Exploring the role of digital technology in the waterborne passenger mobility

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Abstract— **Digitalization is transforming the mobility sector, enhancing efficiency, safety, and sustainability through the integration of digital technologies (DT). While significant progress has been made in urban and cargo transport, the digitalization of waterborne passenger mobility (WPM) remains underexplored. This study addresses the fragmented research on DT applications in WPM by providing a comprehensive analysis of existing practices and emerging technologies. Through a literature review and case study analysis, this research identifies the key DT currently employed across various stages of the WPM lifecycle and analyzes their roles in addressing specific goals (DT for X), highlighting the benefits they provide to the service by optimizing performance, safety, energy efficiency, and sustainability from service, fleet, and terminal perspectives. This study provides a framework and actionable insights for the digital transition of WPM, fostering a more connected, efficient, and sustainable transport system.**

Keywords—Waterborne Passenger Mobility, Digital Technologies, Sustainability

I. Introduction

Digitalization is significantly transforming the mobility sector, enhancing efficiency, safety, and sustainability. Digital technologies (DT) can enable a smarter transportation system in cities by optimizing routes, improving real-time decision-making, and integrating various modes of transport. Moreover, can help improving user experience, reduce operational costs, and support data-driven strategies while ensuring cybersecurity and data privacy. Technology is also reshaping business models through Mobility-as-a-Service and Automation-as-a-Service [1], [2], [3], [4].

However, in the maritime and waterborne transport sectors, digitalization is still in its early stages [5]. Most advancements focus on the inland transport of cargo, particularly in automation and logistics [6]. Some initiatives provide valuable insights into digitalization in waterborne transport from a systemic perspective. For instance, the EU project DIWA [7] explores digital solutions for inland waterway transport, while SMASH!, the Netherlands Forum for Smart Shipping, fosters collaboration among organizations, companies, and stakeholders working on technological initiatives trying avoiding the fragmentation that characterizes the sector. It also proposes a roadmap for the Dutch smart shipping sector [8].

The EU Smart and Sustainable Mobility Strategy aims to foster a clean, digital, and modern economy for transport sector, supporting digitalization and automation, improving connectivity, and ensuring accessibility [9]. Similarly, the International Maritime Organization (IMO) has started addressing the regulatory scope for autonomous ships [10].

Regarding the urban passenger transport sector, waterborne passenger mobility (WPM) has received limited attention in its digitalization efforts.

While some experimental projects and technology applications exist, research remains fragmented, lacking a comprehensive overview or studies that systematically explore the opportunities digital transformation presents for WPM. However, various cases are emerging, particularly in Northern Europe, involving both the integration of technologies into established WPM services and the development of technological innovations and pilot projects.

This study seeks to bridge the existing gap in the literature on digital technologies in WPM. Using literature review, and case studies analysis, it aims to formalize fragmented knowledge and examine emerging cases. The study will explore how DT is currently used in WPM, identifying the key technologies involved and their application across different stages of the WPM lifecycle. Finally, it will analyze the roles these technologies play and the benefits they can bring to the service.

II. Contex and Theoretical Background

A. Waterborne Passenger Mobility

Waterborne passenger mobility is the mobility service that transports passengers through waterways, such as canals, rivers, and lakes within urban or suburban areas [11]. Using ferries, water shuttles, waterbuses, or water taxis, the service can transport people with scheduled or on-demand services [12].

WPM can offer a valuable alternative for coastal and river cities where traditional road transport has reached its capacity limits, particularly dense in urban areas [13]. It represents a complementary mode of transport, offering flexible, multi-stop services capable of moving a larger number of people across a city without the need for bridges or roads, by utilizing natural water infrastructures. This approach can contribute to creating more livable cities.

As stated in the EU Parliament Resolution “Making better use of available capacity of waterborne passenger transport could not only help reduce congestion and CO2 emissions, but also improve air quality and provide better transport services overall” [14].

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By leveraging the potential of digitalization, WPM can significantly contribute to the development of sustainable and smart cities, as well as to the creation of an intermodal and interconnected transport system [15].

WPM is a socio-technical system composed of a cluster of interconnected elements and interdependent social and technical factors [16]. It encompasses all the facilities and services involved throughout the journey—from the departure terminal, through transportation, to the arrival terminal. These elements are designed, manufactured, provided, maintained, and ultimately decommissioned by a diverse network of stakeholders from various organizations and industries. These actors can be summarized in the following categories: Transport Operator, Ship Builder, Waterfront Provider, Service Provider, Energy Provider, Regulators, and Technology Provider [17].

WPM is a system of products, services, and activities where the Transport Operator is the focal actor. The Transport Operator is directly responsible for delivering the service to passengers and coordinating the key activities and facilities involved in the system. Table I describes the key activities across the WPM service lifecycle.

