Modelling, Simulation and Optimisation of Complex Systems in Maritime Transport

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Maritime transport systems represent complex socio-technical environments characterised by strong interdependencies between technical, organisational, environmental, and human subsystems, as well as by pronounced uncertainty and dynamic behaviour. Traditional deterministic planning approaches are often insufficient to adequately capture such complexity or to support robust operational decision-making. This paper examines the modelling and optimisation of complex maritime transport systems by integrating network-based optimisation and stochastic modelling approaches. The methodological framework combines operational research techniques with simulation in order to represent maritime transportation as a directed time–space network with stochastic demand and time windows. Uncertainty related to operational disturbances, port congestion, and variable demand is explicitly incorporated into the optimisation process. A case-oriented application demonstrates how stochastic network-based optimisation can improve routing, scheduling, and recovery strategies compared to purely deterministic approaches. The results indicate that controlled flexibility in arrival times and routing decisions leads to improved operational performance, enhanced resilience, and better trade-offs between fuel consumption, service reliability, and recovery costs. The proposed framework serves as a decision-support tool for maritime operations, providing structured analytical support, while preserving the role of human judgment in safety-critical environments. By bridging systems theory, operational research, and applied maritime modelling, the study contributes to the development of robust decision-support approaches for complex and uncertain maritime transport systems.

KEYWORDS
~ Complex systems
~ Marine transport optimisation
~ Network-based modelling
~ Stochastic time windows
~ Decision support systems

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1. INTRODUCTION

Complex systems have become an integral part of contemporary technological and organisational environments. They are characterised by a large number of interacting subsystems, nonlinear relationships, mixed uncertainties, and emergent behaviour that cannot be fully understood by analysing individual components in isolation. In engineering and transport systems, such complexity is further amplified by dynamic operating conditions, human factors, environmental influences, and economic constraints.

Maritime transport represents a particularly relevant example of a complex socio-technical system. Ships, ports, logistics networks, regulatory frameworks, and environmental conditions form an interconnected structure in which decisions made at one level may generate cascading effects throughout the entire system. While maritime transport is widely recognised for its cost efficiency and high capacity, increasing traffic density, stricter environmental requirements, and growing expectations regarding safety and reliability place significant pressure on traditional planning and management approaches.

In parallel with these developments, digitalisation has introduced new forms of system integration through networked data, interoperable platforms, and analytical tools. Digital ecosystems can be understood as network-based structures in which heterogeneous actors, processes, and data sources are interconnected in order to support operational coordination and optimisation (Buhalis, 2025). Within maritime and transport contexts, such ecosystems extend beyond user-oriented services and increasingly serve as analytical infrastructures for planning, monitoring, and decision support.

To address the challenges associated with growing system complexity, modelling, simulation, and optimisation methods have become essential tools in maritime system design and operation. Mathematical modelling enables the abstraction of real-world processes into analysable structures, allowing researchers and practitioners to explore alternative scenarios, evaluate system behaviour, and support decision-making under uncertainty. However, modelling complex dynamic systems inevitably requires simplifications, which raises questions about model validity, robustness, and practical applicability.

This paper approaches the problem of complex systems from a maritime perspective, with a focus on optimisation and operational research methods. Special attention is given to network-based modelling approaches applied to transportation and logistics, as well as to the integration of risk and uncertainty into decision-support frameworks. By combining theoretical foundations with applied modelling techniques, the paper aims to demonstrate how structured analytical methods can enhance efficiency, safety, and sustainability in maritime operations.

2. RESEARCH ISSUES AND OBJECTIVES

In engineering practice, ships and maritime transport systems consist of numerous interdependent subsystems whose interactions are influenced by technical, organisational, environmental, and human factors. These interactions are often subject to mixed uncertainties originating from incomplete information, stochastic demand, variable environmental conditions, and operational disturbances. As a result, conventional linear or deterministic approaches are frequently insufficient for capturing the real behaviour of maritime systems.

Recent literature highlights that digital and analytical tools increasingly play a role in structuring and coordinating such complex systems. However, the lack of terminological consistency and unified conceptual frameworks often complicates the comparison and evaluation of different digital and optimisation models. In response, efforts have been made to establish consensual definitions that link digital tools with functional system objectives, particularly in the context of complex, data-driven transport and tourism systems (Galvão et al., 2025).

