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How Digital Technologies Can Support Sustainability of the Waterborne Passenger Mobility Ecosystem: A Case Study Analysis of Smart Circular Practices in Northern Europe

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Abstract: To tackle the significant increase in traffic congestion and pollution in urban areas, waterborne transport systems can offer a more efficient and environmentally friendly alternative, decreasing traffic congestion on roads, noise, and pollution emissions, with reduced infrastructure requirements. Developing a sustainable waterborne passenger system requires a multidisciplinary approach and a systemic view, which involves various stakeholders and knowledge. Digital transition can encourage a better management of resources and enables systems integration promoting circular economy and ecosystem models, which create interrelations among systems. The aim of this study is to identify circular practices adopted in the waterborne passenger mobility (WPM) ecosystem driven by digital technologies. A holistic perspective which considers all the system of actors and their mutual interactions has been adopted. Five case studies have been selected in Northern Europe and analyzed by applying the Smart Circular WPM Ecosystem framework, previously developed by the authors. The analysis identifies a list of Smart Circular practices resulting from the application of digital technologies during specific lifecycle stages, involving certain actors' categories, and enabling circular principles. The case studies analysis also highlighted unexplored or under-considered fields of action which can be the base for further research.

Keywords: waterborne passenger mobility; sustainability; circular economy; digital technology; multidisciplinary approach; ecosystem perspective; green technology

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1. Introduction

In urban areas, the exponential growth in population and economic activity has led to a significant increase in traffic congestion and pollution. A high percentage of the global population lives in urban areas situated near the sea or along rivers, featuring numerous water channels like canals and fjords. Revitalizing urban water transport systems and seamlessly integrating them into a multimodal transport network of the city can reduce traffic congestion on roads, energy consumption, noise, and pollution emissions.

Compared with the public transport on the road, ferries can move a larger number of people between two sides of a city, requiring less infrastructure, such as roads or bridges; moreover, they can provide a multi-stop and flexible service across waterways.

The European Green Deal has developed a specific plan called the Sustainable and Smart Mobility Strategy, which sets clear targets for achieving the first milestone in 2030 on the path to a zero-emissions society. The strategy lays a base for how the transport sector can achieve its green and digital transformation towards a smart and sustainable future.

Despite waterborne transport representing a valuable opportunity for the sustainable development of urban mobility, there are still some challenges to overcome to reduce resource exploitation, emissions, and waste in the sector and its ecosystem of actors.

Developing sustainable waterborne passenger mobility systems requires a multidisciplinary approach and a systemic view, which involves various stakeholders. Digital transition can encourage a better management of resources and enables systems integration promoting circular economy and ecosystem models, which create interrelations among systems.

These actions required the employment of different types of knowledge coming from Design, Systemic Thinking, Business and Management, Information and Communication Technologies. At the same time, it is essential to engage multiple stakeholders pertaining to diverse industries and organizations but sharing the same goal of delivering a sustainable waterborne mobility system.

The aim of this study is to identify circular practices adopted in the waterborne passenger mobility (WPM) ecosystem driven by digital technologies, or rather Smart Circular practices. The concept of Smart Circular Economy comes from the literature of the business and management discipline as a new paradigm that explores the relation between digitalization and circular economy, demonstrating how digital technologies can facilitate circular economy and circular strategies [1,2].

This research undertakes the study of Smart Circular Economy in relation to the WPM assuming an ecosystem perspective that considers all the system of actors and their mutual interactions. Such a holistic approach can foster circular practices strengthening the systemic nature of circular economy.

The WPM sector has been moving its steps towards sustainability, especially in the last years [3,4], but there are no real examples or literature about circular economy applied to this specific mobility service. Various studies and European projects are actively dedicated to advancing sustainability within the maritime sector, incentivized by the IMO (International Maritime Organization) Strategy on climate neutrality target [5], but most of them adopt a vertical approach that focuses particularly on alternative propulsion systems and fuels, on hull design or on operational measures, such as improved navigation and vessel allocation systems [6]. There is currently a limited body of literature that explores Eco Design strategies and Lifecycle assessment from a product development perspective particularly centered on the transport means (i.e., the vessel), or concerning the supply chain of emerging fuels such as hydrogen [5,7]. This highlights a shortcoming in addressing both Circular Economy principles and the broader ecosystem level of mobility services in the existing literature. Examples of studies on smart and green ports adopt a network-based perspective, incorporating some circular cases. However, these studies tend to maintain a focus on the port domain and logistics, rather than exploring broader ecosystem-level considerations [8–11].

In academic literature, the theme of digitalization is predominantly addressed within the broader maritime sector, but formal studies in various domains are still lacking [12]. Additional knowledge from grey literature, including reports from the maritime sector and European projects, emphasize the potential of digital technologies in enhancing door-to-door trips, lifecycle management, and the safe and automated operation of assets through their tracking, monitoring, and connectivity capabilities [13]. Digital technologies are also used in waterborne passenger mobility to enhance passengers' experience through apps or other touchpoints that facilitate route consultation and real-time status checking, or ticketing operations [14].

Therefore, the WPM context highlights a shortage or even a complete absence of knowledge regarding the ecosystem approach, circular economy principles, and digitalization. In these thematic areas, two primary gaps can be identified: a shortage of a comprehensive ecosystem approach and a lack of studies examining the utilization of digital technologies to facilitate circular strategies.

Analyzing the state of the art of sustainable and digital practices already implemented in the sector is useful to understand how much they trend towards possible circular approaches and to read the mechanisms that foster such practices.

This study intends to recognize potential circular principles inherent in the sustainable innovative actions undertaken by the sector. It also seeks to examine the support provided by digital technologies and the involvement of the actors' ecosystem in achieving these actions to uncover further opportunities that can trigger a systemic approach and circular economy.

Five cases have been chosen in the Northern European region where advancements in innovation and sustainability of the WPM sector are notably progressed due to their land morphology and the higher dependency on the waterborne transport. These five case studies have been analyzed by applying the Smart Circular WPM Ecosystem framework [15], previously developed by the authors, and revisited with further details according to progresses made in the research.

This paper is structured in four sections. Section 2 describes the theoretical background and the context on which this study is based deepening on the WPM sector and its ecosystem, and the concept of Smart Circular Economy. Section 3 introduces the methods, describes the Smart Circular WPM Ecosystem framework and the case studies. Section 4 illustrates and discusses the application of the framework on the case studies and the results. Finally, Section 5 presents conclusions and further developments.

2. Context and Theoretical Background

This section presents an overview of the WPM sector defining the boundaries and state of the art.

Moreover, it introduces the main theoretical concepts upon which this study and the analysis parameters are grounded.

2.1. The Waterborne Passenger Mobility (WPM) Ecosystem

The "waterborne passenger mobility" ecosystem refers to the mobility service that transports people through waterways (like canals, rivers, and lakes) within an urban area [15].

The main transportation types include canal or river passenger transport, water shuttle services, water bus and taxi services. When it refers to public transport, it encompasses vessels that transport individuals in scheduled services within the urban areas [16].

