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SUMMARY OF THE DOCTORAL THESIS

Cadru conceptual bazat pe inteligența artificială (AI) pentru lanțurile logistice: Integrarea transportului maritim, portuar și urban

AI-based framework for logistics chains: Integrated maritime, port, and urban transport

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LIST OF ABBREVIATIONS

3D	Three-dimensional
5G	Fifth generation
AAWA	Advanced Autonomous Waterborne Applications
AGV	Autonomous Ground Vehicle
AI	Artificial Intelligence
AIS	Automatic Identification System
AJOT	American Journal of Transportation
AM	Antemeridian
AOC	Ashore Operations Center
AR	Augmented Reality
ASV	Autonomous Surface Vehicle
BBC	British Broadcasting Corporation
CCTV	Closed Circuit Television
CO_2	Carbon Dioxide
COLREG	Convention on the International Regulations for Preventing Collisions at Sea
CPU	Central Processing Unit
DFFAS	Designing the Future of Full Autonomous Ship Project
DGPS	Differential Global Positioning System
EDI	Electronic Data Interchange
ENC	Electronic Nautical Charts
EO	Electro-Optic
ERP	Electronic Road Pricing
EV	Electric Vehicle
FAA	Federal Aviation Administration
FPGA	Field Programmable Gate Array
GA	Genetic Algorithm
GDPR	General Data Protection Regulation
GIS	Geographic Information System
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPU	Graphics Processing Unit
IMO	International Maritime Organization
IR	Infrared
ISO	International Organization for Standardization
IT	Information Technology
ITS	Intelligent Transport System
KPI	Key Performance Indicator
LA	Los Angeles

LB	Los Angeles Bay
LIDAR	Light Detection and Ranging
LTE	Long-Term Evolution
MAS	Mayflower Autonomous Ship
MASS	Maritime Autonomous Surface Ship
MOBI	Mobility Open Blockchain Initiative
MPA	Maritime Port Authority
MSC	Maritime Safety Committee
MW	Megawatt
NOx	Nitrogen Oxides
OT	Operational Technology
PM	Postmeridian
POLA	Port of Los Angeles
PSA	Port of Singapore Authority
RFID	Radio Frequency Identification
RL	Reinforcement Learning
RNN	Recurrent Neural Network
ROC	Remote Operation Center
SAR	Synthetic Aperture Radar
SOLAS	Safety of Life at Sea
USA	United States of America
TEU	Twenty-foot Equivalent Unit
ICT	Information Technology and Computers
TX	Texas
UAV	Unmanned Aerial Vehicle
EU	European Union
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VCAS	Vessel Collision Avoidance System
VHF	Very High Frequency
VR	Virtual Reality
VRP	Vehicle Routing Problem
VTOL	Vertical Takeoff and Landing
VTS	Vessel Traffic System

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INTRODUCTION

Global supply chains are undergoing a profound transformation, driven by simultaneous changes in several fundamental dimensions. On the one hand, the rapid expansion of e-commerce has placed intense pressure on logistics networks, which are required to deliver faster, more reliable, and more personalized deliveries. On the other hand, growing concerns about sustainability are forcing a rethinking of traditional operations in order to reduce carbon footprints, optimize resource consumption, and align with new regulatory requirements. At the same time, advances in digital technologies have created the conditions for a new logistics paradigm, in which data, automation, and artificial intelligence are becoming central components of the decision-making process.

In this complex context, maritime transport continues to play a strategic role, accounting for approximately 90% of the total volume of goods worldwide (Lau et al., 2024) . However, the performance of this sector cannot be analyzed in isolation. The efficient delivery of goods increasingly depends on the synchronization of the entire logistics chain, from the movements of ships at sea to handling in ports and final distribution in congested urban environments.

The problem identified in this research is the lack of real integration between the three major components of the logistics chain: maritime transport, port operations, and urban logistics. Each of these has independently made notable progress in digitization and automation.

The thesis explores both the technological foundations of this integration and the practical challenges associated with data governance, interoperability, and industrial adoption. From a methodological point of view, the proposed solution is tested through a combination of modeling and simulation. The MATSim and SimPy platforms are used to build realistic logistics scenarios, in which interactions between autonomous ships, digitized port terminals, and urban distribution networks are modeled.

This research aims to demonstrate the feasibility of intelligent integration of logistics segments, from sea to city, in a unified, data-driven framework supported by adaptive algorithms. The results provide evidence of the technological feasibility of such a model and outline clear prospects for its practical implementation. In addition, the analysis highlights the essential role of artificial intelligence not only as an automation tool, but also as a facilitator of predictive, dynamic, and transparent logistics governance.

The proposed conceptual framework contributes to the reconceptualization of modern logistics, in which operational decisions are not made in silos, but in interconnected networks that communicate and adapt in real time. This vision reflects the growing need for intelligent multimodal mobility, in which resources are distributed efficiently, environmental impact is minimized, and collaboration between logistics actors becomes a determining factor of competitiveness and sustainability.