TABLE I. WPM KEY ACTIVITIES ACROSS THE LIFECYCLE

Activity	Description
Service Planning	the Transport Operator defines routes, stops, and schedules to meet passenger needs
Fleet Planning	the Transport Operator determines the number of vessels required and their operational profiles
Fleet Procurement	the Ship Builder manufactures and delivers vessels tailored to the operational requirements
Terminals Procurement	the Waterfront Provider constructs docking infrastructure and revitalizes waterfront areas to support the service
Passenger Transport	passengers are transported between terminals using the fleet along predefined routes
Boarding and Disembarking	managing the embarkation and disembarkation of passengers at terminals
Ticketing	managing systems for passengers to purchase, validate, or reserve tickets, either digitally or on-site
Passenger Communication	providing real-time updates about the service status, including delays, disruptions, or schedule changes
Bunkering and Charging	refueling or recharging vessels at terminals
Fleet Maintenance	conducting regular maintenance, upgrades, or modifications to ensure vessels remain safe, efficient, and compliant with regulations
Terminal Maintenance	maintaining docking infrastructure and terminal facilities to guarantee service reliability and safety
Vessel Decommissioning and Component Disposal	decommissioning end-of-life vessels and managing the recycling or disposal of their components
Vessel Waste Disposal	disposing of waste generated during vessel operation
Docking Infrastructure Decommissioning	dismantling docking infrastructure and managing the reuse, recycling, or disposal of materials

B. Digital Technologies

Digital technologies encompass tools, systems, and applications that facilitate the creation, processing, and transmission of digital data. Digitalization enables the seamless sharing and dissemination of data across vertical and horizontal value chains, as well as within broader networks. This capability allows for continuous tracking, provision, and collection of information throughout the system and across various lifecycle stages, enhancing resource efficiency and supporting more informed decision-making [18], [19], [20], [21].

Digital Technologies have been categorized in various ways and there is not a unique consensus in the literature, moreover many technologies often overlap and work together in in synchronicity within a system. Among the different classifications found in the literature, digital technologies can be grouped into macro-categories such as (1) the Internet of Things (IoT), physical objects equipped with sensors and connected to a network via the internet, which share information and communicate with other systems, enabling seamless data exchange, (2) Big Data and Analytics (BDA), involving the analyzes of vast amounts of unstructured data using data mining and advanced analytics techniques, to identify patterns, trends, and associations that improve decision-making and optimize processes, (3) Additive Manufacturing (AM), encompassing techniques for creating three-dimensional objects by layering materials based on a digital computer-aided design, enhancing enhances flexibility, production speed, and customization in manufacturing, and (4) Augmented and Virtual Reality (AVR), technologies enhancing user experiences by adding digital elements to the real world or simulating realistic environments, which includes technologies designed to protect computer systems and networks from theft, damage, or unauthorized access while ensuring secure and transparent transaction recording [22], [23].

III. METHODOLOGY

The use of digital technologies in WPM is increasing, and the literature provides various examples and cases of DT applications. However, this research remains highly fragmented, and a comprehensive analysis of how DTs are utilized, their roles, and the benefits they bring has not yet received significant attention.

A literature review was conducted using the Scopus database with the following query: (TITLE-ABS-KEY ("waterborne passenger" OR "passenger ferr*" OR "inland passenger") AND TITLE-ABS-KEY ("digital*" OR "smart" OR "technology 4.0")). This query combined the WPM domain with the broader concept of digitalization. To include publications focusing on specific digital technologies, a second query was used: (TITLE-ABS-KEY ("waterborne passenger" OR "waterborne mobility" OR "passenger ferr*" OR "inland passenger") AND TITLE-ABS-KEY ("internet of things" OR "big data" OR "additive manufacturing" OR "virtual reality" OR "simulation")). The search was limited to publications from 2019 to 2025, yielding a total of 55 papers. After screening these results, 33 papers were selected for further analysis. Grey literature is essential for identifying real-world cases and emerging projects that, while not yet covered in academic literature, are advancing the use of DT in WPM. A total of 10 case studies, analyzed using reports and documents from organizations and company websites, were included in the results. The analysis of results from academic and grey literature identified and examined digital practices based on the digital technologies utilized, the WPM activities they support, and the benefits they bring to the service. Digital practices have been categorized on the types of benefits they offer highlighting the potential roles that DT can play in enhancing WPM.