The central research issue addressed in this paper is how complex maritime systems can be effectively modelled and optimised in order to support management decisions under uncertainty. Particular emphasis is placed on the application of operational research methods and network-based models for transportation optimisation, risk management, and recovery from disruptions in shipping networks.

The specific objectives of the paper are:

- to analyse the characteristics of maritime transport as a complex system with interconnected subsystems and nonlinear dynamics;
- to examine modelling and simulation approaches suitable for representing maritime logistics and transport networks;

- to demonstrate the application of optimisation techniques, including network diagrams and stochastic modelling, in maritime transportation planning;
- to evaluate the role of risk and uncertainty in decision-making processes within shipping systems;
- to illustrate, through applied examples, how optimisation models can improve operational efficiency, safety, and economic performance.

By addressing these objectives, the paper seeks to contribute towards the understanding of complex system modelling in the maritime domain and to provide a structured analytical framework that bridges theoretical concepts and practical applications.

3. METHODOLOGY AND MODELING APPROACH

This study adopts a systems-oriented methodological framework that combines mathematical modelling, simulation, and optimisation techniques to analyse complex maritime transport systems under uncertainty. Given the nonlinear structure, interdependencies, and stochastic behavior inherent in maritime operations, a purely deterministic approach is insufficient. Instead, the methodology integrates operational research methods and network-based models to support decision-making in complex and dynamic environments.

The methodological positioning of this research aligns with the concept of digital ecosystems, in which complex operational environments are represented as interconnected networks of processes, data flows, and decision nodes. Such ecosystems provide a suitable analytical foundation for modelling maritime transport systems as structured networks, enabling formal representation of dependencies, constraints, and alternative operational paths (Buhalis, 2025).

The research methodology is structured around three main components:

(i) conceptual modelling of the maritime system as a complex network,
(ii) formulation of optimisation problems using operational research techniques, and
(iii) simulation-based evaluation of alternative scenarios under uncertainty.