CHAPTER 1 RESEARCH OBJECTIVES AND OVERVIEW OF THE THESIS

1.1 Motivation and context

Global supply chains face increasingly complex challenges as they strive to meet the growing demand for fast, reliable, and sustainable delivery of goods. E-commerce continues its rapid expansion, forcing logistics service providers to adapt their networks to cope with growing volumes and consumer expectations for near-instant delivery. At the same time, maritime transport accounts for approximately 90% of total freight volume, underscoring the sector's essential role in connecting international markets (Lau et al., 2024; World Bank, 2020) . However, many stages of current logistics chains (from offshore transport to urban distribution to the end customer) remain fragmented, with no real-time coordination or overall management framework.

A comprehensive, end-to-end approach to logistics—leveraging artificial intelligence (AI), Internet of Things (IoT) data flows, and blockchain-based transparency—can yield significant efficiency gains. By synchronizing all stages of shipment, from the arrival of the ship at port terminals to final door-to-door delivery, companies reduce dwell time, congestion, and emissions. This integration also addresses growing stakeholder concerns about sustainability.

Such integration can be modeled as a multi-objective optimization problem, in which the logistics system seeks to simultaneously minimize transit time, emissions, and costs:

$$U = \propto \cdot T + \beta \cdot E + \gamma \cdot C \quad (1.1)$$

where T is the total delivery time, E represents CO_2 emissions, and C is the operational cost. The values α, β, γ express the relative importance assigned to each criterion, depending on the objectives of the company or the legislator.

In this context, there is a clear opportunity to develop a unifying framework that combines maritime autonomy with port digitization and urban logistics optimization (particularly by reducing delivery times). By integrating these traditionally separate research streams—through advanced analytics, AI algorithms, real-time IoT-based updates, and secure data sharing—logistics systems become more adaptable, transparent, and sustainable. This thesis aims to demonstrate how a convergent, AI-based conceptual framework can respond to the urgent need for efficiency and resilience across the entire logistics spectrum, from sea to city.

1.2 Problem statement

Despite notable advances in maritime automation, port digitization, and AI-based solutions for end-customer deliveries, the logistics chain remains largely fragmented. Many research efforts and industry initiatives focus on improving specific segments, such as autonomous shipping or drone-based last-mile delivery, but fail to create a coherent "end-to-end" plan. This fragmentation leads to disjointed processes, where data and optimization efforts between maritime, port, and land

logistics operations require considerable resources and coordination. InFigure1 .1 , an integrated logistics framework based on artificial intelligence is proposed that solves the problem of supply chain fragmentation.

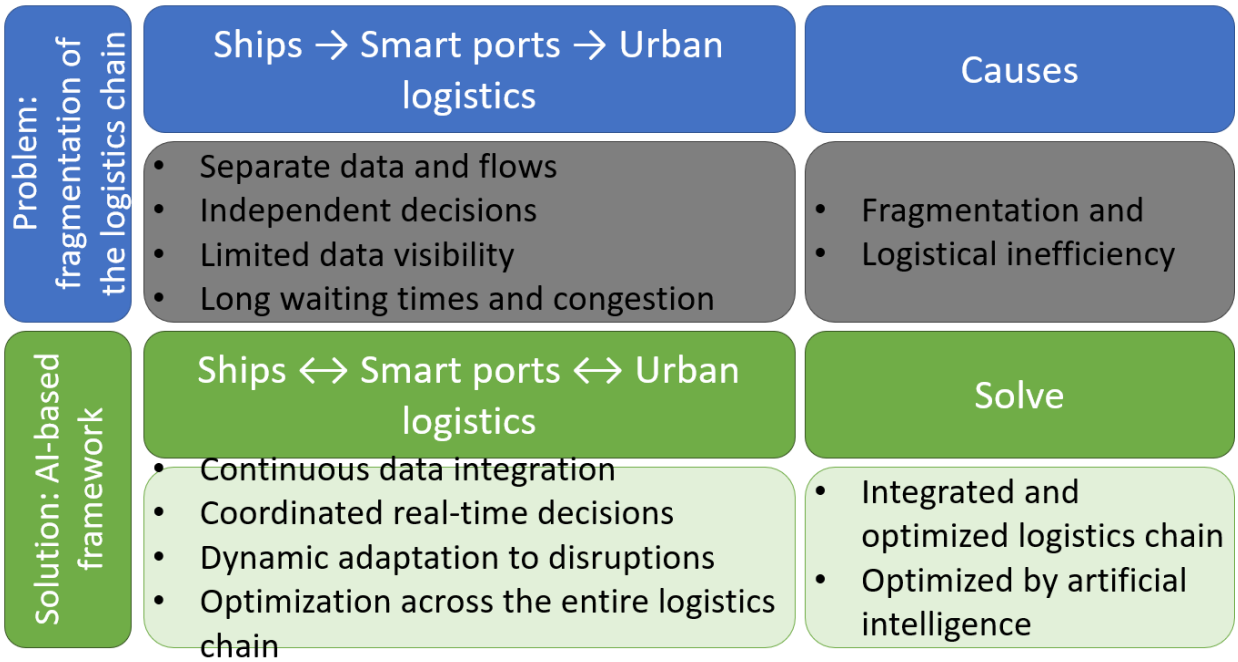


Figure1 .1 . Flow chart – cause, problem, solution. Source: author.

