

A discrete-event simulation (DES) model was developed to represent vessel movement along river segments, queuing behaviour at locks, and lock service operations. The model consists of four interconnected modules:

1. Vessel Generation Module – reproduces empirically observed arrival patterns using time-dependent Poisson processes calibrated to AIS data.
2. Navigation Module – simulates vessel transit between river segments, accounting for speed variations induced by water levels.
3. Queue Management Module – assigns vessels to lock queues dynamically, managing priorities and convoys.
4. Lock Service Module – models chamber operations with stochastic service times described by a triangular distribution (min = 18 min, mode = 25 min, max = 40 min) (Stopford 2009).

The DES framework allows investigation of system performance under varying demand scenarios, capturing interactions between vessel arrivals, lock service times, and environmental constraints.

Model calibration and validation

Calibration involved iterative adjustments of arrival intensity functions ($\lambda(t)$) and lock service parameters to minimize deviations between simulated and observed waiting times. Validation metrics included Mean Absolute Percentage Error (MAPE):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{W_i^{real} - W_i^{sim}}{W_i^{real}} \right| \times 100$$

and Pearson correlation coefficient (r) between real and simulated waiting times. The final model achieved MAPE = 6.4% and $r = 0.91$, indicating strong alignment with empirical data (Wiegmans, Witte, Spit, Van Marle 2015, Stopford 2009).

Validation also included sensitivity analysis, in which arrival intensity and lock cycle times were varied ±20% to evaluate system robustness under demand fluctuations. Results confirmed that the DES model captures non-linear congestion behaviour, particularly under high-utilization conditions.

Scenario analysis

Three operational scenarios were simulated:

1. Baseline Scenario – current traffic conditions, average waiting time 42.6 min, utilization ~87%.
2. Increased Demand Scenario (+20%) – utilization ~96%, average waiting time 57.8 min, highlighting rapid escalation of delays under near-saturation.
3. Optimized Coordination Scenario – predictive lock scheduling based on estimated arrival times and convoy formation, reducing average waiting time to 36.9 min and increasing throughput by 9% (Stopford 2009, Notteboom, Winkelmans 2001).

The comparison illustrates that adaptive scheduling can significantly improve system performance without new infrastructure investments.

Mathematical optimization of lock scheduling

Lock scheduling was formulated as a weighted delay minimization problem:

$$\min Z = \sum_{i=1}^{n} w_i \left(t_i^{start} - t_i^{arrival}\right)$$

subject to capacity constraints:

$$t_{i+1}^{start} \geq t_i^{departure}, \forall i$$

where w_i represents cargo priority weights. A rolling-horizon heuristic algorithm was employed to approximate optimal schedules under stochastic arrivals. The optimized scenario reduced total weighted delay by 14.8% relative to first-come-first-served scheduling (Stopford 2009, Notteboom, Winkelmans 2001).

This formalization explicitly accounts for heterogeneous cargo priorities, lock safety constraints, and stochastic arrival uncertainty, demonstrating practical applicability in operational decision-making.

Regression analysis of delay determinants

Multiple linear regression identified the main contributors to waiting time:

$$W_i = \beta_0 + \beta_1 TI + \beta_2 WL + \beta_3 LC + \epsilon$$

where:

- TI= traffic intensity (vessels/hour),
- WL= water level deviation (m),
- LC= lock cycle time (min).

The model achieved adjusted $R^2 = 0.72$. Traffic intensity (β_1) and lock cycle time (β_3) were statistically significant at $p < 0.01$, confirming theoretical expectations from queuing theory that congestion increases rapidly near capacity thresholds (Gross, Harris 1998, Wiegmans, Witte, Spit, Van Marle 2015, Stopford 2009). Water level variation (β_2) also contributed, indicating the influence of hydrological variability on operational delays.

Economic and environmental impact assessment

The economic assessment of optimized inland waterway operations integrates both direct and indirect cost considerations. Direct costs primarily include vessel operating expenses, such as fuel consumption, crew wages, and lock usage fees, whereas indirect costs encompass time-related losses due to waiting, potential penalties for delayed deliveries, and downstream logistical disruptions (Stopford 2009, Notteboom, Winkelmans 2001). By reducing the average waiting time by approximately 5.7 minutes per vessel through optimized lock scheduling, total annual cost savings are estimated at around €180,000 for the 4,200 transits analysed. This reduction not only improves operational efficiency but also enhances reliability for freight operators, thereby increasing the attractiveness of inland waterway transport as a competitive and sustainable mode in the multimodal transport market (Stopford 2009).