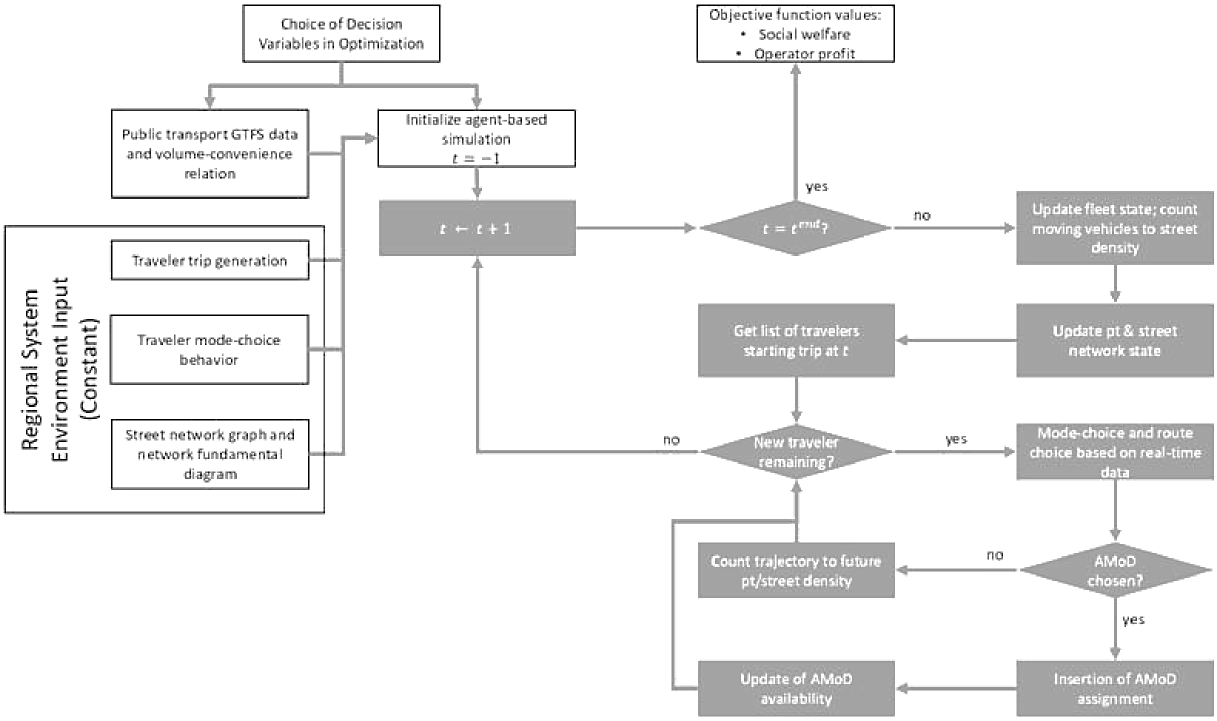


Figure 1. Optimisation framework for maritime routing under stochastic time windows. The framework integrates operational data, network-based modelling, optimisation, and simulation in order to support routing and scheduling decisions in maritime transport systems under uncertainty. Source: adapted from classical optimisation and simulation frameworks in operations research (Ahuja et al., 1988; Barković, 2001).

3.1. System Representation and Network Modelling

Maritime transport systems are represented as directed networks in which nodes correspond to ports, waypoints, or operational states, while links represent feasible movements or transitions between these states over time. Each node is defined by a spatial and temporal position, allowing the integration of both routing and scheduling dimensions into a unified modelling framework.

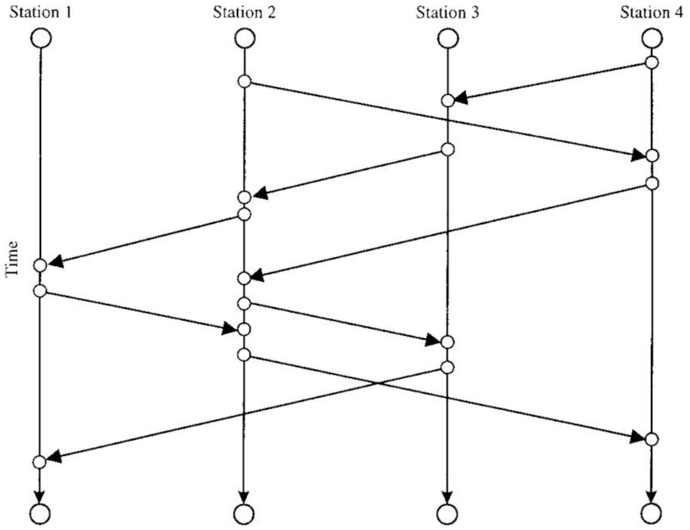


Figure 2. Directed time–space network representation of a maritime transport system. Nodes represent vessel states at specific ports and time instances, while directed links represent feasible sailing transitions between them. Source: adapted from Ahuja et al. (1988).

The maritime transport system can be represented as a directed network structure in which nodes correspond to ports or operational states, and links represent feasible vessel movements.

The conceptual representation of such a system is illustrated in Figure 1.

This network-based representation is consistent with contemporary digital system models, where interoperable components and data flows form the basis for analytical optimisation and decision support. By adopting such a representation, the model captures both physical transport processes and information-driven coordination mechanisms within maritime operations.

3.2. Optimisation Formulation

Based on the network representation, optimisation problems are formulated with the objective of minimising total operational costs while satisfying technical, operational, and regulatory constraints. The objective function typically includes fuel consumption costs, penalties associated with delays, and penalties related to missed connections or disrupted cargo flows.

Decision variables represent controllable operational parameters such as route selection, sailing speed, and cargo allocation. Constraints ensure the feasibility of solutions by maintaining flow conservation for vessels and cargo, respecting port capacities, and enforcing scheduling and safety requirements.

The optimisation problem is formulated as a constrained network flow problem defined on a directed time–space network. The objective function minimises total operational costs, while feasibility is ensured through flow conservation, capacity, and temporal constraints. This formulation enables systematic evaluation of alternative routing and scheduling decisions within a unified analytical framework.

3.3. Incorporation of Uncertainty and Risk

Uncertainty is incorporated into the modelling framework through stochastic parameters related to demand variability, time windows, and operational disturbances. Rather than treating uncertainty as an external disturbance, the model explicitly integrates stochastic elements into the optimisation process.

This approach is consistent with recent analytical frameworks that use digital and AI-supported systems to enhance predictive capability and robustness, while preserving human responsibility for final decision-making (Koo et al., 2025).