1.3 Research objectives

Addressing the fragmentation that persists between autonomous maritime operations, port digitization, and last-mile logistics requires a holistic rethinking of the entire supply chain. While advanced technologies—such as AI, geospatial systems, IoT, and blockchain—have each proven promising in their respective fields, a comprehensive framework that seamlessly unites these elements from ship to shore and beyond remains underdeveloped. To help fill this gap, this thesis pursues the overall goal of designing and validating an integrated, AI-based conceptual framework capable of synchronizing maritime autonomy, port workflows, and land transport to final delivery destinations.

To achieve operational efficiency in an integrated logistics system, the aim is to minimize an overall cost function:

$$\min_{x \in X} C(x) = \sum_{i=1}^{n} c_i(x_i) \quad (1.2)$$

where x is the vector of logistics decisions (e.g., routing, scheduling, resource allocation), and $c_i(x_i)$ represents the cost associated with each component in the chain. This formulation reflects the need for real-time algorithmic coordination, supported by artificial intelligence.

Given this conceptual framework, we have developed and tested simulation models to validate and refine the proposed system. These models use agent-based simulations—using the MATSim and SimPy platforms—to reproduce how autonomous ships, port operations, and state-of-the-art fleets respond to factors such as weather, traffic, and fluctuating demand. By integrating machine learning techniques (genetic algorithms, learning by deep reinforcement learning), the simulation environment assessed how quickly and efficiently the logistics chain can adapt to disruptions or changing conditions.

1.4 Research questions

Starting from the discussion on how an end-to-end logistics framework based on artificial intelligence could unify maritime, port, and last-mile operations, this research attempts to address a set of essential questions that analyze both the technological and managerial dimensions of such an integrated system. First and foremost is the question of *how artificial intelligence can effectively harmonize autonomous maritime vessels, digitized port operations, and land distribution flows into a coherent network (Q1).*

Closely linked to these technical concerns is a second, equally important question: *how can advanced optimization algorithms—such as reinforcement learning or genetic algorithms—transform daily logistics decisions and dynamically adapt to disruptions (Q2)*?

A third major question revolves around the broader organizational and political landscape. Even the most sophisticated technical solutions may struggle to gain traction if they do not align with regulatory frameworks, standards, or stakeholder incentives. This raises the question *of how port authorities, shipping companies, and last-mile operators can structure governance, cybersecurity protocols, and data-sharing agreements in a way that encourages collective engagement.* Consequently, it is necessary to determine *how policy directives—such as emissions caps, congestion charges, or international shipping regulations—might influence the pace and scale of digital transformation (Q3).*

Finally, the study asks *how success can be measured in an ecosystem that spans the high seas, coastal terminals, urban road networks, and ultimately, customer doors. By identifying and refining key performance indicators—from average dock wait time to final delivery time and carbon footprint—research can measure the true impact of an integrated architecture compared to traditional, isolated " " approaches (Q4).* These performance indicators not only provide insight into operational improvements, but also highlight areas where technology may require further

CHAPTER 2 DIGITAL TRANSFORMATION IN TRANSPORT

Digital transformation is the process of integrating digital technologies into all aspects of an organization's business, with the aim of fundamentally improving how it operates and delivers value to its customers. In the transport services industry, digital transformation manifests itself through the introduction and intensive use of digital tools such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, and geospatial technologies to optimize operational flows and enhance the efficiency and sustainability of logistics.

Digital transformation in transport refers to the shift from traditional manual processes to digitally enabled operations across all modes of transport (Remez, 2024) . In practice, this means replacing paper-based, human-centric workflows with automated, data-driven systems. For example, decades ago, transport handling relied on physical documents and phone calls; today, much of this work is done through integrated software platforms that use GPS tracking, telematics, and predictive analytics, making transport more efficient and cost-effective (Remez, 2024) .

Geospatial technologies (such as GPS and geographic information systems, GIS) underpin many innovations in transportation, enabling precise navigation, asset tracking, and spatial analysis. Together, AI, IoT, blockchain, and geospatial technologies form the backbone of the digital transformation of transportation, supporting a transition to smarter, more integrated, and more sustainable mobility systems (seeFigure2 .1).

