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Research Article/ Review Article/ Perspective Article (Remove where relevant)

Towards intermodal resilience: a critical review of sensor-enabled synergies between MASS and CAVs

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Abstract (250 words) Style Name

All In the context of the ecological and digital transition of port cities, the con-vergence between autonomous surface ships (MASS) and connected and autonomous vehicles (CAV) represents a promising, yet largely unexplored opportunity for the creation of resilient, low-impact intermodal transport. This study reviews the literature on sensor technologies and data exchange systems currently used in smart ports — such as the OnTrack and Just-in-Time Shipping projects in Rotterdam — and analyzes their potential interoperability with autonomous mobility strategies. The OnTrack project at the port of Rotterdam, for example, was developed to optimize rail traffic management between the port and the hinterland. Thanks to this platform, operators can consult real-time information on train arrival and departure times, location, container loading/unloading status, and terminal operations progress. At the same time, the Just-in-Time Shipping project aims to reduce ship emissions and waiting times through dynamic arrival time optimization (ATA), based on geofencing and real-time digital communications with the port. Through the analysis of selected case studies, it is possible to explore how the port-city interface can be rethought thanks to distributed networks of sensors that monitor both the marine and urban environments. The review highlights how shared environmental sensors and predictive logistics made possible by BIM, IoT, and digital twin systems, could facilitate dynamic coordination between autonomous land and sea agents, improving adaptive planning and promoting sustainable mobility within complex port ecosystems.

Keywords: Port-city integration; Intelligent transport systems; Predictive planning

Highlights

- Synergy between MASS and CAVs fosters resilient and smart intermodal transport.
- Sensor networks and digital twins enable adaptive, low-impact port-city systems.
- BIM-based data integration enhances efficiency and sustainability in smart ports.

1 Introduction

The development of autonomous vehicles, both land and sea-based, represents one of the frontiers in contemporary mobility. Although environmental perception and detection systems are still in the experimental phase, the most promising strategy currently is the development of an applications with simultaneous localization and mapping (SLAM) algorithms [1]. These applications require high computing and data transmission performance, but it is now clear that these technologies will form the core of future transport infrastructure. Intelligent transport systems (ITS) are a means of improving safety and increasing infrastructure capacity, objectives that are directly linked to the development of autonomous driving [2]. They are recognized as one of the most effective responses to contemporary challenges in the transport sector, such as increasing congestion and high energy consumption. As defined in Directive 2010/40/EU of the European Parliament and of the Council [3], ITS con-sists of the application of information and communication technologies to road transport, involving infrastructure, vehicles and users, and integrating traffic and mobility management with interfaces to other modes of transport. Although today the term is used to refer to systems applicable to all modes of transport and thus to the concept of intermodality, its origin remains closely linked to road transport. In general, ITS has three main dimensions: intelligent vehicles, informed travel and connected transport infrastructure, outlining a technological framework that paves the way for the transition towards increasingly integrated and efficient mobility networks [4].

Integration with big data analysis tools and machine learning applications opens up innovative perspectives not only for traffic management and safety, but also for the introduction of value-added services for users, institutions and port authorities, such as eco-path finder systems for emission control [5]. In this perspective, ports are ideal contexts for testing and consolidating these innovations: being by their very nature intermodal nodes, where maritime, land and rail flows converge, they represent true experimental laboratories in which to test connectivity and interoperability between different types and levels of vehicular automation. In fact, the operational complexity of ports, characterized by the coexistence of maritime traffic, inland handling vehicles and hinterland connections, offers a privileged test bed for experimenting collaboration between intelligent systems and verifying their effectiveness in real scenarios with a high density of interactions.