Uncertainty is treated as an endogenous component of the model rather than as an external disturbance. Stochastic parameters related to demand variability and time windows are integrated directly into the optimisation framework, allowing the evaluation of solution robustness across multiple operational scenarios.

3.4. Simulation and Decision Support

Simulation is employed as a complementary tool to optimisation modelling, allowing the evaluation of system behaviour under different operational and environmental conditions without exposing real systems to risk. By combining optimisation results with simulation-based validation, the methodology supports informed decision-making and provides insights into system resilience and performance sensitivity.

The proposed methodological framework does not aim to replace human decision-makers, but rather to provide structured analytical support for complex operational choices. Optimisation and simulation results serve as decision-support inputs, enabling operators and managers to evaluate alternatives based on quantified criteria.

3.5. Methodological Positioning and Reference Framework

The methodological approach adopted in this study is grounded in established principles of systems theory, operational research, and maritime transport optimisation. Network-based modelling and optimisation techniques are widely recognised as effective tools for analysing complex transport and logistics systems, particularly in maritime environments characterised by interdependence, uncertainty, and dynamic behaviour.

Operational research methods, including linear and mixed-integer programming, have been extensively applied to maritime routing, scheduling, and resource allocation problems. In parallel, simulation-based approaches have proved valuable for evaluating system performance, reliability, and risk under stochastic and uncertain operating conditions.

The framework proposed in this paper is consistent with these established approaches, while extending them through an explicit integration of uncertainty, risk-oriented modelling, and network-based decision support. By combining optimisation and simulation within a unified methodological framework, the study contributes to a more robust, practically applicable analysis of complex maritime systems. Do not use any styles or automatic formatting, except those provided by the template itself. Fonts used for the preparation of this template are widely and freely available (within the scope of text editing tools such as Microsoft Word, LibreOffice, etc).

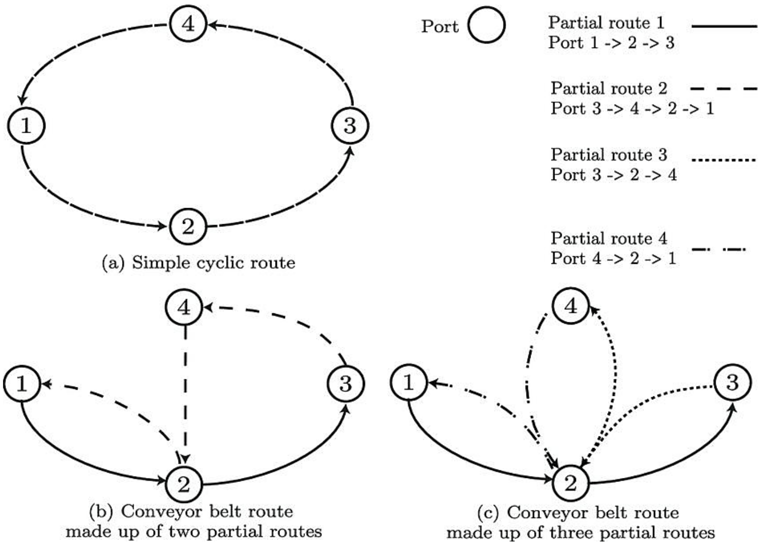
4. APPLICATION AND CASE STUDY: NETWORK-BASED MODEL WITH STOCHASTIC TIME WINDOWS

The proposed modelling framework is intended as a decision-support prototype rather than a universal optimisation solution. While the case study illustrates the applicability of the approach in a realistic maritime context, results should be interpreted as indicative rather than directly generalisable to all shipping networks or fleet configurations.

4.1. Problem Description and Modelling Framework

The case study addresses the problem of maritime transportation planning under uncertain operational conditions, with a particular focus on route optimisation, scheduling, and recovery from disruptions. The maritime transport system is modelled as a directed time–space network in which nodes represent vessel positions at specific ports and time instances, while links correspond to feasible sailing or operational transitions between these states.

Each node is defined by a triplet (vessel, port, time), enabling the integration of spatial and temporal dimensions within a unified modelling framework. Links represent possible vessel movements at different sailing speeds and along alternative routes, accounting for operational constraints and recovery options. The resulting directed network captures multiple feasible trajectories for vessels and cargo flows across the shipping system.