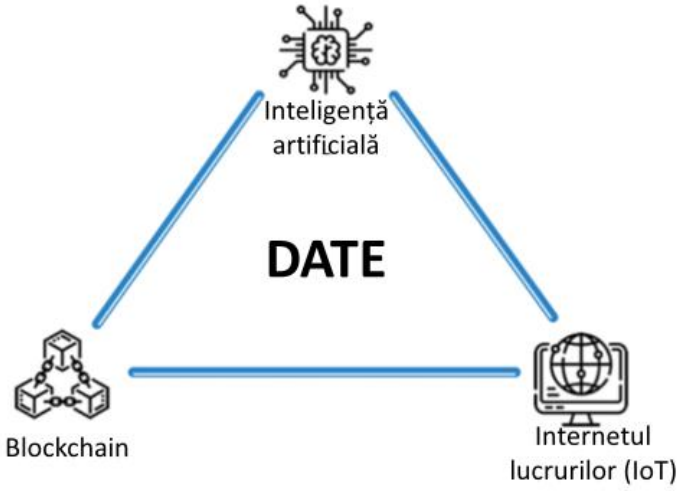


Figure2 .1 . The interaction of modern digital technologies. Source: Tapscott (2021)

2.1 General trends in transport digitization

CHAPTER 3 LONG-DISTANCE MARITIME TRANSPORT

Maritime transport is the backbone of world trade, carrying the vast majority of international goods. Over 90% of the volume of global merchandise trade is transported by sea, underscoring the critical importance of maritime transport to the global economy (MSC, 2022) . However, the traditional maritime logistics sector faces significant challenges in terms of efficiency, costs, and sustainability. Operations are often based on manual, paper-intensive processes that slow down port activity and vessel turnaround, while suboptimal routes lead to increased fuel consumption and emissions. In an era of increasing environmental regulations and shrinking profit margins, there is an urgent need to digitize maritime transport in order to streamline workflows and reduce waste.

Maritime Autonomous Surface Ships (MASS) are ships equipped with automation systems that can operate with minimal or no human intervention. The International Maritime Organization has defined four degrees of autonomy (seeTable 3.1) for such ships (MSC, 2019) .

Level of autonomy	Who operates	Who decides
MASS 1. Ship with crew on board	Crew on board	Captain on board
MASS 2. Remotely controlled ship with navigators on board	Remote team. Intervention possible from on board	Remote team leader or captain on board
MASS 3. Unmanned, remotely controlled vessel	Remote team	Remote team leader
MASS 4. Fully autonomous ship	Onboard computer system	Onboard computer system

Table 3.1 . Degrees of autonomy according to the Maritime Standardization Committee. Source: MSC(2022) .

CHAPTER 4 URBAN TRANSPORT AND DELIVERY TO THE END CUSTOMER

Digital transformation has emerged as a key factor in addressing these urban mobility challenges. By integrating advanced technologies such as artificial intelligence, the Internet of Things, and automation, cities are transforming traditional transport networks into smarter, data-driven systems. IoT sensors now provide real-time data on traffic flows, vehicle locations, and road conditions to AI algorithms that can make split-second decisions to optimize mobility (CSoica, 2025)).

4.1 Autonomous solutions for transport from factory to maritime hub

Transport from factory to maritime hub is the first stage in the global logistics chain and has a direct influence on the efficiency and operational costs of the entire transport system. This initial stage ensures the transfer of manufactured goods to ports of embarkation, from where they are distributed to international markets. The integration of AI and geospatial technologies in this phase has the potential to revolutionize the way logistics flows are managed, providing solutions for route optimization, real-time monitoring, and reduced environmental impact.

The adoption of sustainable delivery methods, such as cargo bikes, drones, and small electric vehicles, aims to reduce pressure on the urban road network and lower carbon emissions. The impact of these solutions can be estimated by a simplified calculation of total emissions:

$$E = \sum_{i=1}^{n} d_i \cdot e_i \quad (4.1)$$

where:

- d_i is the distance traveled by vehicle i,
- e_i is 's average emission rate (expressed in g CO_2/km),
- E is the total emissions generated by the fleet in a day or delivery interval.

This relationship allows for a comparative assessment of different urban delivery scenarios (with conventional vs. electrified fleets) and supports strategic decisions regarding the transition to a sustainable urban logistics system.

CHAPTER 5 THE PROPOSED INTEGRATED FRAMEWORK AND HOW TO IMPLEMENT IT

This chapter defines an integrated framework that connects the maritime, port, and urban segments into a single operational logic. The framework is based on three components: field data collection and interoperability, a decision layer that uses machine learning algorithms, and an execution layer that applies control policies in real time. In urban areas, the same logic translates into adaptive traffic light control and fleet routing to reduce delays and sudden variations in traffic flows. The framework is designed for gradual implementation across existing infrastructures, with few but explicit parameters that can be calibrated locally.