IV. Results and Discussion

Among the 43 digital practices identified, the majority are applied at the product level, with most focusing on the vessel, a few on the terminal, or on the vessel-terminal system. Only a small number are implemented at the service level. This highlights the maritime and waterborne transport sector's predominantly vertical approach, which typically centers on the transportation means. AVR technologies are widely adopted, particularly during Fleet Planning, where they are used to evaluate the performance of vessels and their components through advanced modular modeling and simulations. Studies highlight the use of simulations for vessel design and general arrangement, as well as for navigation, to assess safety and sustainability performance [24], [25], [26], [27]. Other studies focus on specific vessel components, such as simulations for hull performance, for the sustainability and safety of propulsion systems, or for energy efficiency, and battery storage capacity [28], [29], [30], [31], [32], [33], [34]. Few articles address simulations related to autonomous navigation, focusing on technology development and safety evaluation [35], [36], whereas one of the real-world cases employs model-based system engineering and parametric modeling to enhance the flexibility and reconfigurability of the fleet [37]. AVR technologies are also applied during Service Planning to evaluate service performance, safety, and intermodality opportunities [38], [39]. AVR technologies can also be beneficial during Fleet Maintenance, supporting simulations for evaluating the energy savings of a retrofitted vessel [40].

Another application of digital technologies during Fleet Planning involves leveraging BDA through machine learning techniques to develop a data-driven battery life prediction model for real-time optimal power control, enhancing energy efficiency and reducing costs [41]. AM technologies can be advantageous for Fleet Procurement, as 3D-printed vessels optimize production processes and enable flexible part replacements during Fleet Maintenance [42]. This technology can also be applied to the production of terminal facilities, such as pontoons, where the use of fully recyclable materials for 3D printing promotes sustainability during the Decommissioning phase [43]. Fleet maintenance operations can be supported by software (combining IOT and BDA technologies) that simplifies maintenance tasks by providing the crew with precise instructions, helping to maintain systems in optimal condition. This not only facilitates the crew's work but also enhances predictive maintenance capabilities [44].

During the operational phase of the WPM service, both academic and grey literature reveal that the technologies commonly used are IOT in combination with BDA. An increasing number of studies and cases are exploring autonomous navigation for vessels, which has the potential to optimize performance, enhance energy efficiency, reduce fuel consumption, and lower operational costs [42], [45], [46], [47], [48], [49], [50], [51]. Additionally, IOT and BDA technologies are enabling autonomous and automatic operations, such as docking via automatic bow ramps[45], autonomous steering systems [52], [53], and quick charging through smart connectors for vessel charging at terminals during stops [52], [54]. The collection of data through sensors and IoT devices, combined with analysis and interpretation by BDA systems, provides numerous opportunities for the service. Managing real-time data can support monitoring the fleet's status and the overall service, for improving vessel performance, optimizing service routes and fleet capacity, enabling predictive maintenance, and enhancing real-time communication with passengers [51], [55], [58]. Moreover, data management can facilitate the development of digital platforms that coordinate journeys across multiple transport modes, enabling seamless intermodality [55]. Furthermore, monitoring systems can enhance vessel safety by preventing ferry overloading through a combination of sensors, wireless data communication, and statistical analysis functions [56].

IOT and BDA are beneficial for managing energy consumption through Power Management Systems in electric engines and renewable energy technologies. Fully electric propulsion, combined with solar panels on the rooftop, enables emission-free service with minimal impact on the power grid [46].

Finally, data management and IOT devices enhance the user experience by enabling passengers to make payments through the app or integrated contactless systems on board, streamlining payment processing [57]. Additionally, smart devices can provide passengers with essential feedback for operations like boarding and disembarking, enhancing both usability and safety [58].

In Table II results have been organized and categorized based on DT macro-categories and WPM activities, highlighting the roles of DT in each WPM activity and their corresponding aims (DT for X).

DT for X categorizes the role of DT in addressing specific goals within the WPM activities, considering vessels, terminals, and the overall service lifecycle. It describes how different DT can benefit the WPM in terms of Vessel Performance Optimization, Safety, Energy Efficiency, Fleet Flexibility, Manufacturing and End-of-Life Optimization, Predictive Maintenance, Service Efficiency, Passenger Experience, and Intermodality. DT for Vessel Performance Optimization refers to DT aiming at improving the overall performance of vessels, such as optimizing propulsion systems, hull designs, and navigation to enhance speed, efficiency, and operational effectiveness. DT for Safety, refers to the use of technologies to ensure the safety of vessels, crew, and passengers, including real-time safety monitoring systems, risk assessments, and emergency response capabilities. DT for Energy Efficiency, refers to solutions that focus on reducing energy consumption and improving fuel efficiency, such as integrating renewable energy sources, optimizing engine performance, and monitoring energy usage throughout the vessel's operation. DT for Manufacturing and End-of-Life Optimization refers to technologies that optimize the production, maintenance, and decommissioning processes of vessels and terminal infrastructure, such as 3D printing for production and the use of recyclable materials for decommissioning. DT for Predictive Maintenance refers to solutions that use IOT sensors and data analytics to predict and detect when maintenance is needed, enabling proactive interventions to reduce unexpected failures, improve system longevity, and optimize uptime.