It embodies all the facilities and services which operate during the journey from the departure terminal to the transportation, to the arrival terminal. The basic elements of the system can be summarized as follows: employees at the shipping companies, ships as a means of transport, waterways as the traffic routes, passengers as the objects of transport, and terminals as infrastructures [8,17].

Waterborne mobility has the potential to be a significant component of future urban sustainable transportation, offering solutions to traffic congestion on roads and railroads and contributing to more livable cities by freeing up land space. Its advantages include faster travel in congested urban areas, flexibility to change routes easily in case of accidents, and the utilization of existing natural water infrastructures. Waterborne transport also provides a scenic and enjoyable travel experience, attracting both tourists and offering a pleasant mode of transport for locals.

However, despite its environmental benefits, waterborne passenger mobility remains a source of greenhouse gas emissions and other pollutants. Recent studies and European projects, influenced by the IMO (International Maritime Organization) Strategy on greenhouse gas emissions and climate neutrality targets, focus on enhancing the sustainability of the maritime sector. Most efforts concentrate on cargo and long-range ships, with some attention to ro-ro pax ships and ferries, exploring alternative fuels, propulsion systems, hull design, and operational measures. While a systemic approach is starting to emerge, there is a need for more exploration from an ecosystem perspective.

The urban mobility sector, including waterborne passenger mobility, is undergoing transformation due to major trends such as digitalization, servitization, and automation. Digital technologies are enabling adaptive and integrated door-to-door trips (from the passenger's place of origin to the final destination, encompassing also other necessary modes of transport), ensuring the safe operation of assets, optimizing space and infrastructure capacity, and constantly monitoring the lifecycle management of assets and equipment. In the waterborne transport sector, companies are increasingly using technology to enhance the passenger experience before and during travel, including the development of apps and digital touchpoints for route consultation, easy ticket booking, operator evaluation, and real-time travel status checks.

Considering the ecosystem of the WPM means to explore the activities of multiple organizations that belong to different industries [18] and move the perspective beyond organizations' boundaries towards the network of actors that mutually interact to contribute to a collective outcome or value proposition [18–20].

The WPM ecosystem can be defined as the system of actors and their multilateral interactions that concur to co-create the mobility service that transports passengers from a location to another, through waterways, in urban areas.

2.2. Circular Economy and Digital Technologies

Smart Circular Economy identifies a system leveraging digital technologies throughout lifecycle phases to implement circular strategies and practices, aiming at value creation [1,2].

Coming from the literature of the business and management discipline, it has grown in recent years as a new paradigm that explores the relation between digitalization and circular economy, demonstrating how digital technologies can enable circular economy and circular strategies.

Established by the Ellen MacArthur Foundation, the concept of circular economy refers to an economic system that aims at changing the current linear economy, reshaping the way resources are managed, products are manufactured and utilized, and materials are treated afterward. It is based on three principles: eliminating waste and pollution, promoting the circulation of products and materials at their highest value, and fostering the regeneration of nature [21].

Digital technologies comprise tools, systems, and applications that enable the creation, manipulation, and transmission of digital data [22,23].

Digitalization enables the sharing and transmission of data along both vertical and horizontal value chains, extending even beyond them in larger networks. This allows constant tracking, provision, and collection of information across the system and throughout lifecycle stages. As a result, it enhances resource efficiency, improves decision-making processes, and contributes to the effective implementation of circular strategies [23,24].

3. Methods

This study undertakes the analysis of five case studies from Northern Europe to explore the relation of circular economy and digital technology in the WPM ecosystem.

The case study analysis is performed by using the Smart Circular WPM Ecosystem framework [15], previously developed by the authors, and revisited with further details according to progresses made in the research. The framework is described in all its elements and constitutes the base for the parameters used to read and understand the five cases.

3.1. Smart Circular WPM Ecosystem Framework

The Smart Circular WPM Ecosystem is a transportation system for passengers on waterways, which performs circular strategies and practices enabled by digital technologies, through its network of actors, in order to enhance sustainability along its lifecycle [15]. The framework of the Smart Circular WPM Ecosystem (Figure 1) "interrelates the WPM ecosystem with smart circular strategies to explore possibilities of the use of digital technologies in enabling circular practices" [15].

The framework comprises three main blocks: the WPM ecosystem, lifecycle stages, and Smart Circular strategies that apply digital technologies to circular economy.

The WPM ecosystem describes the network of actors that collectively contribute to deliver the value proposition of the WPM system, specifically consisting of transporting people through waterways within an urban or suburban area.

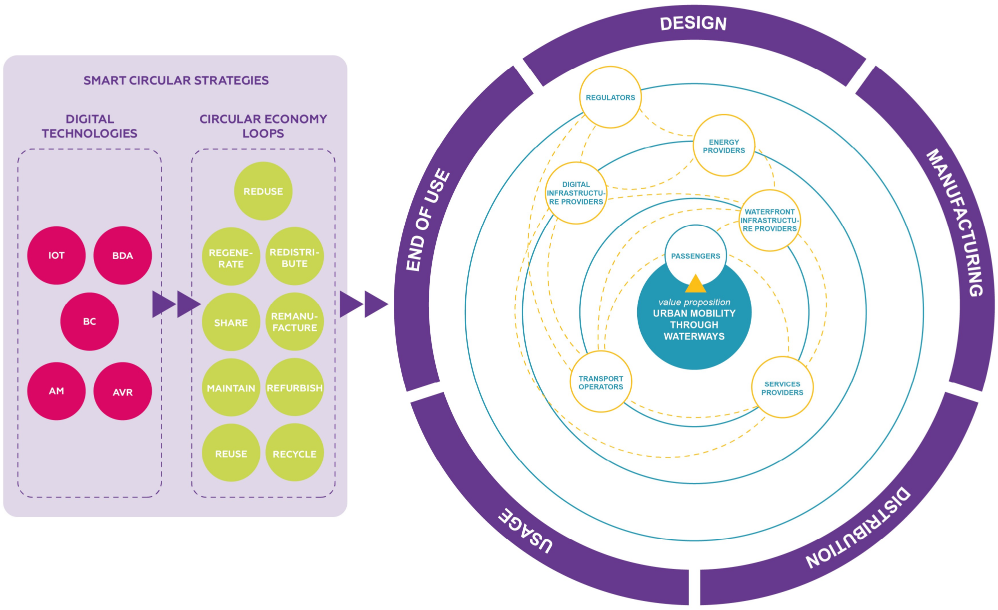

Figure 1. Smart Circular WPM Ecosystem framework.

Actors are grouped in categories according to the service domain (e.g., means of transport, terminal, technology, etc.) they deal with. To the previous conceptualization of the framework, the category of Digital Infrastructure Providers has been added, functional to distinguished from other infrastructure providers when the discussion is leveraged on digitalization.

