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Paving the Way Towards Zero-Emission and Robust Inland Shipping

A. Kirichek[a*], J. Pruyn[a,b], B. Atasoy[a], R. R. Negenborn[a], R. Zuidwijk[c], J.H.R. van Duin[a,b], K. Tachi[d] and M. van Koningsveld[a,e]

[a] Delft University of Technology, Delft, the Netherlands
[b] Rotterdam University of Applied Sciences, Rotterdam, the Netherlands
[c] Erasmus University Rotterdam, Rotterdam, the Netherlands
[d] Expertise and Innovation Centre Barging, Rotterdam, the Netherlands
[e] VanOord, Rotterdam, the Netherlands
*Corresponding Author o.kirichek@tudelft.nl

Abstract

Several measures have been developed to prevent emissions from inland water transportation. However, it is challenging to weigh all the aspects to identify the pathway that will ultimately result in zero-emission inland shipping. A data-driven virtual representation of the inland shipping system can be used to evaluate zero-emission strategies, effectiveness of policies and technologies, and consequences of their implementation. This multi-level digital twin can realistically represent the system with all relevant components, which needs to be validated using real-world data. Subsequently, future scenarios can be imposed on the digital twin, and the proposed intervention measures can be applied, based on which their efficiency can be assessed together with the inland shipping sector.

This study discusses the essential aspects of designing a digital twin for an IWT. Three aspects are considered essential: individual ships, logistics chains, and infrastructure. As these research topics span various scales, ranging from a single vessel to an entire infrastructure network, an agent-based approach is suitable for forming the basis of the digital twin. Consequently, potential interventions can be considered, ranging from the application of new technologies to individual vessels to policy measures implemented for an entire shipping corridor or various bunker infrastructure strategies in the network. Additionally, the impact of the implemented interventions can be evaluated at any desired scale, ranging from the individual ship level and its emissions to the network level and aggregated emissions in an entire area, or the impact on the logistics chain.

Keywords: Emissions, PATH2ZERO, Multi-level digital twin, inland waterway transport, Energy transition, Sustainability.

1. INTRODUCTION

Inland waterway transport (IWT) is vital to the European economy. This mode of transport is highly efficient and contributes significantly to a region's trade volumes. Furthermore, the IWT is one of the most energy-efficient modes of transport per ton of transported goods, consuming only 17% of the energy required by often-congested road transport and 50% of rail transport. This sector already plays an important economic role in transporting goods and passengers in Europe. Despite its efficiency, IWT contributes to greenhouse gas emissions. Given the projected growth in the European economy, emissions from IWT will rise unless proactive measures are taken. The Paris Agreement set the ambition to limit global warming to 1.5 °. In line with the Paris Agreement, the EU aims to become a carbon-neutral economy by 2050, with a 55% reduction in CO_2 emissions by 2030. To achieve these goals, the 2019 European Green Deal reaffirmed that the EU transportation sector must reduce its emissions by 90% by 2050. A significant proportion (75%) of the inland freight transported by road today should be shifted to inland waterways and rail. The Green Deal also called for measures to increase the unused capacity of inland navigation. With the Sustainable and Smart Mobility Strategy of December 2020, the European Commission outlined the planned transformation of the EU transport system, including a 25% increase in IWT and short-sea shipping by 2030, and 50% by 2050. This will require measures, such as improved connections and a more modern shipping infrastructure that ensures year-round navigability. Its untapped potential to increase capacity justifies the renewed attention it has recently received in terms of sustainable development.

Several emission reduction measures have been developed in recent decades [1], [2], [3], [4]. Currently, there are no obvious pathways toward zero-emission shipping because of the many

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uncertainties regarding all aspects of zero-emission shipping. The aim of this study is to address the challenges of shipping, transport chains (logistics), and infrastructure in the transition to zero-emission (ZE) IWT. The remainder of this paper is organized as follows. First, up-to-date emission reduction measures for inland navigation were categorized. Second, the challenges in accelerating the transition and filling the remaining knowledge gaps are discussed. Third, the potential of digital twin solutions for accelerating the transition to zero-emission and robust inland navigation is discussed. Finally, conclusions are summarized.

Table 1. Average annual emission factors of the inland navigation fleet for diesel engines and total emissions of IWT reported by CCNR [4].

Emissions	g/kWh	Total (kt)	Sources
CO_2	673-771	4149	[4],[5],[7]
CO	1.3-5.3	38	[4],[5],[6]
NO_x	3.75-10.8	61	[4],[5],[6],[7]
N_2O	0.017-0.019	-	[5]
NH_3	0.0021-0.0024	-	[5]
PM	0.01-0.6	2	[5],[6],[7]
SO_2	0.004-0.486	-	[5]
VOC	0.2-1.2		[5],[6]
CH_4	-	0.2	[4]

2. EMISSION REDUCTION MEASURES FOR IWT

2.1 Types of emissions from IWT

The vast majority of inland ships today use diesel engines, which are similar in principle to those used in non-road mobile machines, locomotives, and small-sea vessels. However, it is essential to note that IWT uses low-sulfur diesel (EN590), which is similar to automotive fuel. The distinction between non-road mobile machines, including IWT and road transport, is evident in the regulatory standards. Until NRMM STAGE V, regulations for non-road machines were less stringent than those for road transport, particularly concerning emission limits for air pollutants. For instance, the permissible levels of pollutants such as NO_x and PM are much higher. The combustion of fuels produces emissions of various greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In addition, inland shipping generates other air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), and particulate matter (PM).