TABLE II. ROLES OF DT DURING THE WPM ACTIVITIES

DT	WPM Lifecycle Activity	Roles	DT for X	References
AVR	*Service Planning*	• simulations for service operational optimization (routes and schedules, intermodality integration) • simulations for service safety	DT for Service Efficiency DT for Safety	[38], [39]
	Fleet Planning	• simulations for vessel performance optimization (hull performance, propulsion systems, energy efficiency, general arrangement) • simulations for vessel safety • simulations for autonomous navigation • virtual prototyping for modularity and reconfigurability	DT for Vessel Performance Optimization DT for Safety DT for Energy Efficiency DT for Fleet Flexibility	[24], [25], [27], [29]
	Fleet Maintenance	• simulations for energy evaluations (of retrofitting vessel)	DT for Energy Efficiency DT for Predictive Maintenance	[40]
AM	*Fleet Procurement*	• streamlining production processes • enhancing flexible design adjustments	DT for Manufacturing and End-of-Life Optimization DT for Fleet Flexibility	[42]
	Terminal Procurement	• streamlining production processes • enhancing flexible design adjustments	DT for Manufacturing and End-of-Life Optimization	[43]
	Fleet Maintenance	• facilitating part replacements • enhancing flexible design adjustments	DT for Predictive Maintenance DT for Fleet Flexibility	[42]
	Docking Infrastructure Decommissioning	• streamlining disassembly • employing recyclable materials	DT for Manufacturing and End-of-Life Optimization	[43]
IOT & BDA	*Fleet Planning*	• energy performance optimization	DT for Energy Efficiency	[41]
	Fleet Maintenance	• supporting decision-making • enabling predictive maintenance	DT for Predictive Maintenance	[44]
	Passenger Transport	• optimization of navigation (autonomous navigation) • optimization of service (routes and schedules, fleet capacity, intermodality) • fleet safety	DT for Vessel Performance Optimization DT for Service Efficiency DT for Safety DT for Intermodality	[42], [42], [45], [46], [47], [48], [49], [50], [51], [59]
	Boarding and Disembarking	• optimization of operations (autonomous docking and automatic systems)	DT for Service Efficiency	[45], [52], [53], [54]
	Bunkering and Charging	• optimization of operations (automatic charging systems)	DT for Service Efficiency	[51]
	Ticketing	• optimizing the booking and payment process	DT for Passenger Experience	[57]
	Passenger Communication	• enhancing usability • enhancing safety	DT for Passenger Experience DT for Safety	[58]

DT for Service Efficiency refers to digital technologies that optimize service operations, such as route planning, scheduling, and automating tasks to streamline operations and reduce delays or inefficiencies. DT for Passenger Experience refers to technologies that enhance the overall passenger journey, including smart ticketing, real-time communication, payment systems, and improving boarding and disembarking processes. Finally, DT for Intermodality refers to digital solutions that facilitate the seamless integration of different transportation modes to provide passengers with coordinated, multi-modal travel experiences, and improve the efficiency of the overall transport system.

V. CONTRIBUTIONS AND FUTURE DEVELOPMENTS

This article addresses a significant gap in the literature on DT in WPM by conducting a comprehensive literature review and analyzing case studies to formalize fragmented knowledge and explore emerging applications. It identifies the key DT currently employed across various stages of the WPM lifecycle, and analyzes their roles in addressing specific goals (DT for X), highlighting the benefits they provide to the service.

This study makes significant theoretical and practical contributions to the maritime transport and digital technologies fields. Theoretically, it develops a comprehensive framework categorizing digital technologies across various WPM activities, enhancing the understanding of their roles in optimizing performance, safety, energy efficiency, and sustainability, from a service, fleet, and terminal perspective. It also contributes to domains such as mobility and smart cities advancing theories on intermodality and integrated transport systems. Practically, the study provides actionable insights for WPM operators and stakeholders, offering solutions for improving operational efficiency, safety, sustainability, and passenger experience.

Given the early adoption of certain technologies in the sector and the low maturity level of implementation in some of the case studies, the potentiality of this findings would benefit from further empirical investigation. Future research should engage with relevant stakeholders to examine the challenges and barriers to adoption, as well as to uncover potential unintended consequences arising from the integration of these emerging technologies.

Additionally, further developments on these issues will benefit from deeper analyzing digital practices by interviewing stakeholders to identify additional opportunities across different WPM activities. It will contribute to further exploring DT for X categories, investigating how digital practices are interrelated, compatible, or complementary, and how they can be integrated in a comprehensive and holistic way. This systematization can lay the foundation for defining a comprehensive framework and guidelines to achieve DT for

X goals, thereby creating sustainable, safe, high-performing, and cost-efficient WPM systems that benefit all stakeholders and end users.

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