(a) Simple cyclic route

(b) Conveyor belt route made up of two partial routes

(c) Conveyor belt route made up of three partial routes

Figure 3. Example of Network-based routing alternatives in a maritime transport system. Source: adapted from classical network flow modelling approaches in maritime transport optimisation (Ahuja et al., 1988; Barković, 2001).

This modelling approach allows the representation of complex interdependencies between ships, ports, and cargo, while providing a structured basis for optimisation and simulation analyses.

Nodes represent ports and time states, while arcs represent feasible sailing routes. The optimisation model evaluates alternative vessel trajectories subject to stochastic time-window constraints.

4.2. Objective Function and Constraints

The optimisation objective is to minimise total operational costs associated with maritime transport operations. The objective function includes the following components:

- fuel consumption costs, representing a significant share of total operating expenses and strongly dependent on vessel speed and routing decisions;
- penalties for delayed cargo, reflecting loss of service quality, and reduced customer satisfaction;
- penalties for missed connections, accounting for operational disruptions and downstream effects within the transport network.

The optimisation problem is subject to a set of constraints ensuring solution feasibility:

- flow conservation constraints for vessels and cargo across ports and network nodes;
- port call constraints ensuring that scheduled port visits are either executed or explicitly omitted;
- capacity constraints related to vessel loading and port handling operations;
- temporal constraints linking arrival and departure times within defined time windows.

4.3. Incorporation of Stochastic Time Windows and Demand

To reflect real operational conditions, the model explicitly incorporates uncertainty through stochastic time windows and stochastic freight demand. Arrival and departure time windows are treated as random variables, capturing variability caused by weather conditions, port congestion, and operational disturbances.

Stochastic demand is modelled to account for fluctuations in cargo volumes and last-minute changes in transport requirements. By integrating these stochastic elements into the optimisation framework, the model allows the evaluation of system performance across multiple scenarios rather than relying on a single deterministic solution.

This approach improves the robustness of routing and scheduling decisions and provides greater flexibility in managing delays and recovery strategies.

4.4. Network Optimisation and Recovery Strategies

The directed time–space network enables the evaluation of recovery actions in response to operational disruptions, such as vessel delays or missed connections. Instead of removing delayed cargo from the model and assigning penalty costs only, the network structure allows alternative routing and rescheduling options to be explored.

Each container flow is represented by an independent subgraph, allowing the shortest path problem to be solved for each cargo unit under the given cost structure and constraints. Recovery strategies include speed adjustments, alternative port calls, and modified routing paths within the network.

Operations research techniques are applied to evaluate all feasible alternatives and identify cost-effective recovery solutions within a limited computation time. The optimisation model provides quantitative decision support, while preserving the role of human operators in the final decision-making process.

4.5. Case Study Results and Discussion

The case-oriented analysis demonstrates that incorporating stochastic time windows and stochastic demand into the network-based optimisation model improves operational performance compared to purely deterministic approaches. In particular, the results show that gross profit per day can be significantly increased by allowing controlled flexibility in arrival times and routing decisions, rather than attempting to strictly maintain fixed schedules through speed variation alone.

The findings indicate that stochastic modelling enables better trade-offs between fuel consumption, service reliability, and recovery costs. Moreover, the network-based framework effectively captures cascading effects caused by delays, providing valuable insights into system resilience and vulnerability.

5. DISCUSSION AND CONCLUSION

The results of the presented case study confirm that network-based optimisation models provide a suitable analytical framework for addressing the complexity of maritime transport systems. By explicitly incorporating uncertainty through stochastic time windows and demand variability, the proposed approach enables a more realistic representation of operational conditions and supports robust decision-making.

From a broader perspective, the findings align with technological trends identified in the context of sustainable blue economy development, where digital technologies, networked systems, and analytical tools are increasingly applied to improve efficiency, resilience, and sustainability of maritime operations (The role of technology in a sustainable blue economy, 2025).

Rather than enforcing strict adherence to fixed schedules, the model demonstrates that controlled flexibility in routing and timing can improve overall system performance. The proposed framework thus serves as a decision-support tool that complements, rather than replaces, human expertise in safety-critical maritime environments.

The findings also highlight the importance of network-based representations in capturing cascading effects within maritime transport systems. Delays and disruptions propagate across interconnected vessels and ports, and their impacts cannot be adequately assessed without a systemic view. Optimisation, combined with simulation, offers valuable insights into system resilience and vulnerability, particularly in environments characterised by high uncertainty and operational interdependence.