Starting from passengers, who are the users of the waterborne transportation system requiring travel from one location to another, the other categories are as follows [15]:

- Transport Operators. Companies or organizations producing, owning, and operating the waterborne vehicles used for passenger mobility. Transport operators offer to passengers a transport means (vessels) and on-board transport services.
- Waterfront Infrastructure Providers. Entities responsible for constructing, maintaining, and operating the physical infrastructure that facilitates waterborne passenger mobility, including ports, docks, and terminals. They offer to passengers a place to arrive, to depart, to shift route, and to wait (i.e., terminals) and related services. Furthermore, Infrastructure Providers furnish Transport Operators with operational spaces for departures and arrivals, docking areas, as well as bunkering and energy recharge services.
- Service Providers. Companies that provide ancillary services related to waterborne passenger mobility, such as ticketing, booking, or food service. They offer to Transport Operators and Waterfront Infrastructure Providers services which will be delivered to passengers on board or at terminals; moreover, they offer services directly to passengers.
- Digital Infrastructure Providers. Entities or organizations that offer a digital environment or tools, encompassing both hardware and software solutions. They concur to create a digital network where digital technologies and services can support and complement operations happening within and between vessels, waterfronts, and services.
- Energy Providers. Companies that supply fuel or electricity for vessels and related infrastructures. They provide energy sources for infrastructures and terminals also used by Transport Operators to load and restock ships.
- Regulators. Government agencies or authorities responsible for overseeing and regulating the operation of waterborne transportation systems, ensuring safety and compliance with relevant laws and regulations. They deliver guidelines for all the actors' categories, especially Transport Operators, Waterfront Infrastructure Providers, and Energy Providers to regulate and manage safety, environmental, and technical issues.

Lifecycle stages indicate the lifespan phases during which Smart Digital strategies happen or rather the moment during which digital technologies are applied to the WPM ecosystem to enable and perform circular practices.

Smart Circular strategies describe the role of digital technologies in enabling circular principles to generate Smart Circular practices and foster the WPM ecosystem toward sustainability.

Digital technologies are encompassed in five clusters [25,26]: Internet of Things (IOT), Big Data Analytics (BDA), Blockchain and Cybersecurity (BC), Additive Manufacturing (AM), and Augmented and Virtual Reality (AVR).

- IOT. It refers to physical objects embedded with sensors connected within a network through the internet. These objects are capable of sharing information and communicating with other systems.
- BDA. It refers to the analysis of large amounts of unstructured data using data mining and advanced analytics techniques. This process helps identify patterns, trends, and associations that can be utilized to enhance decision making and optimize processes. Artificial intelligence is often employed to collect and analyze these data, as well as to train machine learning and deep learning algorithms.
- BC. These technologies embedded practices of safeguarding computer systems and networks from theft, damage, or unauthorized access, and secure and transparent recording of transactions.
- AM. It encompasses techniques used to create three-dimensional objects by depositing materials in layers, starting from a digital computer-aided design. This technology enhances flexibility, production speed, and customization in manufacturing processes.
- AVR. These technologies enable the addition of digital elements to the real world allowing the simulation of real situations and providing an enhanced user experience. AR adds digital elements to a live view, while VR is based on computer-generated simulations of three-dimensional environments.

Slightly updated from the first conceptualization of the framework to increase the consistency with the case studies, circular principles are categorized based both on circular loops proposed by Ellen MacArthur Foundation and on the 4Rs circular principles [18,21].

Given the absence of concrete examples of the application of circular economy in the specific sector of WPM, categories have been grouped to facilitate functional analysis. This approach aims to identify potential circular practices as a starting point for further exploration.

- Reduce. It refers to increasing material and energy efficiency and reducing emissions and waste.
- Regenerate. It encompasses the use of non-toxic material, or renewable energy, and the regeneration of natural ecosystems.
- Share. Use of products by multiple users thereby reducing the number of products needed to be made to satisfy more people. This approach promotes resource efficiency and contributes to a more sustainable use of goods.
- Maintain. Maintaining the product in its current state of quality, functionality, and/or appearance despite wear and tear. This practice aims to prolong the lifespan of the product, reducing the need for frequent replacements and contributing to resource conservation.
- Reuse. Keeping the product in use in its original form and for its original purpose, with minor modifications such as cleaning or small adjustments. This approach emphasizes extending the product's lifespan and functionality while minimizing the need for significant alterations or replacements.
- Redistribute. Changing the intended market of a product to target another market, thereby utilizing it at a higher value instead of it becoming waste. This strategy involves finding new applications or markets to prevent its disposal and maximize its value.

- Refurbish. Restoring the product to a good working status through actions such as repairing or replacing components, updating specifications, and improving cosmetic appearance. This process aims to extend the product's lifespan and functionality.
- Remanufacture. When products require more intensive work to remain in circulation and continue to be used, the process involves re-engineering products and components to achieve an as-new status with the same, improved, or upgraded performance, such as retrofitting products.
- Recycle. When products reach the end of their usable life and cannot be refurbished or remanufactured, the process involves transforming the products or components into their basic materials and reprocessing them into new materials.

3.2. Case Study Description

Case studies research has been carried out through desk research performed mapping the expansive European context where numerous projects on sustainability and the maritime sector have unfolded. Notably, a significant proportion of these projects have been executed in central and northern European regions. The first group of 14 case studies was collected by reviewing academic literature, reports, and documents from organizations and companies' websites. Interesting data and insights were also gathered from the TrAM Conference: Water to Land Mobility Hubs in September 2022, attended online [27], and from the Electric Boat Show Conference on May 2023 in Milan [28], where stakeholders from the waterborne transport sector and the urban mobility sector discussed sustainability, new trends, ACES technologies, and intermodality. The data underwent analysis to comprehend various characteristics of the mobility system. This included aspects such as the types of transport means, the number of terminals and lines, the covered geographical area, the pertinent actors within the ecosystem, the geographical scope, the sustainability level, and the degree of digitalization.

After the first mapping phase, five cases were selected through desk research performed to map the Northern European area, where the research on sustainability of the waterborne transport sector is gaining significant importance due to the widespread use of waterways as daily means of public transport. Rotterdam in the Netherlands, Stockholm in Sweden, Stavanger and Fredrikstad in Norway, and Kiel in Germany are countries where the morphology of the territory largely influences urban mobility and determines a high dependency on waterborne transport.

Case studies were selected from public waterway transport systems, whether they were already operational, launched, or in the project development phase. All of them have been developed within the last five years. The selection was based on predefined parameters that are instrumental in delineating the current state of the art and addressing the research question: cases are waterborne transport systems exclusively for passengers, operating in urban or suburban areas, that perform circular economy practices, and at least one of those is enabled by digital technologies.

Each case study is presented with a short description. Table 1, at the end of the section, summarizes the case studies.

3.2.1. Rotterdam, Netherlands—Watertaxi Rotterdam

Watertaxi Rotterdam is one of the main ferry operators of the city of Rotterdam which has the largest port in Europe and one of the world's busiest by annual cargo tonnage.

Watertaxi Rotterdam manages the urban waterborne mobility service with a fleet of 24 vessels, consisting of water taxis (Figure 2) and small ferries, with seven of them powered by renewable energy.

In 2022, they introduced in the fleet the MSTX 22, the first small ferry with hydrogen-based propulsion.

Vessels are made entirely of lightweight aluminum to reduce energy needs and consumption. The fleet is charged by renewable energy from wind and sun coming from the green energy company Eneco; moreover, their main station is equipped with 190 solar panels, generating 50,000 kWh/year [29].