Table 1 summarizes the emission factors of the diesel engines of the inland navigation fleet and total emissions of the IWT. In terms of absolute weight, CO_2 emissions were the most dominant emissions from the IWT. However, external costs or air pollutant emissions may be higher depending on the area in which they are emitted.

2.2 Current strategies for emission reduction from IWT

The main strategy for achieving ZE IWT is to use energy carriers with a low well-to-wake carbon intensity. Substantial leaps in emission reduction for the IWT can be achieved by a transition to renewable and/or low-carbon fuels complemented by alternative energy converters. Various alternatives to diesel can be considered. These can be divided into three groups.

- Biofuels: biomass-based energy sources;
- E-Fuels: fuels produced by renewable electricity;
- Electricity.

Figure 1, adapted from [8], shows well-to-wake CO_2-equivalent emissions for current fossil fuels and alternative fuels that are considered for reducing emissions from IWT. The data suggests that biofuels can substantially decrease the emissions from IWT as tank-to-wake emissions can be minimized as confirmed by a number of studies [9]. At the same time, a long-term strategy can be focused on minimizing the emissions to zero by drawing more attention to E-Fuels and electricity. The storage of the latter can provide a promising alternative to other types of fuels for IWT as battery systems can either be integrated into the hull of the ship or can be installed in a standard container that could then be inter-changeably stored on the ship.

Other emission reduction strategies mainly focus on ship-related or logistics-related measures. Ship-related measures include technologies that can be incorporated into a ship to reduce the ship’s emissions compared to the original ship design. These measures focused on novel designs, retrofits, or newly built ships. With the support of sensing, computation, and communication technologies, new techniques for decision support and control can be developed to optimize operational decisions from an emission-aware/sustainability perspective. Furthermore, new technologies include solutions for a ship's propulsion system, which consists of the ship’s hull and propeller. The measures aim to optimize energy consumption by reducing ship resistance, improving thrust efficiency, improving power generation efficiency or retrofitting current engines.

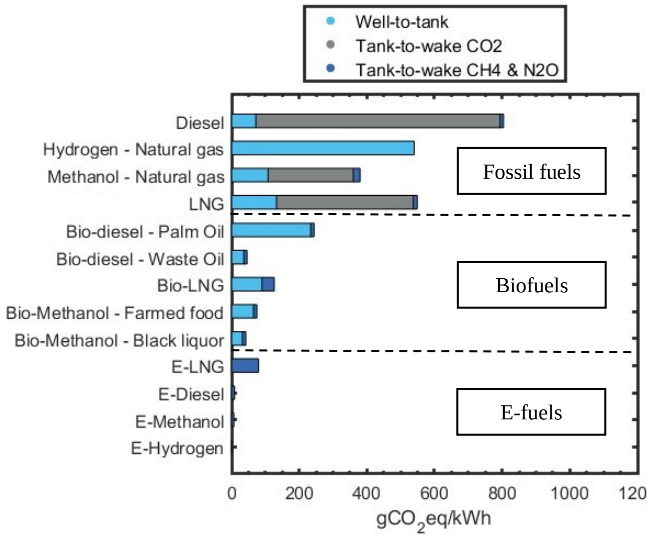

Figure 1: Reported well-to-wake CO_2-equivalent emissions for current and alternative energy carriers for IWT (adapted from [8])

Logistics-related measures include optimizing sailing routes to ensure that the most efficient paths are taken, minimizing empty voyages to enhance transport efficiency, and maximizing cargo loading to ensure optimal utilization of available capacity. Furthermore, other operational measures can involve advanced scheduling to avoid congestion at ports, terminals, and locks.

Over the past two decades, several measures have been developed to reduce emissions from IWT. These measures can be divided into ZE measures that lead to ZE IWT and measures that can reduce emissions from the IWT to a certain level. Both categories can be further categorized into technical (ship-related) and operational (logistics-related). An overview of the currently available emission reduction measures for IWT is shown in Figure 2.

Apart from measures related to alternative fuels and retrofitting/replacing existing engines to use these fuels, other measures offer a smaller impact than alternative energy carriers. However, these measures are important to achieve robust energy consumption during the transition to renewable and/or low-carbon fuels supplemented by alternative energy converters.

2.3 Ship’s emission reduction measures

2.3.1 Retrofitting and replacing engines

One of the short-term emission reduction strategies can be focused on retrofitting or replacing existing engines with alternative fuels. Currently, there are two types of engines for introducing new fuels.

1) Compression ignition engine: Air is compressed so much that it heats up and ignites the fuel. Fuels with different auto-ignition temperatures require different engine types. The following fuels can potentially replace diesel in this type of engine [10]: vegetable oil, DME (dimethyl ether), GTL (gas-to-liquid), BTL (biomass-to-liquid), and HVO (hydrotreated vegetable oil).