In this context, the management of ports of the future will require close interaction between different types of autonomous vehicles. In the macro field of ITS, we find, on the one hand, MASS (Maritime Autonomous Surface Ships), which depend on advanced communication systems: vessel traffic services (VTS), intelligent re-mote central control (RCC) terminals, and radar-based support systems, automatic identification systems (AIS), smart buoys, and real-time monitoring. on the other hand, connected and autonomous vehicles (CAVs), already being tested in container terminals, which require dedicated infrastructure, smart lanes, geofencing techniques, and electric charging stations. However, the real leap forward lies in the possibility of enabling these two systems to communicate within a common digital infrastructure, capable of exchanging data in real time and integrating operational, environmental, and traffic information through interoperable platforms supported by IoT, AI, and BIM. From this perspective, the smart port is configured as a coordinated and resilient hub, capable of linking maritime and land flows within a low-emission intermodal network. This article fits into the context of the dual ecological and digital transition affecting port cities and argues that the integration of MASS and CAV represents a promising but still largely unexplored opportunity for the development of a sustainable, resilient, and environmentally friendly intermodal transport system. The methodology adopted is based on a qualitative review of the scientific literature and the analysis of emblematic case studies, with a specific focus on the port of Rotterdam, one of the most advanced internationally in terms of digitalization. The comparative analysis with emerging urban strategies for autonomous mobility aims to explore the potential of shared environmental sensing, digital interoperability, and predictive logic between maritime and land transport networks, outlining scenarios of technological co-evolution useful for port-city interface planning.

2 Smart ports: transition scenarios and challenges

The growing complexity of ports, characterized by the coexistence of different activities, equipment, and ecosystems, makes the development of innovative management models crucial to coping with ongoing transformations. This is where the concept of the smart port comes into play, understood as the evolution of modern ports towards systems capable of responding flexibly to challenges by combining digitalization, sustainability, and interconnection [6]. However, what is innovative today may prove insufficient tomorrow, as existing digital solutions are not enough to define a truly 'smart' port: multi-level integration is needed. A smart port is therefore an evolutionary perspective rather than a fixed model, aiming not only to automate processes but also to increase efficiency, port-city integration, and the use of alternative energy sources.

Among the most significant cases, the port of Rotterdam represents an exemplary model in the experimentation of digital solutions. The OnTrack application, developed to optimize rail traffic management between port and hinterland, allows opera-tors to access real-time information on train schedules, locations, container loading/unloading, and terminal operations. Originating from the HAROLD project, the system has reduced communication errors, replacing unreliable e-mails with standardized data flows, with benefits for railway companies, sea and river terminals, and logistics providers [7]. Rapid technological progress has also introduced new port classifications, distinguishing fifth- and sixth-generation ports. The former, including Shanghai, Singapore, Hamburg and Rotterdam, provide handling services at the highest global standards and act as intermodal hubs, integrating infrastructure and superstructure through advanced IT systems. The still-theoretical sixth-generation port, instead, combines expanded storage capacity and advanced container management with proactive stakeholder dialogue, oriented toward planning future cargo needs [8].

A smart port is a complex ecosystem where technologies optimize logistics and strengthen resilience. Its main features concern the collection, integration, and analysis of large data flows from sensors, monitoring systems, and platforms, turning them into predictive decision-making tools. Data-driven management reduces waiting times, optimizes resources, and improves safety. Digital interoperability among ships, terminals, land operators, and cities is enabled by IoT, AI, blockchain, and digital twins. Automation systems include MASS, CAVs, robotic cranes, and auto-mated container handling, integrated into common traffic and logistics platforms [9].

Sustainability is equally central, involving emission reduction through strategies such as Just-in-Time Arrival and renewable energy, as well as careful management of noise, air quality, and environmental impacts. A smart port also acts as an inter-modal hub coordinating sea, rail, and road flows in real time, and must be resilient to uncertainties such as climate variations or traffic peaks. Finally, it should strengthen the port-city interface, connecting infrastructures and communities to create a more inclusive and safer environment.

According to Behzad Behdani in "Port 4.0: a conceptual model for smart port digitization," the smart port model rests on three key dimensions: process automation, coordination and integration, and data-driven decision-making [10]. Business pro-cess automation (BPA) reduces human intervention through advanced technologies and standardized procedures, improving safety, efficiency, and control.

The port sector is a dense network of actors operating at different scales—shipowners, port and customs authorities, shippers, companies, and local business-es—making coordination and integration essential. Managing these interactions affects both efficiency and global trade flows, as each transaction generates large volumes of information requiring timely processing and sharing. Moreover, ports are increasingly embedded in port-city ecosystems, where political and urban plan-ning decisions influence operational strategies. In Europe, cases like Hamburg and Rotterdam show how port activities intertwine with urban services, underlining the need for multi-level governance. ICT thus becomes the key enabler to foster coordination, reduce inefficiencies, and mitigate information asymmetries.