5.1 The proposed conceptual framework for logistics chains

Figure 5.1 illustrates the conceptual framework for an integrated maritime-urban logistics framework, highlighting the interactions between autonomous ships, smart ports, and AI-based urban distribution within a multimodal network. The figure shows an integrated logistics flow, in which each link, starting with the autonomous ship, continuing with the smart port and central warehouse, and culminating in multimodal distribution, is connected to a central *cloud* server. Each component benefits from IoT technologies for real-time data collection (ship position, container load level, delivery vehicle status, etc.), and artificial intelligence provides mechanisms for continuous analysis and optimization in terms of routing, load management, and resource planning.

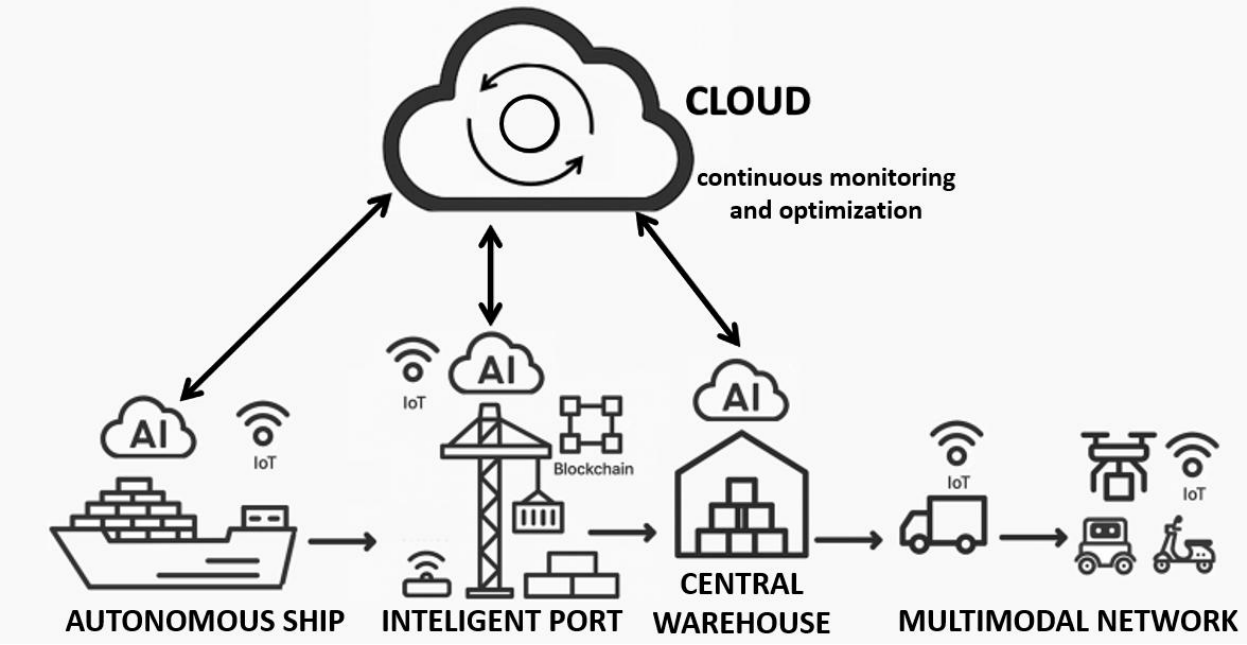


Figure5 .1 . Proposed conceptual framework. Source: author.

Figure5 .2 illustrates the components of a Vessel Traffic System (VTS) and the data links between them, highlighting the communication channels for raw sensor data and for processed data, instructions, commands, and feedback (Andrei et al., 2024) .