2) Spark ignition engine: the fuel-air mixture will not ignite until a spark is created. The compression ratio is much lower (typically 1:11) than 1:20 for compression ignition in compression ignition engines. The following fuels are used in engines [10]: gasoline, ethanol, methanol, natural gas, biomethane (both CNG and LNG), and hydrogen.

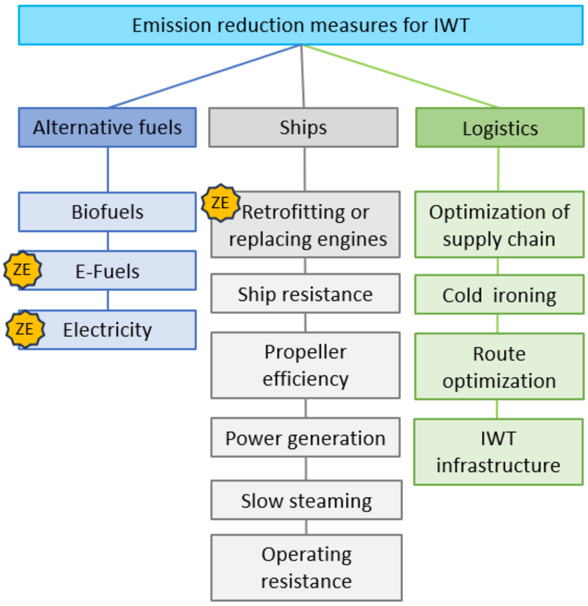

Figure 2: Overview of the current emission reduction measures for IWT. ZE indicates zero-emission measures.

Alternative fuels can be used in three main ways:

1) Mono-fuel: Changing the engine type requires major adjustments because parts of the engine must be rebuilt. Therefore, it is easier to install new engines.

2) Dual-fuel: Two fuel systems on a ship. Typically, a small amount of diesel fuel is used as the pilot fuel to initiate the ignition process, followed by combustion of the selected alternative fuel. The side-to-side use of two mono-fuel engines is also considered an emission-reduction strategy.

3) Designing new ships: selecting the right energy convertors and energy carriers for new ships (e.g. electric drive using batteries, fuel cells).

For energy carriers, the focus is on ZE tailpipe emissions (batteries, hydrogen, and hydrogen carriers), although bio or synthetic diesel combined with internal combustion engines is considered because of their high TRL and positive impact in the short term. Further reduction of air pollutant emissions from combustion engines can already be achieved with available Stage V engines (e.g., Euro VI and NRE engines); however, a comparison with ZE tailpipe solutions from a full well-to-wake and life cycle viewpoint still has to be made. Matching power configurations (internal combustion, fuel cells, and batteries) are also included, while bunkering is limited to the traditional transfer or charging and swapping of containers and tanks as the two most likely options.

2.3.2 Ship resistance

Reducing the ship's resistance lowers the power required for a given speed and thus lowers fuel consumption and emissions. Considering the current weather conditions, currents, and hull fouling, an extra effective propeller power is required to overcome the additional resistance. Ship resistance is particularly affected by ship design, design speed, and hydrodynamics of the hull.

The structural design of the hull of an IWT ship should be optimized based on the specific route and dimensions of the waterway, as well as hydrodynamic conditions (e.g., low water level and current velocities) that affect the ship's resistance.

The ship design and propeller selection can be optimized through better structural design and advanced materials. Fiber-reinforced plastic composites, high-strength steels, and aluminum alloys are the primary lightweight materials currently used in the maritime industry [11]. Research and application of metal sandwich panels and lightweight steel-composite sandwich panels with novel joining methods have shown their advantages. These novel arrangements and lightweight materials are expected to be widely used in superstructures, secondary structures, and components for all types of inland vessels.

In addition, advanced hull coatings can reduce frictional resistance, resulting in fuel savings.

2.3.3 Propeller efficiency

The main opportunities for optimizing propulsion efficiency in an IWT relate to hull efficiency and relative rotative efficiency, which depend on high-efficiency propellers, improving wake distribution, and recovering rotational energy.

A more homogeneous wake translates into better propeller efficiency. Wake equalizing devices, such as ducted propellers, wake equalizing ducts, and nozzles, aim to improve wake distribution and reduce flow losses around the working propeller. Another group of power-saving devices is aimed at recovering rotational energy from the water downstream of the propeller and converting it into thrust. Many devices have also been proposed to recover some of the rotational energy of water.

2.3.4 Power generation efficiency

Currently, there are some opportunities for fuel savings in the main and auxiliary engines, as well as in the various energy-consuming equipment on board ships. New technologies are currently targeting traditional diesel engines. However, all of these engine technologies have nearly reached their limits in terms of improving energy efficiency. The potential for further fuel savings is typically less than 1%. However, converting to battery-electric sailing can save approximately 50% of the energy, because the thermal loss in the conversion of electrical power to mechanical power at the propeller shaft is much lower.