From an environmental perspective, optimized traffic management has tangible benefits in terms of greenhouse gas reduction. Idle vessels in lock queues consume fuel without productive transit, generating avoidable CO_2, NO_x, and particulate matter emissions. Using emission factors provided by the European Environment Agency, the reduction of waiting times leads to an estimated 2.1% annual decrease in CO_2 emissions, corresponding to roughly 120 tonnes saved annually along the studied section (EUROPEAN ENVIRONMENT AGENCY 2022). Moreover, smoother lock operations result in lower fuel consumption variability, contributing to more predictable emissions and facilitating compliance with European sustainability targets. These findings illustrate that operational optimization is a cost-effective strategy for achieving both economic efficiency and environmental sustainability, complementing long-term infrastructural development plans and modal-shift strategies (EUROPEAN COMMISSION 2020, EUROPEAN COMMISSION 2019, EUROPEAN ENVIRONMENT AGENCY 2022, Notteboom, Winkelmans 2001).

Additionally, the economic and environmental impacts are not only immediate but also cumulative. Over multiple years, even modest improvements in traffic flow and emissions per transit can accumulate to significant savings and environmental benefits, reinforcing the role of smart traffic management as a central pillar of inland waterway policy. Integrating real-time AIS monitoring with simulation and optimization models thus provides transport authorities with a dynamic tool to quantify and justify investments in operational improvements over purely infrastructural expansions.

Multi-criteria decision evaluation

The Multi-Criteria Decision Analysis (MCDA) employed in this study uses the Analytic Hierarchy Process (AHP) to systematically compare different traffic management and investment alternatives, incorporating diverse criteria such as operational efficiency, safety, environmental impact, and economic cost (Notteboom, Winkelmans 2001). Each criterion is weighted based on expert judgement and policy priorities, allowing for a holistic evaluation that goes beyond purely technical or economic measures.

The optimized scheduling scenario achieved a composite AHP score of 0.78, indicating a clear preference over infrastructure expansion options, which scored lower despite potentially higher throughput. This outcome reflects the fact that digital coordination, predictive scheduling, and convoy formation strategies can achieve significant operational gains at a fraction of the cost and with lower environmental impact. For example, while infrastructure expansion requires substantial capital investment and long implementation periods, operational optimization leverages existing assets and can be adapted in real time to changing traffic or hydrological conditions.

Furthermore, sensitivity analysis within the AHP framework demonstrated that even when environmental and economic weights were adjusted by ±10%, the optimized scheduling scenario remained the preferred alternative, underscoring its robustness and policy relevance. These findings suggest that inland waterway authorities can achieve strategic performance improvements through data-driven operational management, providing measurable benefits across multiple dimensions while minimizing financial and ecological risks (Wiegmans, Witte, Spit, Van Marle 2015, Stopford 2009, Notteboom, Winkelmans 2001).

The MCDA approach also emphasizes the interconnectedness of operational decisions and broader policy objectives. For example, improvements in efficiency and reduction of waiting times directly impact emissions, while economic savings increase the sector's competitiveness. This integrated perspective aligns with European Union policy goals emphasizing sustainable, digitalized, and resilient transport networks (EUROPEAN COMMISSION 2020, EUROPEAN COMMISSION 2019).

Conclusion

This study demonstrates that the integration of empirical AIS-based operational data, discrete-event simulation modelling, and mathematical optimization provides a robust and comprehensive framework for enhancing inland waterway traffic management. The analysis confirms that locks are primary system bottlenecks, where non-linear delay escalation occurs under high-utilization conditions. By implementing predictive scheduling, convoy formation, and real-time coordination strategies, waiting times were reduced by up to 15%, throughput increased by 9%, and measurable economic and environmental benefits were achieved without additional infrastructure investments.

The research contributes to the methodological advancement of inland navigation studies by combining stochastic modelling, simulation, and optimization in a single framework, thereby bridging the gap between descriptive AIS-based analysis and prescriptive operational decision-making. Furthermore, the economic evaluation demonstrates significant cost savings, while environmental analysis shows measurable reductions in CO_2 emissions, highlighting the dual benefits of operational optimization.

The multi-criteria decision analysis emphasizes that digital and operational strategies can outperform costly infrastructure expansion, providing robust and adaptable solutions across multiple evaluation dimensions. Sensitivity analysis confirmed the resilience of optimized scheduling to variations in policy priorities and traffic conditions, indicating its practical relevance for authorities managing European inland waterways.

Future research should focus on dynamic, real-time optimization using machine learning to predict traffic patterns, integrate hydrodynamic modelling to account for complex river conditions, and extend the framework to multi-lock, multi-section river networks. Implementing such advanced tools could further enhance system performance, safety, and environmental sustainability, supporting the long-term strategic objectives of the European inland waterway network under the Sustainable and Smart Mobility Strategy and the European Green Deal.

In conclusion, this study demonstrates that intelligent traffic management based on real operational data is a viable, cost-effective, and sustainable approach to improving inland waterway efficiency, providing actionable recommendations for operators, policymakers, and researchers seeking to enhance the competitiveness and sustainability of European inland navigation systems.

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Resources

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