Figure 2. Watertaxi Rotterdam operating its shared mobility service. Credits: Iris van den Broek—Rotterdam Make It Happen.

The service encompasses both a scheduled ferry system and an on-demand shared water taxi service through 50 different terminals. Through the Watertaxi Operation System developed by the maritime innovation group Flying Fish, passengers can easily book their trips between any of the 50 jetties in the city. The user receives real-time booking suggestions based on the network state.

Trips around the city can be combined in smart ways to maximize fleet capacity and minimize fuel consumption and emissions. Through the DyNaMo Databox, it is possible to collect position and motion data used in the planning software to compare the fleet state with the planned state. Furthermore, health data of the boat systems can be used to make maintenance procedures more effective [30].

3.2.2. Stockholm, Sweden—Zeam (Zero Emission Autonomous Mobility)

The Norwegian shipping company Torghatten in collaboration with Zeabuz, a company leader in autonomous technology for the maritime sector, developed Zeam, the electric and autonomous passenger ferry service connecting Kungsholmen and Södermalm in Stockholm (Figure 3). The aim of Zeam is to revitalize urban waterways with cost-cutting waterborne mobility solutions through autonomy-as-a-service, benefiting both mobility and ferry operators [31]. Launched in June 2023, the ferry departs three times an hour from each side. It is entirely electric, and it is mainly charged by solar panels placed on its rooftop, obtaining an emission-free service that minimally burdens the power grid. The autonomous navigation system, overseen by an on-board crew operator, can manage more performing and energy-efficient routes and operations according to the surroundings [32].

3.2.3. Stavanger, Norway—Medstraum and the TrAM Project

Norway highly depends on fast ferries because of the territorial morphology.

In Stavanger region, 56% of public transport emission is accounted for by transport through waterways, mostly by the fast ferries [27].

Many residents live in the nearby islands, and to reach the city center, ground transport is slow and lengthy, whereas ferries provide a fast solution for a quicker commute.

Figure 3. Zeam operating between Kungsholmen and Södermalm in Stockholm. Credits: Torghatten/Zeabuz.

The TrAM project, a European project aiming to create a zero-emission, high-speed passenger vessel using advanced modular production, developed its first ferry system currently operating in Stavanger. The first vessel, Medstraum (Figure 4), was launched in 2022. The service is provided by two vessels covering the urban and suburban areas with a multi-stop commuter route between Stavanger and the nearby islands. Vessels are entirely electric with an autonomy of 1.5 h. The service charges around fifteen times every day at Fiskepiren, a mobility hub that connect bus, train, bicycle, pedestrian, and car sharing routes. This water–land mobility hub fosters intermodality and resource efficiency of the whole transport system. Stakeholders collaborate through a unified platform that manages different transport modes in a more efficient way. The Kolumbus app facilitates ticketing and travel management for passengers across various mobility routes.

Figure 4. Medstraum vessel operating in Stavanger. Credits: Marius Knutsen/Maritime Cleantech.

The project developed a toolkit of methods and software tools using model-based system engineering that allowed deeper modular system integration and completely new types of digitalized production between all of the development partners [33,34].

The process integration enabled by the system allowed ship manufacturers to co-produce vessels with enhanced energy efficiency. A lightweight aluminum structure, a smaller electrical motor, an improved hull shape, and optimized component design resulted in reduced energy needs and consumption.

This modular and standardized design enables parts and components to be easily replaceable and eventually to be reused for future vessels of the same type. New vessels could be designed and built by piecing together pre-existing modules instead of starting from scratch, making the process more efficient and cost-effective [35].

Kolumbus is the mobility provider of the city and the shipowner of the ferries developed by the consortium of the TrAM project. The consortium is composed of manufacturers of the maritime industry, companies and research institutes specialized in technologies, and local government organizations, engaging both the public and private sector.

3.2.4. Fredrickstad, Norway—Hyke by Hydrolift Smart City Ferries

Hydrolift Smart City Ferries (HSCF) is a spin-off of the Eker Group, a Norwegian company specialized in design, development, and manufacturing services of the automobile sector, established in 2019. Moved by the idea of exploiting underutilized waterways as sustainable sources of transporting people and goods, (HSCF) developed Hyke (Figure 5), a zero-emission and autonomous waterborne shuttle to support cities, solve pollution and congestion problems, and contribute to smarter urban mobility [36].

Figure 5. Shuttle 0001, first model produced by Hyke, ready to operate. Credits: Hyke.

Hyke ferries are entirely electric and are charged by renewable energy from solar panels on the built-in rooftop and automatic wireless charging while docked at terminals. The docking system is equipped with auto-centering and auto-mooring technology, which creates a safe, stable connection even with wind and waves. Upon safely docking, the ferry automatically initiates wireless charging, enhancing run-time without the need for larger batteries, thereby reducing weight and cost. The docking system utilizes standard jetty modules, offering a low-cost compatible solution with existing jetties that is easy to deploy or relocate as needed.

Integrated sensor packs monitor the surroundings, enabling autonomous navigation to improve operational efficiency and optimize vessel performance and routes.

The vessel is designed for mass production, based on modularity and standardization to improve its lifecycle impact (i.e., Hyke has the capability to achieve approximately 90% reduction in CO_2 emissions) [37].

Hyke Shuttle 0001 has been launched for commercialization in 2023 and HSCF is weaving collaborations with local operating partners.

3.2.5. Kiel, Germany—Captn (Clean Autonomous Public Transport Network)

Kiel is a city in northern Germany with a strong connection to waterborne transport, and its port plays a crucial role in both regional and international trade. Given its territory surrounded by fjords and divided by the Kiel Canal into two main shores, waterborne mobility plays a fundamental role in the urban daily life of the area. Besides the city ferry transport transitioning towards a zero-emission propulsion giving an emphasis to intermodality, the University of Kiel is running the CAPTN project. The initiative aims to advance well-connected intermodal water–land mobility and autonomous driving with a focus on the development of an autonomous and clean passenger ferry that would connect the east and west banks of the Kiel Fjord [38].

CAPTN is a brand umbrella which encompasses a network of projects each with a specific focus on a particular aspect of the mobility ecosystem including vessels, digital infrastructure, and energy supply. The projects VAIARO and WAVELAB (Figure 6) are actively engaged in developing autonomous ferry concepts, utilizing rechargeable batteries and hydrogen fuel cell propulsion systems.

Figure 6. Research vessel MV Wavelab by CAPTN. Credits: https://www.deutzmag.com/captn-e-la-rete-per-il-trasporto-pubblico-di-nuova-generazione-sullacqua/ accessed on 29 November 2023.

Meanwhile, FJORD AREA and FJORD 5G are dedicated to establishing a digital test area and a 5G communication system to facilitate robust data management. Utilizing a digital twin for virtual simulation during the design phase typically leads to a reduction in the physical assets required, thereby enhancing the overall resource efficiency of the process. Moreover, the project FLEX is constructing a comprehensive framework for data collection and analysis supported by artificial intelligence and seamless integration of connected systems. FLEX will implement efficient processing and analysis to improve mobility forecast and manage optimized ferry routes and operations. Finally, the ENERGY project is dedicated to establishing a supply chain for renewable energy, encompassing the development of methods for conversion, storage, as well as the transport and utilization of this sustainable energy source.