In addition, more emphasis is being placed on reducing NO_x and particulate matter emissions from IWT engines. For CCNR Stage II engines, this reduction is achieved at the cost of a reduced fuel efficiency. Flexible power options, such as power-take-off/power-take-in configurations and hybrid propulsion, can be considered to save fuel. However, the new Stage V engines use SCR to reduce NO_x emissions, which allows engine management systems to be tuned for maximum fuel efficiency while reaching even higher NO_x reduction levels.

2.3.5 Slow steaming

Slow steaming is the practice of operating ships at speeds lower than the design speed. This measure was introduced in the maritime industry to reduce fuel costs and is used by nearly all global shipping companies in the current context of the sluggish shipping market. Slow steaming has been shown to be the most energy-efficient operational measure for individual maritime vessels because fuel savings and emission reductions of up to 60% can be achieved, depending on the extent of speed reduction. Although mandatory speed reduction may directly lead to emission reductions from the IWT, speed restrictions for inland vessels may be difficult to apply because of safety concerns.

2.3.6 Operating resistance optimization

The main objective of operating resistance optimization is to minimize the calm water ship resistance (i.e., frictional and residual resistance) for specific shipping routes and payloads using draft, trim, and ballast optimization. The hull form is usually optimized for a single speed and load condition, which is normally the design speed at the design draft. With the different speeds and loading conditions encountered in practice, the resistance can be optimized. Varying ship drafts or trims will change the wetted surface area, waterline length, and resistance, and can be considered for more robust ship designs, considering the specific routes and conditions expected during the lifetime of the ship.

2.4 Logistics’ emission reduction measures

Transport chain measures for emission mitigation are focused on using operational efforts that include reducing power demand and improving energy efficiency. Several promising operational measures for navigation, supply chains, and logistics have been developed by the industry [12]–[14]. Typically, these measures can be grouped into the following sub-groups: optimization of supply chains, cold ironing, route optimization, and optimized usage of infrastructure, all of which need to be considered in relation to the energy supply.

2.4.1 Optimisation of supply chains

The measures related to the supply chain can be grouped into the following sub-groups: trading network design, economies of scale, and port services.

The design of the trading network, in terms of the number of vessels, size of vessels, and commercial speed, has an important impact on IWT emissions. Shipping companies must find solutions for fleet deployment from different perspectives. Another challenge is to determine the shipment frequency, shipment size, and schedules that need to be assigned to many constraint conditions.

Cargo capacity utilization is another important consideration when designing capacity deployment in service networks. Trade demand may fluctuate owing to various factors, and shipping companies need to alter their service networks accordingly to achieve higher capacity utilization with the objective of minimizing costs and emissions. However, considering various factors such as freight rates, operations, ports, and logistical systems, there should be an optimal ship size and deployment for different trading routes.

An efficient turnaround in ports results in more voyages or the same voyage number with a slower and more fuel-efficient sailing speed. Therefore, the time spent at the port significantly affects the operational costs, benefits, and level of energy efficiency. Reducing the time in the port and anchorage is an important consideration for reducing fuel consumption and ship emissions, which depends primarily on the operation and service of port terminals. Improvements in berth allocation planning, assignment, and scheduling of quay cranes; integrated planning to improve loading/unloading efficiency; and reduction of unproductive time through faster document processing and check procedures would lead to a reduction in energy use.

2.4.2 Cold ironing

Cold ironing is the practice of supplying shoreside electrical power to a ship at the berth, while its diesel generators are turned off. As shoreside electrical power can be from low-carbon or zero-carbon energy sources, such as wind power, hydropower, solar power, or nuclear power, cold ironing is an important option for reducing shipping emissions. Although the fuel consumption while berthing at ports is a small proportion of the total energy consumption in the life of a ship, the overall benefits of cold ironing are significant because they simultaneously reduce emissions, toxic exhaust gas emissions, and noise pollution from ship berthing at ports, with benefits for the coastal ecosystem and the physical and mental health of people living nearby. In the future, cold ironing may also be used to recharge batteries as an energy source for the propulsion of vessels that have daytime operations and stay long in ports during the night. A clear example of this is the short-distance ferry operation.

2.4.3 Route optimization

Route optimization could be an overall name for the concept, as well as ship routing, scheduling, speed optimization, and trim optimization. More often, different kinds of optimization measures are currently used together and even combined with slow steaming, supply chain, and logistics to optimize energy consumption, thus reducing emissions.

Ship routing and scheduling methods were initially employed to shorten distance, optimize time, improve safety, and reduce costs. Recently, they have become important focal points for energy efficiency and emissions reduction. The main objective of ship routing is to choose the route of minimized ship resistance (e.g., at low water conditions and narrow sections), waiting times for passing locks and bridges, and undesirable vessel disturbance by selecting calm weather conditions. However, ship scheduling also considers temporal aspects, that is, the time of cargo loading/unloading, sailing, bunkering and refueling, anchoring, and hoteling. The use of different energy sources implies that the optimization for routing and scheduling needs to consider not only the transportation flow, but also the energy flow. where and when to visit an energy facility, for example, a charging station or any energy supply location, by which the ship becomes part of the decision-making process. For routine shipping lanes, ship particulars, water level conditions, currents, and specific waterway dimensions on the route, service, and waiting times at bridges and locks are also considered.