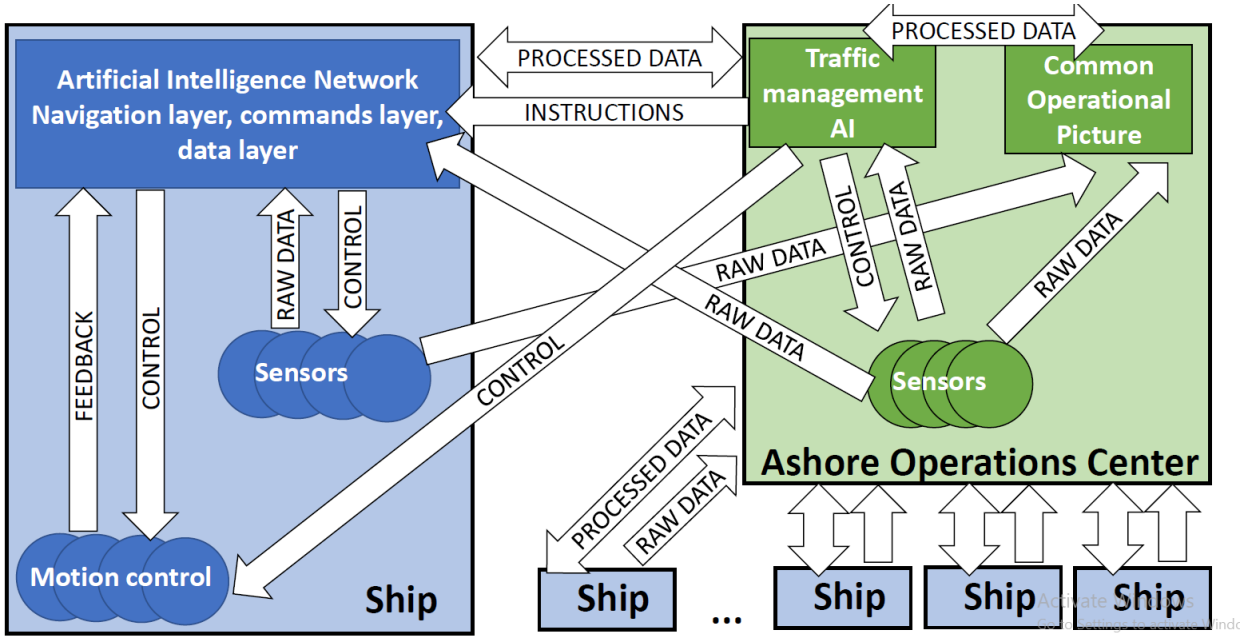


Figure5 .2 . VTS components and interactions between it and subcomponents . Source: Andrei, Scarlat, and Ioanid(2024) .

Sensor systems on board ships and those controlled by AOC are fundamental to the success of autonomous maritime operations. On-board sensors are classified as mandatory (permanent) sensors, such as those used for position determination (GNSS), and task-specific sensors, used for precise tasks such as docking. These sensors include advanced geospatial technologies such as synthetic aperture radar (SAR), sonar, infrared (IR) cameras, LiDAR, and GNSS, as well as other types of sensors, such as inertial sensors or ship engine sensors, which play a central role in providing accurate data about the ship and its environment, used for efficient navigation and collision avoidance (Scarlat et al., 2023) .

CHAPTER 6 GENERAL CONCLUSIONS AND FURTHER RESEARCH PERSPECTIVES

6.1 Main findings and answers to research questions

This chapter consolidates the insights gained from the analysis, which includes a review of the literature, the conceptual framework, methodology, empirical results, and discussion, and demonstrates how these findings answer the initial research questions posed in Chapter 1. By synthesizing evidence from simulation experiments, correlated with real-world examples and theoretical developments, it confirms the extent to which an integrated logistics framework based on artificial intelligence can indeed deliver greater efficiency, resilience, and sustainability in modern supply chains. To facilitate rigorous tracking of goal achievement, Table 6.1 summarizes the direct link between each research question (Q1–Q4), the relevant sections of the thesis, and the degree to which they have been achieved.

Table6 .1 . The link between research questions and the contributions of chapters to the achievement of research objectives.

Question	Relevant contributions	Chapter, page that answers	Degree of achievement
Q	Theoretical basis of digital transformation and interoperability	Chapter 2, Sections 2.1–2.3, pp. 11–23, Chapter 3, Section 3.1, pp. 31–34	Achieved
	Maritime-port integration (autonomous ships and smart ports)	Chapter 3, Sections 3.2–3.3, pp. 34–43	
	Synchronization of ship arrival and unloading times with land fleets	Chapter 4, Section 4.2, pp. 60–61	
	Integrated AI conceptual framework and multimodal architecture	Chapter 5, Sections 5.1–5.2, pp. 74–111	
Q2	The role of AI and ML in logistics decisions	Chapter 2, Section 2.4, pp. 23–28	Achieved
	Optimization of maritime routes (GA, RL)	Chapter 3, Section 3.4, pp. 44–49	
	Last-mile optimization (VRP, RL)	Chapter 4, Sections 4.3–4.4, pp. 62–68	
	MATSim & SimPy simulations, empirical results	Chapter 5, p Sections 5.2–5.3, pp. 99–115	
Q3	Regulatory framework for autonomous ships	Chapter 3, Sections 3.1–3.2, pp. 31–37	

	Urban rules (low emission zones, congestion charges) and smart mobility	Chapter 4, Section 4.2, pp. 60–61	Achieved, requires pilot projects
	Connected infrastructure (IoT) and data protocols	Chapter 4, Section 4.5, pp. 68–72	
	port nodes and blockchain	Chapter 5, Section 5.4, pp. 115–116	
Q4	Definition of preliminary KPIs	Chapter 4, Section 4.3, pp. 62–65 Chapter 5, Section 5.2.5, pp. 106–108	Completed
	Multi-objective evaluation	Chapter 5, Section 5.3, pp. 111–115, Table 5.2 and Figure 5.10, pp. 113–114	

6.2 Contribution to academia

Building on the main findings and their implications, this subsection presents how the integrated logistics framework based on artificial intelligence proposed in this thesis brings new perspectives and advances the current academic discourse in several ways.