Table 1. Summary of the identified case studies and the related circular principles implemented. Only circular principles enabled by the use of digital technologies, highlighted in bold, were selected to be analyzed through the Smart Circular WPM Ecosystem framework.

Case	Description	Status	Addressed Circular Principle
Watertaxi Rotterdam	Urban water taxi service of 24 vessels offering scheduled ferry service and on-demand shared service.	Launched (2020)	Regenerate: electric zero-emission ferry charged by renewable energy from wind and sun, and production of 50,000 kWh/year from the solar panels at the terminals. Reduce: vessels entirely made by lightweight aluminum to reduce energy needs and consumption. **Share: trips around the city combined in smart ways to maximize fleet capacity and minimize fuel consumption emission.** **Maintain: maintenance procedures more effective by using the data collected from the fleet monitoring.**
Zeam	Autonomous passenger ferry operates one line in the city center, departing three times an hour.	Launched (2023)	Regenerate: electric zero-emission ferry charged by renewable energy from solar panels on the rooftop. **Reduce: autonomous navigation improving vessel performance and route optimization.**
TrAM Project	European project aiming to create a zero-emission, high-speed passenger vessel using advanced modular production. A ferry system with two vessels operates in urban–suburban multi-stop commuter route between Stavanger and the nearby islands.	Launched (2022)	Regenerate: electric zero-emission ferry charged by renewable energy at terminal. Reduce: vessel's structure made by lightweight aluminum, smaller electric motor, improved hull shape, and components' details redesigned to reduce energy needs and consumption. **Reduce: water–land mobility hub to foster intermodality and resource efficiency of the entire transport system.** **Refurbish: standardized and modular design allowed, by a toolkit of methods and software tools, enabling parts and components to be easily replaced.**
Hyke	Norwegian zero-emission waterborne mobility start-up aiming to help cities solve pollution and congestion problems by deploying networks of zero-emission electric, autonomous ferries for mobility and last-mile logistics.	Launching for commercialization (2023)	Regenerate: electric zero-emission ferry charged by renewable energy from solar panels on the rooftop and automatic wireless charging while docked at terminal. **Reduce: autonomous navigation improving vessel performance and route optimization, autonomous docking and charging.** Refurbish: standardized and modular design enabling parts and components to be easily replaced.
CAPTN	Well-connected intermodal water–land mobility and autonomous driving focus on ferry system. The initiative is composed of more projects.	Ongoing project (from 2018)	Regenerate: ferry utilizing hydrogen fuel cells and rechargeable batteries charged by renewable sources. **Reduce: use of virtual simulation instead of physical assets to test the project.** **Reduce: autonomous navigation improving vessel performance and route optimization.**

4. Results

4.1. Application of the Smart Circular WPM Framework to Case Studies

This section presents the results of the application of the Smart Circular WPM framework to the five cases selected.

Cases are analyzed starting from the circular principle they addressed by performing a circular practice, or rather from the circular principle they aim to fulfill. For each principle identified, the main digital technologies involved are selected by understanding how digitalized solutions facilitate circular practices. Additionally, the identified technologies are associated with specific lifecycle phases in which they are applied.

Finally, the main categories of actors involved are selected based on those who have directly introduced a change within the system or an innovation, to concur with the activation of the circular practice.

In some cases, the same actor can carry out more functions relating to different actors' categories.

4.1.1. Watertaxi Rotterdam

Watertaxi Rotterdam (Figure 7) performs circular practices by sharing and maintaining. Sharing is enabled by the combination between IoT and BDA technologies which, through an algorithm for automatic fleet planning, can combine trips around the city in smart ways to maximize fleet capacity and minimize fuel consumption and emissions. Instead of booking on-demand personal service, users can share the vessel with other users looking for similar routes by receiving real-time booking suggestions based on the network state. The integration of IoT and BDA also enhances the effectiveness of maintenance procedures through data collected by the DyNaMo Databox. These data aid in monitoring the system, thereby preventing or predicting malfunctions. Both smart circular practices happen during the usage phase of the ecosystem lifecycle.

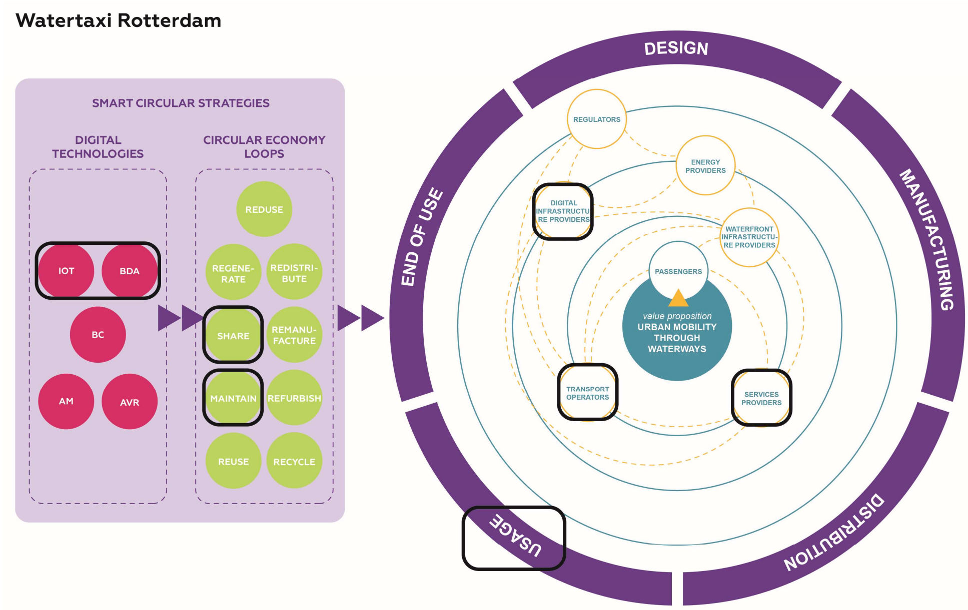

Figure 7. Smart Circular WPM Ecosystem framework of Watertaxi Rotterdam. Digital technologies, circular principles, lifecycle stages and actors involved are underlined with a black box.

The main actors' categories involved in the application of the practices are Transport Operators (Watertaxi Rotterdam, which is the waterborne mobility operator, and the shipyard), Digital Infrastructure Providers, and Service Providers (the company that developed the algorithm and the databox, which also provides the app for the ticketing and booking management, offering a complementary service).

4.1.2. Zeam

Thanks to its autonomous navigation system, Zeam (Figure 8) is reducing energy consumption and emission discharge. Through the use of IoT and BDA, the system can manage displacements of the fleet according to the surrounding areas, choosing more optimal routes and operations. The practice happens during the usage phase of the ecosystem.