2.4.4 IWT infrastructure

Inland navigation can only function optimally if there is a new or existing infrastructure that is always navigable, properly maintained, suitable for use by existing and future fleets, and meets traffic needs.

To enable quantification of opportunities and bottlenecks, new research should focus on shallow water effects and payload vs. draught, and account for squat, ambient currents, engine age, partial engine loads, and alternative energy carriers on a transport graph that contains information on depth, current, and IWT infrastructure. Linked to waterways, locks, bridges, terminals, and berth services should be considered to allow operational improvements and achieve realistic fuel usage.

2.5 Fuel infrastructure for IWT

The transition to ZE energy carriers for IWT requires the construction of new facilities and infrastructure that are necessary to support the use of alternative fuels. The IWT offers valuable opportunities for being close to land-based infrastructures and operating within a regulatory regime that is less complex than international shipping in terms of developing a sufficient network for clean energy (including electricity). An IWT can have better access to a dedicated network of fuelling locations (energy hubs). Simultaneously, the current technical regulations for IWT fuel infrastructure (CESNI/ES-TRIN) are more complex than international shipping (IMO). In addition, for the placement of a new fuel infrastructure, riverbank properties, including safety, should be considered.

3. KEY CHALLENGES

There is a stalemate where the ship owners (demand) and energy producers (supply) are not daring to commit to a solution for the future ZE energy carrier. Thus, the energy transition is at its core in terms of the uncertainty of the best choice for a future energy carrier. Looking at the best choice for a vessel within a given logistical concept leads to suboptimal patchwork of energy carriers. However, selecting a single carrier might be beneficial from the production and supply perspective, but not the overall best solution, as different vessel types will have different possibilities to adapt, depending also on their sailing profile and the type of business they are in (e.g., long-term contracts for fixed routes versus ad hoc spot-market-driven assignments). There is deep uncertainty surrounding the actual benefits of potential solutions (new energy carriers or powering options). All solutions are still in the demonstrator or single application phase, and not market-ready development. This means that their performance will improve in the future, and thus, no reliable selection can be made. Methods that consider this uncertainty in the transport chain, design, and retrofitting are required to address this issue.

Second, there is a lack of coherent action or a clear vision towards the future. While only at the demonstrator level, each research project or pilot promotes its solution as the best option. Currently, research rarely looks beyond pilot projects and remains unaware of integration issues for other stakeholders in the sector. To alleviate this issue and reduce overall uncertainty, a broad approach is required. An action to integrate insights and bring together all types of stakeholders is required.

Furthermore, there is insufficient uptake and use of available data. In the last decade, many new sources of data have been introduced (Satellite, AIS, Engine data), and it will become even easier to collect (and communicate) in the coming years. This could lead to an Industry 4.0 revolution, but currently, this data is only sparsely used. Unlocking these data to improve vessels and transport operations will empower the sector to improve its efficiency and sustainability.

Next, the cross-sectoral transition toward a ZE fleet and the required development of cutting-edge green technologies in vessel design and equipment can be addressed. Such technology development projects involve formidable investments, the returns of which include high levels of technology, demand, and regulatory uncertainty. Faced with such uncertainty, companies should seek to form joint development alliances with other companies, academic institutions, non-profit organizations, and governmental bodies.

Finally, and most importantly, there is a lack of economic incentive to go green. Except for operational measures, all further investments in lowering emissions and environmental impacts have not yet offered any return. Going green has become a feasible business model in other sectors (built environment, cars, and even food). As IWT is mostly a sector that deals with business-to-business operations, it is further away from the consumer, and there is less pressure to go green. Cargo owners, such as Heineken and Ikea, need to take the lead in green transport and require effective incentives to support this movement.

4. DESIGNING DIGITAL TWIN FOR ZE AND ROBUST IWT

Evaluating the effectiveness of ZE policies, strategies, and technologies for emission reduction and assessing the consequences of their implementation in the broadest sense of the inland shipping system is a challenging task.

A data-driven virtual representation of the inland shipping system can be potentially used to assess the efficiency of the proposed solutions and capture the potential trade-offs of the interventions in the system. This digital twin can model the present system with all relevant components in a realistic manner, which can be validated using real-world data. Subsequently, future scenarios can be imposed on the digital twin, and the proposed intervention measures can be applied, based on which their effectiveness can be assessed.

To speed up the transition and cover the remaining gaps in knowledge, an approach that considers the diversity of the inland fleet and its operators, which looks at the individual options for vessels at various time horizons, the interactions of vessels in the corridor, and the bunkering infrastructure, is required. An approach that is data-driven, not only from a technological or logistical perspective but also from a social perspective, that not only supports questions of ship owners, cargo owners, bunker operators, terminal operators, and policymakers but also brings the sector together for the discussion. This approach does not reinvent the wheel but aims to integrate knowledge from previous projects and projects on IWT and the energy transition that runs in parallel, providing an integrated living lab built on diligent research.