The third dimension, data-driven decision-making, extends the port tradition of cargo recording with ICT, sensors, GPS, RFID, and traffic systems. External data sources such as weather or road conditions allow predictive and preventive models. Big Data Analytics improves efficiency — e.g., rational allocation of tugs, pilots, and vehicles — while reducing emissions and consumption and supporting the manage-ment of unforeseen events. Yet without solid coordination frameworks, data risks remaining fragmented, limiting its transformative potential [9-10].

3 Application and limits of Connected Autonomous Vehicles in port areas (CAVs)

This The development of Connected and Autonomous Vehicles (CAVs) is based on advanced perception systems and the integration of sensors that enable real-time reconstruction of the surrounding environment, decision-making and interaction with intelligent infrastructures. On-board sensors – radar, LiDAR, cameras, ultrasonic sensors and inertial units – work in synergy through sensor fusion, enabling vehicles to detect obstacles, predict trajectories and adapt driving in complex scenarios. In parallel, algorithms based on machine learning and deep reinforcement learning applied to non-signalized intersections show how optimized decision-making can reduce collisions, travel times and congestion [11].

In the port context, this technology takes on particular significance. Terminals and retroport areas, with high densities of vehicles, machinery and operators, are privileged environments to test sensor reliability and vehicle-to-infrastructure (V2I) interoperability. However, port infrastructure is not always ready to support CAVs: adaptation requires investments in IoT networks and distributed sensors along lanes, gates and aprons [12]. This challenge is amplified by investment cycles of 30-50 years, while autonomous technology evolves much faster.

In advanced ports such as Rotterdam and Hamburg, pilot projects integrating geofencing, dedicated lanes, charging stations, distributed sensors and monitoring systems are underway. These experiments improve safety, reduce labor costs and test issues such as cybersecurity and interoperability. This scenario includes Auto-mated Guided Vehicles (AGVs), designed to transport goods in controlled environments. Moving along predetermined routes with guides, sensors or digital maps, AGVs avoid obstacles and optimize movements. In port terminals they connect docks and yards, reducing waiting times and risks. Their integration with predictive systems and digital twins enables more efficient coordination of logistics [13].

Beyond AGVs, autonomous trucks and automated shuttles are transforming in-land handling. In Singapore and Shanghai, automated terminals employ autonomous trucks [14], while in Rotterdam AGVs and shuttles connect docks to storage areas [15]. In Qingdao, autonomous trucks replaced terminal tractors, significantly in-creasing speed and reliability [16].

Some ports have also adopted predictive platforms to optimize planning. The Port of Busan developed an AI framework to predict ship arrivals and improve punctuality, generating economic benefits [17]. Similarly, the Port of Panama applied predictive analytics to reduce delays and congestion [18]. These experiences show how integrating CAVs and predictive platforms can make ports safer, more efficient and coordinated, reducing waiting times, risks and energy use.

Integrating these solutions with predictive management platforms allows coordinated planning with ships, reducing bottlenecks and optimizing loading/unloading. In the future, CAVs could become the land link of the MASS system, creating an autonomous intermodal chain connecting ship, port and hinterland.

The current phase is still transitional, with hybrid solutions combining partly autonomous vehicles with intelligent infrastructures (induction loops, roadside units, sensors), evolving towards full autonomy. European examples – from the HEAT project in Hamburg [19] to the RobobusLine in Helsinki [20] – show how distributed sensing and centralized supervision remain crucial for safety in the experimental phase. These applications, though limited, are essential for collecting data, consolidating interoperability standards and developing scalable platforms for complex infrastructures.

CAVs should not be considered isolated entities, but mobile nodes within a connected ecosystem, exchanging data with vehicles, port management systems and urban infrastructures. The main challenge is convergence between on-board sensors and port environmental sensors, enabling predictive interoperability that can extend to autonomous land mobility.