Regarding the holistic integration of artificial intelligence across multiple modes of transport, previous research has often focused on isolated modes of transport (e.g., maritime or urban last mile) rather than a continuous flow from port to city distribution. Studies investigating AI-based optimization frequently focus on either vessel scheduling or road routing, rarely linking the two within a single framework. By integrating maritime, port, and last-mile operations into a unified AI-based decision-making platform, the thesis demonstrates how cross-domain synergies (e.g., real-time coordination between port arrival times and downstream delivery schedules) significantly improve overall efficiency. This expands the literature on multimodal logistics by empirically validating that integrated AI solutions outperform separate, locally optimized systems.

While the concept of synchromodality (dynamic selection of optimal modes based on real-time data) has emerged in logistics theory, practical or simulation-based studies quantifying the performance gains of an AI-driven synchromodal system have been limited. The research provides simulation-based evidence demonstrating substantial reductions in transit time, waiting time, and congestion once modes are coordinated through advanced AI algorithms. This validates the theoretical premise of synchromodality, demonstrating how real-time sensor data, predictive analytics, and autonomous control can be successfully combined. The study thus moves theories in the field of synchromodal logistics from conceptual frameworks to tangible, data-driven results.

Many published AI-based routing or scheduling solutions focus on smaller-scale or single-mode contexts (e.g., only for the last-mile vehicle routing problem). Real-world logistics networks, involving multiple agents, congested roads, port constraints, and uncertain arrivals, introduce levels of complexity often considered too high or too computationally difficult for advanced methods such as genetic algorithms or reinforcement learning. The thesis shows that composite

artificial intelligence techniques (genetic algorithms for route optimization, agent-based simulation for traffic dynamics, and real-time data ingestion for disruptions) can handle more complex scenarios. By carefully adjusting these algorithms to real transportation data (including maritime schedules and urban road networks), the research demonstrates that large-scale optimization is feasible and produces robust, statistically significant improvements. This finding expands the scope of artificial intelligence methods applicable in realistic situations, from one end of the supply chain to the other.

Although sustainable logistics is an increasingly important priority, many optimization models still focus primarily on minimizing costs or time. Few studies comprehensively incorporate emissions and broader environmental indicators into an artificial intelligence-based approach, particularly across different modes. By adopting a multi-objective perspective that includes carbon footprint reduction, the thesis provides empirical evidence of how AI can simultaneously meet operational and environmental goals. The results illustrate that route optimization and capacity management reduce emissions without compromising efficiency, helping to fill gaps in the literature on environmental performance in AI-based multimodal logistics.

There is significant academic work on maritime autonomy or artificial intelligence-based last-mile solutions, but these approaches often lack industrial-level demonstration or face skepticism about real-world feasibility. The synergy promised by digital ports, autonomous ships, and AI-powered urban routing often remains unproven outside of pilot demonstrations. By correlating the proposed integrated framework with examples (including normal vs. disrupted scenarios) and comparing it to a real-world baseline, the research goes beyond purely theoretical or simulation-based claims. Demonstrating that the proposed AI solutions bring measurable improvements in terms of vessel turnaround time, resource utilization, and costs fosters a closer link between theory and practice. This approach highlights the real-world viability of integrated, AI-based methods, guiding both academia and practitioners in operationalizing these concepts.

The literature on AI in logistics sometimes bypasses human and organizational dimensions, particularly policy alignment, stakeholder engagement, and workforce adaptation. However, these factors frequently determine the success or failure of AI innovations. This research examines policy, regulatory, and collaboration issues, highlighting how data standardization, clear regulations for autonomous systems, and stakeholder engagement support the expansion of integrated AI solutions. By synthesizing perspectives from empirical findings, the study contributes to the interdisciplinary knowledge base, emphasizing that real-world implementation depends on more than just the availability of software or hardware; it also requires institutional and social readiness.

6.2.1 Overall scientific significance

By addressing these six areas, the thesis goes beyond the limits of current knowledge on AI-based logistics. It brings together maritime, port, and urban operations into a single platform, integrates sustainability performance indicators alongside operational KPIs, and empirically demonstrates the gains achieved from advanced, large-scale AI optimization in both simulations

and real-world contexts. This dual focus on conceptual breadth (multimodal synergy, sustainability) and practical validation (clear evidence from implemented projects, policy implications) enhances the academic rigor of the study and its real-world relevance.

In conclusion, the thesis contributes a robust, empirically grounded conceptual framework that advances theoretical discussions on synchromodality, AI optimization, and integrated logistics, and also offers practical pathways for adoption in industry. Thus, it enriches the literature by providing proof of concept for an end-to-end AI solution (from autonomous ships to dynamic last-mile dispatching) while highlighting the socio-technical elements necessary to turn this holistic approach into reality.