Three aspects are regarded as vital components of the digital twin: individual ships, transport chains (logistics), and infrastructure (see Figure 3). The input from the community in terms of policies, current pilots, and data is the key to developing a digital twin. The questions identified by the community can be answered through the development of a multilevel digital twin in scientific development. This digital twin consists of the lowest level of heterogeneous agents representing individual vessels to study the potential of measures at the vessel level. A combination of these agents forms traffic at the corridor level and can be used to study more complex interactions and the resulting environmental impact. In addition, transport and energy infrastructure models allow the investigation of policies, business concepts, and more strategic actions at the highest level. This complex model and community are supported by data collected from open sources, project partners, and dedicated experiments. This leads to a holistic approach, which means that the entire transport chain will be considered.

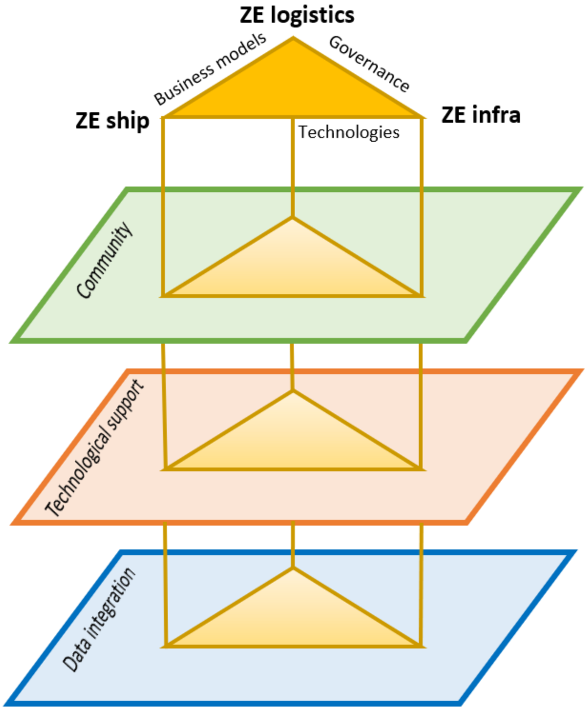

Figure 3: A schematic representation of the interaction between the individual ships, the transport chains (logistics), and the infrastructure in the Multi-Level Digital Twin.

As the main aspects of a digital twin span various scales, ranging from a single vessel to an entire infrastructure network, an agent-based approach can form the basis of a digital twin. Consequently, potential interventions can be considered, ranging from the application of new technologies to individual vessels to policy measures implemented for an entire shipping corridor or various bunker infrastructure strategies in the network. Additionally, the impact of the implemented interventions can be evaluated at any desired scale, ranging from the individual ship level, for example, its emissions or travel time, to the network level, for example, the aggregated emissions in an entire area, or the impact on the logistics chain.

The first attempt to make a prototype of a digital twin for nautical and port traffic and transport was made by the “Digital Twin Vaarwegen,” which used a fairway information system as the digital representation of the fairways, particularly of the Rotterdam-Duisburg corridor. An agent-based approach was used to model the vessels in the fairway network. This digital twin provides insights into the performance of several fleet operation strategies in terms of fleet occupancy on one hand, but it can also be used to evaluate the impact of water discharge variations on operational performance, important emission hotspots, and zoom-in, providing insights into the underlying causes.

Using an agent-based approach in a digital twin, the relevant processes at the individual vessel level can be modeled in detail, and their performance can be tracked in time and space. The agents operate on a graph consisting of nodes and edges that realistically represent the Dutch/European fairway network. Fairway characteristics were derived from the Dutch fairway information system (“Vaarweginformatie”). The developed basic infrastructure provides a necessary foundation for multilevel digital twins. The concrete theme for the multilevel digital twin can be focused on the interaction between nautical traffic-related emissions and user functions. Direct triggers motivating the need for this twin appear at operational, tactical, and strategic timescales:

- Operational: The localized spread of emissions is a health concern in port cities. Research on road traffic and fine dust is currently underway. We aim to extend the current approaches by linking them to nautical traffic. Based on operational vessel data (e.g., AIS data and engine rates), estimates can be made of energy use, fuel consumption, and emissions, close to real time. We aimed to develop algorithms for generating emission patterns (specified in space and time). These patterns can be crosschecked by measuring various emissions. This research can be used to make navigation more sustainable and can be an important input for policymakers.
- Tactical: An important part of nautical traffic and its emissions is driven by the need to move freight. Transport and handling services are provided by transport and terminal operators, and the planning of associated operations has the potential to manage localized emissions. For example, emissions are capped in time and place, thereby constraining planned operations. The findings in the operational arena will inform the management of localized emissions by adaptive planning, which will need to be a collaborative effort by transport and inland terminals, whether on the inland waterway side or the land side.
- Strategic: A major development concern for ports is the restriction of emissions on port expansion and development. Simulation algorithms for predicting shifts in emissions associated with port development and comparing them with current emission patterns should be developed. By including developments in scenarios, such as engine developments, autonomous vessels, and traffic management measures, we can generate insight into the extent to which new developments contribute to future emission patterns.