4 The new frontiers of autonomous navigation: experiments and challenges

The Today, the maritime sector is undergoing a profound transformation, driven by digitization, decarbonization and automation, which are radically changing navigation and port operations [21]. In this scenario, Autonomous Surface Ships (MASS), defined by the IMO as vessels capable of operating with minimal or no human intervention depending on the automation level, represent one of the most promising innovations for maritime mobility [22]. Their development requires systems for situational awareness, route planning, collision avoidance, and monitoring of weather and sea conditions, supported by advanced digital infrastructure and reliable communication networks in offshore and coastal areas [23]. Also crucial is the adapation of international safety regulations (SOLAS, COLREGs) and the role of vessel traffic services (VTS), which act as control centers, providing remote assistance and maneuvering support in complex contexts [23-24]. Despite the potential, challenges remain, from infrastructure obsolescence to the complexity of operations in dynamic environments such as ports, where tides, currents and heavy traffic require continuous real-time adjustments [25]. Early experiments show that integrating on-board sensors, port systems and smart platforms can improve operations: the combined use of sonar, radar, LiDAR and computer vision (SLAM and data fusion) enables more reliable perception of obstacles and safer navigation in restricted areas [26].

The functioning of MASS depends on advanced environmental sensors, redundant communications and centralized databases capable of integrating data from ships and ports. Studies in Paranaguá (Brazil) show how distributed shore-based sensors with decision support systems improve maneuvering reliability and reduce risks. Helio Takahiro Sinohara and Eduardo Aoun Tannuri [27] highlight the importance of integrated systems to support MASS. They propose a technological package of ODAS buoys, tidal and weather sensors, coastal radars and cameras, connected to a control center able to process safe routes and contingency scenarios. The system provides redundancy, multiple communication channels and structured ship-to-port data sharing to ensure predictive information. The goal is not only to develop sensors, but to create an integrated system where port and ship operate as one entity, anticipating conditions and reducing risks.

At Paranaguá, the survey revealed a sophisticated monitoring system with instruments for marine weather, currents, visibility, AIS and traffic management centers. However, critical issues include the need to expand sensor coverage, ensure redundancy, strengthen communications and equip the control center with advanced digital tools to communicate directly with autonomous ships, improving safety and efficiency.

The Port of Rotterdam is a pioneer, with an advanced digital infrastructure based on IoT sensors, smart bollards and cloud platforms that monitor tides, currents, wind and berth availability, providing predictive decision support. The Just-in-Time Ship-ping project at Rotterdam is an emblematic test for MASS efficiency and sustainability. Introduced through geofencing, it activates a “virtual line” 240 nautical miles from the Maascenter buoy: once crossed, the ship receives an Actual Time of Arrival (ATA), allowing precise scheduling and reducing waiting times. Research from the IMO and the Norwegian GreenVoyage2050 project shows that optimizing arrivals in the last 12 hours can cut fuel consumption and CO_2 emissions by up to 4.23%. These results highlight how real-time communication, distributed sensors and predictive logic not only improve efficiency but also support decarbonization and resilience [28].

Overall, the transition toward autonomous navigation extends beyond ship technology to the redefinition of port infrastructures and their interaction with cities. In this perspective, the Just-in-Time maritime model parallels emerging land mobility strategies with CAVs, suggesting scenarios where maritime and land networks share sensors, digital interoperability (BIM, IoT, AI) and adaptive management logics.

5 The predictive port: the role of BIM and Digital Twin in data and process management

The increasing digitisation of ports and transport infrastructure makes it essential to integrate communication networks, distributed sensors and information modelling tools such as Building Information Modelling (BIM).

The digital transformation of ports is progressively driven by the convergence of BIM, IoT and artificial intelligence-based systems, which enable the creation of interconnected digital ecosystems [29]. In this evolving scenario, the UNI 11337-12:2025 standard represents not only a technical update, but also a governance framework for the management of digital information within complex infrastructures. Although the standard is in line with ISO 19650 principles, its real contribution lies in addressing the integration of dynamic data flows from sensor networks, autonomous systems and operational platforms in BIM environments. However, the adoption of the UNI 11337-12:2025 standard also exposes the emerging challenges of data interoperability and governance, particularly in ports where information flows are shared between multiple entities (public authorities, terminal operators and transport networks).

Unlike previous versions, this edition formally introduces BIM-IoT integration for resource lifecycle monitoring and decision support systems. However, it remains largely guideline-based, lacking applicable procedures for interoperability with autonomous transport systems (CAV or MASS). This reveals a regulatory gap between static asset modelling and dynamic operating systems, which are increasingly fundamental in the design of smart ports.