From a practical perspective, the proposed framework serves as a decision-support tool rather than a prescriptive solution. While optimisation models can efficiently evaluate alternative scenarios and quantify associated costs, final operational decisions remain the responsibility of human operators. This balance between analytical support and human judgement is especially important in safety-critical and dynamic maritime environments.

In conclusion, the paper demonstrates that integrating systems thinking, operational research, and stochastic modelling provides a robust and flexible approach to optimising complex maritime systems. The proposed methodology contributes to improved efficiency, safety, and economic performance in maritime operations and offers a foundation for further research into digital decision-support systems and adaptive maritime logistics.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

Ahuja, R.K., Magnanti, T.L. and Orlin, J.B., 1988. Network flows: Theory, algorithms and applications. Cambridge, MA: MIT Press

Barković, D., 2001. Operacijska istraživanja. Osijek: Ekonomski fakultet Osijek

Bilić, M., 2008. Optimizacija lučkih prekrcajnih procesa uporabom sistemske dinamike. Pomorstvo, 22(2), pp. 307–312

Bilić, M., Čovo, P. and Jašić, D., 2012. Optimizacija lučkih operacija. Zadar: Sveučilište Zadar

Buhalis, D., 2025. Smart tourism and digital ecosystems. In: Springer Reference Work on Tourism. Cham: Springer Nature, ch. 175

Dobrenić, S., 1975. Linearno programiranje. Varaždin: Fakultet organizacije i informatike

Galvão, A., Brito e Abreu, F. and Joanaz de Melo, J., 2025. Toward a consensual definition for smart tourism and smart tourism tools. In: Smart Tourism and Tools. Cham: Springer Nature

Golub, I., Antonić, R. and Dobrota, Đ., 2011. Optimizacija rada sustava brodskog separatora teškog goriva primjenom dijagnostičkih metoda zaključivanja. Pomorstvo, 25(1), pp. 173–188

Krile, S., 2013. Planiranje plovidbe s više luka ukrcaja i iskrcaja. Naše more, 60(1–2), pp. 21–24

Koo, C., Shin, S., Gretzel, U. and Xiang, Z., 2025. AI-powered smart tourism 2.0: A 10-year retrospective and updated model. Electronic Markets, 35(1), p. 108. Available at: https://doi.org/10.1007/s12525-025-00648-7

Nadrljanski, Đ. and Nadrljanski, M., 2014. Menadžment rizika. Split: Redak

Nadrljanski, Đ. and Nadrljanski, M., 2016. Teorija sustava i upravljanja. Split: Redak

Nadrljanski, Đ., Nadrljanski, M. and Pavlinović, M., 2021. Digitalno poslovanje u pomorstvu. Split: Redak

Nadrljanski, Đ., Nadrljanski, M. and Vidović, K., 2021. Teorija odlučivanja. Split: Redak

Niu, B., Yang, Z. and Li, L., 2022. Digital transformation in marine transportation: A systematic review. Computers in Industry, 139, 103811. Available at: https://doi.org/10.1016/j.compind.2022.103811

Selvaduray, M., Bandara, Y.M., Zain, R.M., Ramli, A. and Zain, M.Z.M., 2022. Bibliometric analysis of maritime tourism research. Australian Journal of Maritime & Ocean Affairs, 15(3), pp. 330–356. Available at: https://doi.org/10.1080/18366503.2022.2070339

Shinde, S., n.d. Solving transportation problem using linear programming. Available at: https://medium.com/@sohamshinde156/solving-transportation-problem-using-linear-programming-15a6ac1306f5 (Accessed: 29 April 2026)

The role of technology in a sustainable blue economy, 2025. In: Advances in Blue Economy Research. Cham: Springer Nature

Unknown author, n.d. Digital transformation in marine transportation. Available at: https://www.linkedin.com/pulse/digital-transformation-marine-transportation-mariner-update-ibigc (Accessed: 29 April 2026)

Unknown author, n.d. A systematic literature review on maritime transportation optimization using linear programming. Available at: https://www.academia.edu/114685318/A_Systematic_literature_review_on_maritime_transportation_optimization_using_linear_programming (Accessed: 29 April 2026)