4.1 ZE ship

The challenges surrounding emission minimization for IWT can be addressed in the digital twin, starting from the ship perspective. The digital twinning hereby brings together new insights into the role of the digital/cyber ship aspects (ship digitization, communication, and decision making) on the one hand, and the link to the physical ship aspects (new alternative fuels, engines, ship designs) on the other.

To improve the vessel agent and vessel fleet behaviors, the important role that digitization and communication technology will have in improving the operational emission profiles of the future vessel fleet should be addressed. With the advent of more accurate information from a more diverse range of sources (onboard ships, as well on the infrastructure side) [16], and ease of communication between different transport chain systems, it becomes important to consider what information is needed where, when, and at what level of accuracy. This needs not to be considered only from a general efficient navigation perspective, but especially with an integrated view of sustainability and operational emission profile optimization. This is important in addressing both the enhancement of navigation systems onboard existing ships (‘digital retrofitting’) and when considering design choices for the next generation of (newly built) ships. A key challenge is to consider emission profiles in trade-off with levels of ensuring alignment with expectations regarding, for example, arrival times and other indicators for ship quality of service. As such, this task will result in new methods for emission-minimized ship decision-making (navigation, power, and energy management). The overall methodology pursued here is based on the model predictive control concept [17]. In this concept, links between digital twin representations of a ship and corridor dynamics and reduced-order mathematical representations thereof are encapsulated inside a rolling horizon framework to optimize set performance objectives. In addition to the individual (single-agent) ship control perspective, specific attention is given to the distributed (multi-agent) fleet management perspective, in which ships make use of shared information (e.g., for emission-minimized collaborative navigation).

Three different situations can be considered for digital twinning: current ships sailing on diesel, new ships starting on diesel but converting to green energy in the future, and ships built specifically for a single green fuel. Some degree of modularity is seen by many as the best option to deal with this, and MBSE has been shown in Aerospace and Car manufacturing to support this. However, a ship is a much more integrated system in which the performance of subsystems can only be evaluated once the design is complete. The Dynamic Alternative Policy Pathways [18] will be used as a measure to deal with uncertainty in combination with Model-Based Systems Engineering [19] to deal with the modularization of the layout together to ensure the layout optimality of retrofitted, future-ready, and future ships. This will not be possible without the use of Artificial Intelligence principles in layout generation and assessment.

4.2 ZE logistics

A logistics digital twin model should be developed for strategic, tactical, and operational decisions for integrated logistics and energy systems based on various constraints and requirements. In particular, when a hybrid fleet using a variety of energy sources is deployed, challenging decision-making problems arise. The transition toward a ZE fleet and development of the corresponding energy distribution infrastructure not only requires an integrated design, planning, and execution, but also repositioning of several organizational strategies of the parties involved, and realignment of relationships between those parties.

At the strategic level, the integration and matching of viable ZE logistics systems and ZE energy systems deal with network design; the adaptations required for both the terminal and fleet towards ZE energy carriers. Gradual stages of adaptation should be considered to increase support for new energy carriers. Although studied for trucks and ships, the gradual adoption of multiple possible energy sources at the transport chain or network level remains understudied. At the tactical level, the service frequency and scheduling are also affected by the choice of ZE energy carrier. New carriers may change the number of transport types required to operate parts of the network, and the alignment of cargo and energy needs is required. Although a heterogeneous fleet has been studied [20], the consideration of energy in these problems introduces new challenges that will be addressed here. Finally, at the operational level, the routing of the vessels and the required energy distribution, which involves the swapping and charging of container batteries or fuel bunkering operations, must be decided in a similarly integrated way. In particular, ZE energy swapping options, such as battery containers, integrate a second cargo stream, including empty container repositioning [21], into the routing, requiring optimization of charging-related decisions [22] for a fleet. To our knowledge, integral decision support for intermodal transport and energy systems with multiple energy sources has been studied only sparsely and requires further modeling.

The interplay between demand and supply is an important factor for leveraging these uncertainties. Pricing not only leverages the supply and demand of transportation capacity, but also for energy supply. Integral pricing models that incorporate these aspects have received little attention, especially in the context of synchromodal transportation, and require further research. Instead of purchasing expensive assets and forcing a buy-in into a specific design and energy technology, innovative financing models need to be introduced that allow MSEs to purchase options on assets managed as a portfolio. This relates to investment in a green fleet of vessels, which is considered from a technological perspective. In addition to technology and the market, regulations also play an important role in the transition to a ZE IWT. Market parties are calling for regulations that support forerunners, and governments are progressing such regulations, but there are risks that regulations also have rebound effects. Therefore, new business models in the IWT ecosystem are challenged to address the technological, market, and regulatory uncertainties. Requiring new chartering and greening options that reap the benefits of new technologies and market opportunities addresses the uncertainties at hand to be developed.