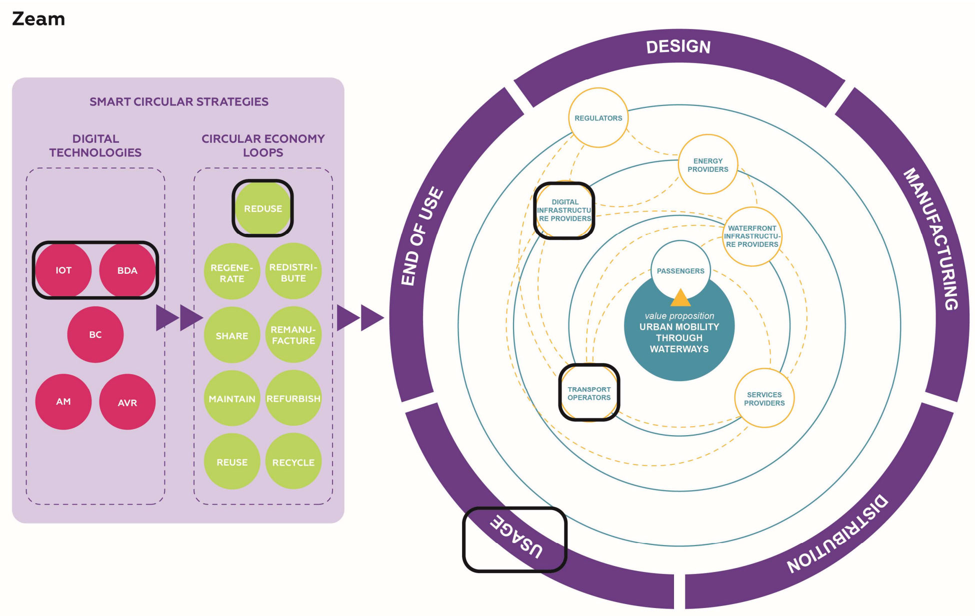

Figure 8. Smart Circular WPM Ecosystem framework of Zeam. Digital technologies, circular principles, lifecycle stages and actors involved are underlined with a black box.

The main actors involved are Transport Operators (the shipping company operating the system) and Digital Infrastructure Providers (the company developing autonomous technologies for the maritime sector).

4.1.3. TrAM Project

The ferry system developed by TrAM project (Figure 9) performs circular practices by reducing and refurbishing. By combining IoT and BDA technologies, the service and the water–land mobility hub operate within a unified platform that efficiently manages the transport system. This integration enables a more effective intermodality in the overall transport network. The Kolumbus app integrates routes from various transport systems, offering passengers a convenient tool for managing their journey seamlessly across different modes of transport, eventually avoiding owned private vehicles. These actions and the establishment of an integrated intermodal transport platform contribute to an overall reduction in emissions and use of resources. It takes place during the usage phase. A refurbishing strategy is fulfilled thanks to the use of AVR technologies which helped to design a modular and standardized product where parts and components can be more easily replaced or be reused for future vessels of the same type. This practice is being enabled in the design phase.

The major actors' categories involved in the achievement of these practices are firstly Kolumbus in the place of Transport Operator as shipowner and mobility provider, and as Waterfront Infrastructure Provider by conducting the implementation of the mobility hub. Kolumbus also acts as Service Provider offering the service of ticketing and journey management through its app. On the other hand, the main actors involved in implementing a better refurbishing vessels' system are Transport Operators and Digital Infrastructure Providers encompassing consortium partners that include manufacturers of the maritime industry, companies, and research institutes specialized in technologies which co-developed the toolkit of methods and tools to achieve modularization and standardization.

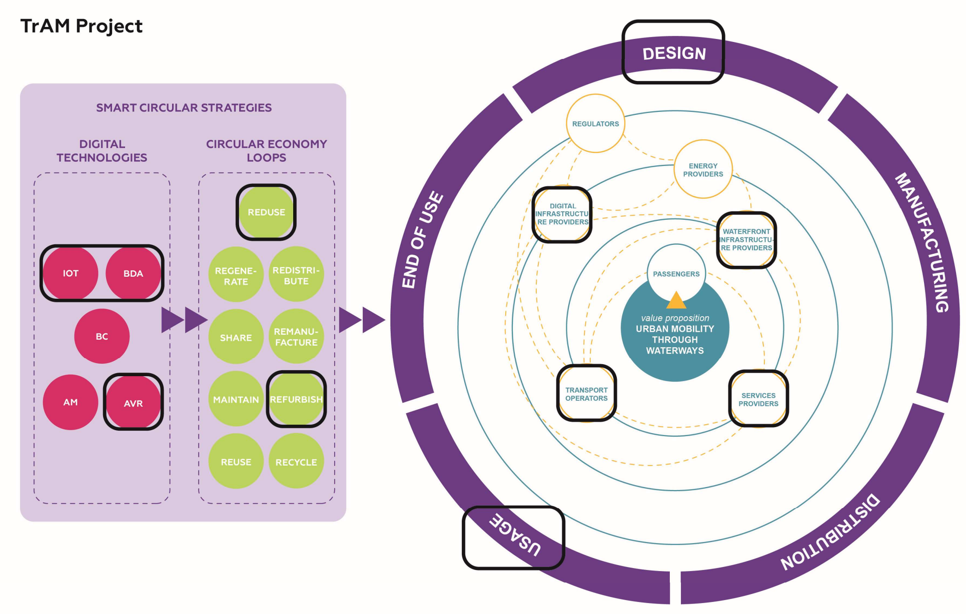

Figure 9. Smart Circular WPM Ecosystem framework of TrAM Project. Digital technologies, circular principles, lifecycle stages and actors involved are underlined with a black box.

4.1.4. Hyke

Hyke (Figure 10) is a ferry system thought to foster a zero-emission urban mobility model using autonomous vehicles. The aim of reducing emissions and enhancing the efficient use of resources is driven by the use of IoT and BDA technologies which enable a condition-aware and autonomous system that optimizes operations both during navigation and during charging at terminal. The circular practice happens in the usage of the ferry system.

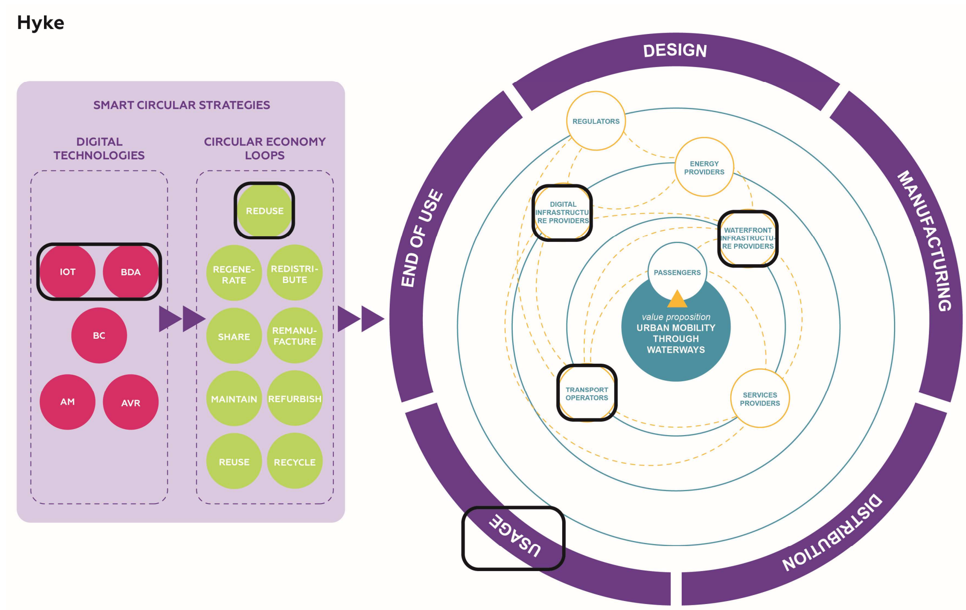

Figure 10. Smart Circular WPM Ecosystem framework of Hyke. Digital technologies, circular principles, lifecycle stages and actors involved are underlined with a black box.