Integrated with digital twins (DT), BIM extends representation to dynamic processes such as traffic flows, port logistics and interactions between autonomous vehicles and infrastructure [30].

A digital twin is a dynamic digital replica of a physical system – e.g. a port, ship or transport infrastructure – powered by IoT sensors and monitoring systems. Its function is twofold: real-time monitoring of operational and environmental conditions and simulation of future scenarios through predictive and artificial intelligence algorithms.

Recent studies [29-30] highlight how the integration of BIM and DT enables real-time synchronisation of physical infrastructure with its digital counterparts, provided that sensor data is accessible and standardised. This enables predictive simulation and scenario analysis, bridging the gap between design and operational management.

Communication between vehicles, infrastructure and BIM platforms can be im-proved thanks to edge computing and Internet of Vehicles (IoV) technologies, which reduce latency and manage large volumes of data in real time [31]. In the port of Rotterdam, integrated monitoring and a digital twin of the port have enabled Just-In-Time arrivals, reducing CO_2 emissions by up to 14% [28].

The European PIXEL project (2018-2021) confirmed this potential. It developed an open IoT platform to centralise environmental and operational data in ports, promoting a first digital twin that replicates port activities. Using the open-source Port Activity Scenario (PAS) tool, PIXEL describes loading operations based on ship calls, equipment use and supply chain data. Tested in Bordeaux, Monfalcone, Thessaloniki and Piraeus, the platform has demonstrated strong potential in port digitalisation. DT has also been used to correlate activity with environmental impact, simulating alternative scenarios and supporting sustainable choices [32].

6 Conclusions

The analysis shows that the transition to smart ports is not limited to the introduction of innovative technologies, but requires a systemic vision capable of integrating automation, sustainability and digital interoperability [34]. The possibility of integrating data from maritime and land-based sensors, coordinating real-time flow management and adopting predictive logics opens up unprecedented scenarios of interoperability, in which autonomy no longer concerns the individual vehicle, but the entire mobility system [35]. Rotterdam adopts a systemic data governance model, emphasizing open data ecosystems and interoperability among stakeholders through the Portbase platform, which integrates BIM, IoT, and AI components. Hamburg follows a public–private hybrid strategy, where the Hamburg Port Authority leads an incremental deployment of CAV corridors and autonomous vessel docking systems, prioritizing safety and gradual integration. Singapore, by contrast, exemplifies a centralized, technology-driven governance model, with the Tuas Mega Port implementing end-to-end automation and AI-enabled MASS coordination.

From a strategic standpoint, these models reveal three governance paradigms:

1. Collaborative interoperability (Rotterdam) – open standards and shared data frameworks;
2. Adaptive integration (Hamburg) – modular and progressive adoption;
3. Centralized optimization (Singapore) – vertically integrated digital control.

From a technical-systemic perspective, these approaches differ in how they combine sensor networks, data fusion architectures, and BIM-based digital twins to manage operations. Yet all converge toward a vision of intermodal autonomy, where terrestrial and maritime systems communicate through unified data infrastructures.

A strategic element in this perspective is the role of BIM. No longer just a geometric modelling tool, BIM, in line with UNI 11337-12 and ISO 19650 standards, is configured as an information management platform capable of extending to the planning and monitoring of sensory networks. The adoption of openBIM and IFC standards guarantees interoperability between heterogeneous systems, making it possible to:

- map sensitive points for the installation of sensors on land and at sea;
- manage the life cycle of equipment (maintenance, upgrades, replacements);
- integrate port digital twins, transforming them into predictive tools for the simulation of operational and environmental scenarios.

This convergence underscores the need for updated standards capable of managing real-time interoperability between BIM, IoT, and autonomous systems. It also reveals the importance of developing a shared governance framework that balances technical interoperability, cyber-security, and operational accountability across interconnected port ecosystems.

Author Contributions

Although the research is the result of the joint work of all the authors, the drafting of the essay is attributed differently to each of them: § 1 by F. Sortino and C. Lo Vecchio; § 2 by F. Sortino; § 3 by C. Lo Vecchio; §4 by F. Sortino § 5 by C. Lo Vecchio; § 6 by F. Sortino and C. Lo Vecchio. Abstract by F. Sortino and C. Lo Vecchio.

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