To achieve ZE IWT, technology alliances will most likely involve cross-sector partnerships, such as partnerships among companies and academic institutions that have very different objective sets as well as organizational processes and norms. Since alliances involve separate independent institutions, they require significantly more coordination than internal R&D projects. Furthermore, the complete alignment of partner incentives is hardly achieved, which makes full cooperation unlikely. In this case, parties tend to follow their private benefits even when they are contradictory to common objectives. The benefits and inherent disadvantages of alliances have spurred research into the determinants of alliance performance. For instance, formal and informal governance, trust, re-evaluation and re-adjustment, partner similarity, and alliance experience play important roles in fostering alliance performance. However, little is known about inter-partner cooperation when alliance benefits involve a mix of commercial gains and social responsibility. In other words, the question remains whether alliances in green technologies perform worse than alliances in technology development for purely commercial motives. To address this, data on technology development projects by leading-vessel builders should be collected.

4.3 ZE fuel infrastructure

To pave the way for a transition to ZE fuel infrastructure, it is crucial to develop knowledge at the infrastructure level (e.g., for the functional design and first-order dimensioning of individual bunkering stations) and at the network level (e.g., to understand the interactions with upstream energy flow and downstream transport behavior). Connecting the infrastructure level to the network level requires practice-oriented insights into the present energy demand and realistic perspectives on potential future energy demand [23], [24].

A promising and widely used starting point is to estimate the resistance experienced by vessels traveling over the network, for example based on the Holtrop and Mennen approach [25]. This resistance can be used to estimate the power that must be provided by a ship's engine. Empirical relationships are available to translate this power into fuel use and emissions. This enables the estimation of network-wide energy-use footprints as a function of time and space.

To enable the quantification of opportunities, bottlenecks, new policy perspectives, and new sustainable business models, the traditional method of Holtrop and Mennen needs to be expanded. Recent research [26], [27] developed a method that includes the latest insights into shallow water effects [28] and payload vs. draught [29], and can account for squats, ambient currents, engine age, partial engine loads, and alternative energy carriers on a transport graph that contains information on depths, currents, and infrastructure (such as bridges, locks, etc.).

Key questions regarding the ZE fuel infrastructure include where bunkering stations should be positioned and their capacity (both in terms of the total amount of energy to be supplied and in terms of desired service levels/allowable waiting times). Several associated knowledge gaps need to be addressed: How can the required bunkering capacity be translated into space requirements? What safety zones should be accounted for when designing infrastructure for different energy carriers? What are the suitable fuel loading concepts and how will these affect the network performance (tank-to-tank)? To what extent can new energy carriers be integrated into the existing infrastructure, or is a separate infrastructure required? etc.

To evaluate the wider feasibility of the new bunkering infrastructure, it is important to connect it with upstream energy flow models, downstream transport, and logistic models. An upstream energy flow model will reveal (changes in) the overall energy flows (well-to-tank), following the selection of a specific mix of alternative fuels combined with future transport scenarios. In practice, decisions for alternative energy carriers may typically be taken up (e.g., when a vessel owner or fleet operator sees certain advantages of a given solution). Recent developments in the global energy market have revealed that it is also important to have a top-down and long-term view of how much energy is required and from where it will be sourced. Downstream transport and logistic models are important to show how alternative energy carriers and energy conversion systems affect the performance of the transport chain. What is the impact of alternative energy carrier/energy converter solutions on the range, speed, and maximum payload of vessels (tank-to-wake)? How will alternative energy carrier/energy converter solutions affect the competitiveness of the IWT mode compared with other transport modes, as well as alternative transport corridors?

Practice-oriented methods should be provided to design zero-emission bunkering infrastructure, such as bunker locations (well-to-tank) and first-order functional designs of bunker facilities (tank-to-tank), as well as upstream energy flow consequences and downstream transport and logistics performance (tank-to-wake).

The investigation of ZE fuel infrastructure includes vessel transportation behavior in time and space, transport capacity and frequency, tank volume, vessel and route combinations, trade flow, handling capacity and time for bunkering sustainable fuel, and fairway information (depth, water flow, wind, wave, locks, bridges, etc.). The digital twin model for ZE fuel infrastructure should be able to simulate two-way traffic in waterways and output energy consumption and ZE fuel demand for different routes. The refueling point density can be determined based on the sailing-range capacity of the vessel.

5. CONCLUSIONS

A number of strategies and technologies are available for reducing emissions from inland waterway transport (IWT). The main strategy for achieving a ZE IWT is the use of alternative energy carriers with a lower well-to-wake carbon intensity. Other ship- and logistics-related measures had a smaller impact than alternative energy carriers. However, these measures are important to achieve robust energy consumption during the transition to ZE fuels.

There is deep uncertainty surrounding the benefits of alternative energy carriers and ZE technologies. A data-driven virtual representation of an inland shipping system can potentially be used to assess the efficiency of the proposed solutions and strategies. This digital twin can model the present system with all relevant components in a realistic manner, which can be validated using real-world data. The input from the community in terms of policies, strategies, and data can be processed by the digital twin, and the proposed intervention measures can be applied to assess their effectiveness.

The multi-level digital twin model for the ZE IWT should be developed for strategic, tactical, and operational decisions for integrated ships, logistics, and fuel infrastructure. This will have important implications for the management of technology development projects that involve a mix of commercial, environmental, and social objectives. Decision-makers on technology investments will exercise better judgment in the design and governance of technology development projects.

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