The innovation is implemented by the Transport Operators' category as the project is held by a single company which manages the design and building of the entire vessel. However, other actors will be involved to implement Hyke as urban transport. To launch

Hyke as a mobility system in cities, HSCF is already making contacts with local operating companies that fall into the Transport Operators' category. The wireless autonomous charging system would be implemented by incorporating the backup battery module on terminals and this will involve other stakeholders belonging to the Waterfront Infrastructure Providers category.

4.1.5. CAPTN

The CAPTN (Figure 11) initiative aims to develop a waterborne mobility system reducing emissions and waste and fostering a better use of resources both during the operations occurring in the design phase and during the usage of the system. In the design phase of vehicles, the use of virtual simulation instead of physical assets reduces the need for producing prototypes or parts for testing. Implementing autonomous navigation, facilitated by IoT and BDA, enables the ferry system to optimize energy performance and routes, leading to more efficient fleet management during the usage phase. The main actors' categories involved in developing the innovations are Transport Operators, performed by the two projects (VAIARO and WAVELAB) developing the autonomous vessels, and Digital Infrastructure Providers, the projects (FJORD AREA, FJORD 5G, and FLEX) building and implementing the infrastructure for testing and simulation, and for data management.

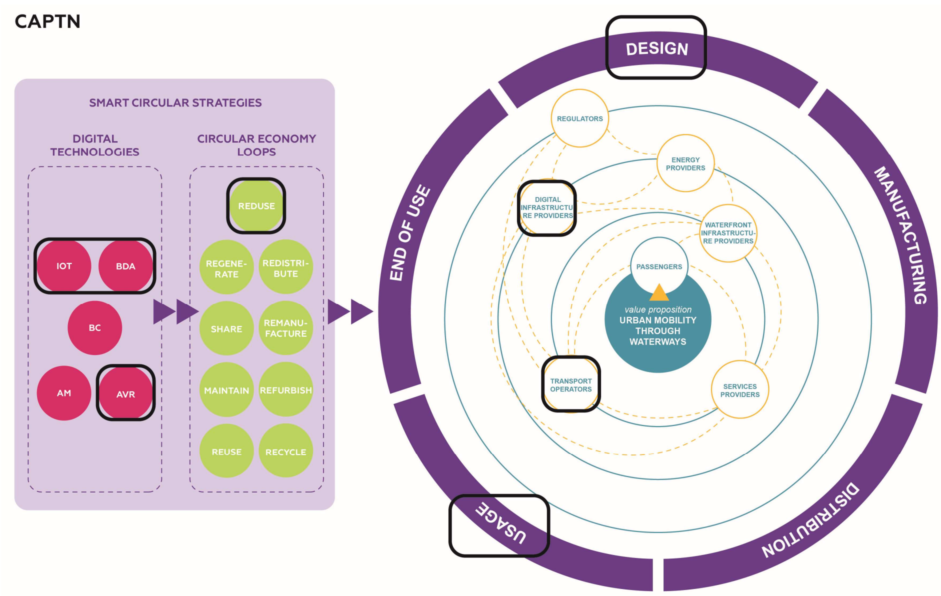

Figure 11. Smart Circular WPM Ecosystem framework of CAPTN. Digital technologies, circular principles, lifecycle stages and actors involved are underlined with a black box.

Figure 12 represents a summary of the five Smart Circular WPM Ecosystem frameworks, showing which digital technologies are used for addressing each circular principle and in which lifecycle phase. Moreover, it shows the actors' categories mostly involved.

4.2. Findings and Discussion

By analyzing data gathered from the application of the framework to the case studies, it is possible to outline Smart Circular practices implemented in the waterborne passenger transport systems of the Northern European area.

The majority of cases perform Smart Circular practices which aim at reducing emissions and waste and increasing material and energy efficiency. These practices are enabled mostly by the combination of IOT and BDA technologies in the usage phase, and include autonomous navigation, autonomous charging, and the creation of an intermodal transport platform. With the use of AVR technologies during the design phase, virtual testing is performed to reduce the use of physical assets.

Case	Reduce	Regen.	Share	Maint.	Reuse	Redistr.	Refurb.	Reman.	Recycle	IOT	BDA	BC	AM	AVR	TO	SP	WIP	DIP	EP	R
Watertaxi Rotterdam			IOT and BDA	IOT and BDA						USAGE	USAGE									
Zeam	IOT and BDA									USAGE	USAGE									
TrAM Project	IOT and BDA						AVR			USAGE	USAGE			DESIGN						
Hyke	IOT and BDA									USAGE	USAGE									
CAPTN	AVR, IOT and BDA									USAGE	USAGE			DESIGN						

Figure 12. Summary of the Smart Circular WPM Ecosystem frameworks applied to the five case studies. Tacking up the colors of the framework, green is used for circular principles, pink is used for digital technologies, purple is used for lifecycle stages, and yellow is used for actors' categories. Actors' categories are abbreviated with initials: Transport Operator (TO), Service Providers (SP), Waterfront Infrastructure Providers (WIP), Digital Infrastructure Providers (DIP), Energy Providers (EP), and Regulators (R).

Other Smart Circular practices identified from the case studies aim at sharing, maintaining, and refurbishing.

Regarding the sharing strategy, a shared on-demand service is enabled and managed by IOT and BDA during the usage phase.

The utilization of IOT and BDA technologies throughout the usage phase enables the monitoring of fleet status to improve the system's maintenance.

Finally, AVR technologies used during the design phase can also support modularization and standardization practices to foster refurbishing strategies.

Table 2 illustrates Smart Circular practices performed in the case studies, indicating the number of cases in which the practice is addressed.

Table 2. Smart circular practices performed in the case studies.

Circular Principle	Digital Technology	Lifecycle Stage	Smart Circular Practice	Number of Cases
Reduce	IOT and BDA	Usage	autonomous navigation	3
Reduce	IOT and BDA	Usage	autonomous charging	1
Reduce	IOT and BDA	Usage	intermodal transport platform	1
Reduce	AVR	Design	virtual testing	1
Share	IOT and BDA	Usage	share on-demand service	1
Maintain	IOT and BDA	Usage	fleet status monitoring	1
Refurbish	AVR	Design	modularization and standardization	1

The integration between IOT and BDA is the digital technology solution most used in the cases, which is especially applied in the usage phase but also during the design phase. AVR technologies are also used exclusively during the design phase.