6.3 Contribution to the industrial environment

In addition to its theoretical and methodological value, this research makes a number of concrete and relevant contributions to the industrial and logistics environment. By realistically simulating the interaction between autonomous maritime transport, digitized port operations, and advanced urban logistics, the paper provides an applicable direction for industry players interested in optimizing multimodal systems.

A first practical contribution consists of the functional validation of an integrated logistics framework using two recognised simulation platforms: MATSim (for multimodal mobility modelling) and SimPy (for discrete flows and port scenarios). These simulations systematically demonstrate that it is possible to efficiently coordinate logistics resources in complex environments where demand is variable and transport conditions may be subject to unforeseen disruptions. The scenarios constructed included not only the technological dimension, but also operational factors such as urban congestion, port berthing times, and synchronization between modes of transport.

The second type of contribution concerns the synchronized optimization of operations. The proposed framework allows operators in the logistics chain to pursue multiple objectives simultaneously—reducing transit time, costs, and emissions—without sacrificing system stability. Unlike traditional solutions, which optimize each segment in isolation (e.g., only the port or only urban transport), the architecture presented in this paper offers a holistic view, where decisions are made based on the entire transport flow, not on individual parts. This aspect is particularly important for logistics hubs, port areas, or last-mile operators that operate in a synchronized manner.

Thirdly, the contribution focuses on the scalability and adaptability of the solution to real industrial contexts. The proposed architecture is modular, allowing for progressive implementations, depending on the digital maturity of the organization or the available resources. For example, a regional port can initially adopt AI components for ship scheduling and then later integrate data from adjacent urban networks. Similarly, an urban logistics operator can benefit from predictive data from the port, adapting fleet routing in advance based on estimated unloading times or delays.

A fourth contribution relates to the use of artificial intelligence as adaptive decision support. By integrating real-time data (IoT, geospatial systems, port signaling), AI can guide decisions on resource allocation, routing, loading, and transport prioritization. This intelligent response capability is particularly useful in today's industrial context, marked by volatility, congestion, and customized logistics requirements. In addition, the integration of machine learning algorithms and scenario-based predictions contributes to increased operational resilience, reducing the system's vulnerability to unexpected events.

Last but not least, the proposed framework is aligned with the strategic priorities of the European logistics industry, particularly with regard to the digitization of supply chains and the transition to low-emission mobility. Both the European Green Deal and recent smart transport strategies encourage interoperability, traceability, and the adoption of data-driven solutions in logistics. This research provides a concrete example of how these principles can be integrated into a functional architecture that can be applied in diverse logistics environments.

The contributions of this paper are not limited to conceptual exploration, but offer clear directions for the practical adoption of an intelligent, efficient, and sustainable logistics model capable of responding to the challenges of today's industrial environment.

6.4 Final remarks

This thesis explored the potential of integrated AI-based logistics to transform how maritime, port, and urban operations are coordinated, demonstrating the efficiency gains and sustainability benefits that arise when data and decisions are truly unified across modes. By combining computational experiments, theoretical knowledge, and case study analysis, the study illustrates that advanced algorithms and real-time data sharing can overcome many of the inefficiencies that plague traditional transportation. The study demonstrates how the strategic use of artificial intelligence can help logistics networks adapt more quickly to disruptions, reduce downtime, and minimize their environmental footprint.

The findings support the conclusion that a single intelligent platform—incorporating elements such as autonomous ships, automated terminals, artificial intelligence-based route optimization, and blockchain-secured data—can orchestrate cargo flows to achieve remarkable improvements in cost, speed, and reliability. While these results underscore the promise of integrated logistics, they also highlight the importance of robust infrastructure, stakeholder collaboration, and favorable regulations. The transition to AI-based systems requires more than algorithmic excellence: it requires alignment of organizational culture, regulatory framework, and technology investments. Only with these supporting elements can the theoretical benefits documented in simulations and controlled pilot projects be realized on a large scale in the real world.

Looking ahead, the research agenda must address the practical barriers and open questions that remain. Future projects could delve deeper into decentralized AI coordination, advanced reinforcement learning solutions, or fully electric fleets to optimize carbon-neutral supply chains.

Furthermore, moving to real-world pilot implementations, where port authorities, carriers, and municipal agencies collectively experiment with data-driven scheduling, will test the sustainability and stakeholder acceptance of such frameworks under real operational pressures.

In conclusion, this paper is both an affirmation of the transformative potential of AI in logistics and a call to action for industry professionals and policy makers. By demonstrating that an integrated approach brings measurable benefits in terms of cost, capacity, and sustainability, it invites us to imagine a near future in which freight transport is not only faster and cheaper, but also cleaner and more resilient. Realising this vision will require ongoing interdisciplinary collaboration, transparent data-sharing agreements and a willingness to invest in advanced digital infrastructures. With concerted efforts, AI-based logistics can become a cornerstone of future supply chains, enabling adaptable, more efficient, and socially responsible movement of goods around the world.