The actors of the ecosystem mostly involved in implementing those practices comprise the Transport Operators category and the Digital Infrastructure Providers.

This trend underlines the actual involvement of the sector in adopting digital technologies and sustainable practices starting from the means of transport, which is the object of the focal actors' category of the WPM ecosystem, or rather those actors that can be considered the primary providers of the service.

The practices happening during the design phase, such as virtual testing and modularization and standardization, are performing at a product level focusing on the vessel and its sustainable performances.

The other practices implemented during usage enable circular opportunities on a more systemic level by examining the service and the relationships among vessels within the environment. This includes interactions between vessels, relationships between vessels and terminals, and connections between the waterborne transport system and other transport systems.

Autonomous navigation and charging, intermodal platform, shared mobility, and fleet status monitoring are among the main actions the transport sector is undertaking for the development of a sustainable and smart mobility. These practices are ingrained in the ACES (Autonomous, Connected, Electric, and Shared) transport, reflecting the direction in which the transport sector is evolving due to recent technological advancements [39].

Especially concerning the intermodal platform and the related concept of the mobility hub, these practices form the foundation of an approach that envisions waterborne transport as an ecosystem within the broader urban mobility ecosystem, seamlessly connecting all modes of transport.

5. Conclusions and Future Developments

This study aims to identify the circular principles inherent in the sustainable innovative actions undertaken by the waterborne passenger mobility sector. It also seeks to provide an overview of the current state of the art and the prevailing directions characterizing this sector. In particular, this study examines the support provided by digital technologies and the involvement of the actors' ecosystem in achieving these actions to uncover further opportunities that can trigger a systemic approach and circular economy.

This study confirmed that the WPM sector is actively working on sustainability by focusing on innovative propulsion systems, such as electric zero-emission or hydrogen fuel cell ferries powered by renewable energy from wind and solar sources. Additionally, efforts are frequently directed towards minimizing energy consumption through initiatives like reducing the vessel's weight, such as employing aluminum structures, and enhancing other components while also improving the hull shape [6].

However, the impact of digitalization on achieving sustainability is particularly found in reducing emissions and resources used through the automation of operations (i.e., navigation and charging), the integration within the other mobility systems, and the use of AVR technologies to implement virtual testing mitigating the need for physical assets. Digitalization also supports the implementation of sharing practices by facilitating continuous data exchange throughout the system. Moreover, it contributes to the improvement of maintenance and refurbishment operations through the constant monitoring of the system during its use, and the modularization of parts during the design phase.

Through the analysis of five case studies selected within the Northern European region and the application of the Smart Circular WPM Ecosystem framework, a list of Smart Circular practices has been defined resulting from the application of digital technologies during specific lifecycle stages, involving certain actors' categories, and enabling circular principles.

The case study analysis highlighted unexplored or under-considered fields of action related to circular principles, technologies, lifecycle stages, and actors' engagement. The research conducted did not uncover examples of the application of AM technologies in the waterborne passenger transport sector; however, progress in research has been observed in the nautical pleasure craft sector and the yacht industry, particularly concerning prototyping, customization, and the replacement of parts and components using AM technologies [40].

CB technologies remain unaddressed within the explored European context, and there is a lack of studies investigating their potential to specifically enable circularity in the WPM sector, despite their direct relevance to data management and sharing.

Further research can focus on understanding how the yet unexplored digital technologies can support circular practices. The following studies may explore the use of additive manufacturing (AM) in enabling circular practices by allowing local, on-demand, efficient, and real-time production. On-demand production of spare parts for repair and upgrading purposes can facilitate, for example, the retrofitting or restoration of terminal or vessel furniture and components, extending the lifetime of the physical assets of the waterborne transport system [15,41].

Other studies may focus on the role of cybersecurity and blockchain (CB) in ensuring trust, transparency, traceability, and security within the digital infrastructure system in which the WPM is implementing Smart Circular practices. These technologies have the potential to foster systems integration ensuring the tracking of resources across the value chain and among the stakeholders of the WPM ecosystem [15,42].

A more in-depth investigation, including field research of the cases and interviews with stakeholders, can investigate how the adoption of digital technologies in other life-cycle stages can be advantageous for circularity; moreover, it may explore how a major engagement of all the actors of the WPM ecosystem can foster circular economy solutions, unleashing its systemic nature [18].

To investigate the impact of Smart Circular strategies on actors and their interconnected relationships, participatory research with stakeholders will be undertaken. This exploration aims to understand how these actors can influence and be influenced by such strategies, how the ecosystem needs to be modified to become smart and circular, and if it would be necessary to conceive new actors, relationships, or touchpoints, ultimately leading to reimage, redesign, and reshape the ecosystem to promote a sustainable mobility system.

The authors previously introduced the Smart Circular Waterborne Passenger Mobility (WPM) Ecosystem framework as both a methodology and a tool for examining the state of the art, identifying gaps, and discovering opportunities for implementing a smart and circular model within the ecosystem. This document presents an updated version of the framework, refined through more in-depth studies. The suggestion for future research involves direct engagement with stakeholders within the WPM ecosystem to enhance and further detail the framework and its elements. This research emphasizes and undertakes a multidisciplinary approach that involves different types of knowledge, and which is directly related to the involvement of actors from different industries and fields having certain roles within the waterborne passenger ecosystem. This multidisciplinary and multilevel view is inevitably required when a holistic and ecosystem perspective is considered.

This research contributes to the advancements in sustainability and circular economy, particularly in the waterborne mobility sector, where the knowledge on the issue is still fragmented [3,4]. It paves the way for a new research stream that considers the potential of digital technologies in achieving a circular waterborne mobility system, and the implications on the entire ecosystem and its actors.

These findings involve the overall urban mobility sector and urban environment studies. By considering waterborne transport as a system integrated within a multi-modal mobility ecosystem, this study proposes to explore new developing patterns for sustainable solutions that fit into urban transport ecosystem management. The mobility sector is developing its trends towards the ACES (autonomous, connected, electric, shared) concept [27,39]. Mobility-as-a-service and electric propulsion systems have been largely widespread in the last few years, especially in car mobility and micro-mobility. Autonomous and interconnected vehicles represent one of the predominant themes in both public and private transport on land continuing to advance through studies and prototypes [27].

This study contributes significantly to the achievement of Smart Circular Economy models in the WPM ecosystem, but further research is needed to deepen the issue and define a methodological framework for developing design strategies and guidelines. A comprehensive understanding of the entire system which engages all the actors and considers every phase of the ecosystem's journey is essential for advancing the research towards its objective.

The more considerable challenges to shift the sector towards a smart and circular model lie in the ecosystem dynamics. The role of actors, their interactions, and cooperation are essential elements to foster integrated and enduring solutions. This cooperation among transport operators, infrastructure, service, digital, and energy providers can be enhanced through the value chain integration enabled by digitalization.

Policymakers are recommended to pursue that direction through the development of a normative infrastructure that can support the adoption and the use of digital technologies, as well as the application of circular strategies within the ecosystem. The development of strategies and guidelines for practitioners such as stakeholders, designers, and policymakers will be the subject of future activities of this research.

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