Optimizing Bunkering Station of Alternative Fuels for Inland Waterway Transport

Pourbeirami Hir, Maryam; Kirichek, Alex ; Pourmohammadzia, Nadia; van Koningsveld, Mark

Publication date
2025

Document Version
Final published version

Citation (APA)
Pourbeirami Hir, M., Kirichek, A., Pourmohammadzia, N., & van Koningsveld, M. (2025). *Optimizing Bunkering Station of Alternative Fuels for Inland Waterway Transport*. 2118-2124. Paper presented at IAME 2025 Conference, Bergen, Norway.

Optimizing Bunkering Station of Alternative Fuels for Inland Waterway Transport

Maryam Pourbeirami Hir[1*], Alex Kirichek[1], Nadia Pourmohammad-Zia[1], Mark van Koningsveld[1,2]

[1]Section of Rivers and Ports, Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628CN, Delft, Netherlands

[2]Van Oord Dredging and Marine Contractors, Schaardijk 211, 3063NH, Rotterdam, Netherlands

(*M.pourbeiramihir@tudelft.nl)

Abstract

Inland waterway transport (IWT) is increasingly recognized as a cleaner, more efficient alternative to road transport for freight movement. However, the successful adoption of zero-emission fuels—particularly hydrogen and battery power—depends on the strategic location and capacity of bunkering and charging stations. This extended abstract presents a multi-stage framework that combines simulation and mixed-integer optimization to identify where and how these stations should be deployed. First, a simulation model estimates the fuel consumption of vessels under varied waterway conditions, vessel dimensions, and hydrodynamic influences. Next, an optimization module, modeled within the supply chain, aims to minimize capital and operating expenses while ensuring sufficient fuel availability. Strategically placing multi-fuel stations in high-demand locations reduces infrastructure redundancy and ensures flexible operations. This study underlines the critical role of well-planned bunkering infrastructures and highlights the potential for future expansions in zero-emission vessel networks.

Keywords

Inland waterways, battery-electric, green hydrogen, simulation, optimization

1 Introduction

The urgent need to reduce greenhouse gas (GHG) emissions and address climate change has driven global policies, such as the Paris Agreement, to prioritize sustainable development within the transport sector (Qin et al., 2021; Jiang et al., 2023). IWT offers a sustainable alternative for freight movement due to its lower GHG emissions and enhanced efficiency compared to road transport (Prause et al., 2022). By leveraging waterways for transportation, governments can alleviate road congestion, reduce emissions, and optimize fuel consumption. This positions IWT as a crucial component in the transition towards more sustainable transport solutions (Kirichek et al., 2024; Turan et al., 2017; Prause et al., 2022).

Despite its advantages, the effective deployment of zero-emission fuels, such as hydrogen and battery power, is restricted by the limited availability of bunkering and charging infrastructure (Saif and Elhedhli, 2016). Bunkering stations, in particular, are essential for ensuring reliable access to fuel or electrical power along inland routes. The strategic location and capacity management of these stations directly influence vessel operational efficiency, overall emissions, and total transport costs (Hir et al., 2023; A. Guimarães et al., 2019; Jiang et al., 2023). If such stations are poorly distributed, vessels risk unplanned detours or fuel shortages, reducing the attractiveness of alternative fuel adoption. Conversely, an overabundance of stations inflates capital and operational expenses without guaranteeing proportional improvements in service reliability.

This study presents a framework to optimize bunkering station locations and capacities for hydrogen and battery-powered vessels in IWT. The framework integrates simulation and optimization to design a resilient bunkering network capable of accommodating variations in vessel activity, environmental conditions, and operational constraints. Simulation models vessel fuel consumption under different physical conditions and vessel characteristics, while optimization identifies station placement that minimizes costs and ensures adequate fuel availability.

2 Methodology

This research adopts a multi-stage approach that merges simulation and optimization to develop an efficient bunkering network for alternative fuels in IWT. By incorporating real-world factors such as waterway depth, vessel dimensions, and operational variability, the methodology determines how bunkering stations should be distributed and sized for both hydrogen and battery-powered vessels.

In the initial simulation phase, the model estimates energy demand across the waterway network by replicating vessel behavior under diverse physical conditions. This process considers vessel properties, including length, beam, draft, and engine characteristics, along with site-specific features such as channel width, depth, and currents. Sailing behavior is also captured by tracking realistic speeds and power requirements. These parameters enable the calculation of fuel consumption for each vessel through a resistance algorithm, which then provides insight into the maximum driving range based on tank size or battery capacity. Hydrogen vessels, for instance, typically store fuel at higher energy density but may require specialized bunkering facilities, whereas battery-electric vessels demand more frequent charging stops to maintain their operational schedule.

After the simulation generates detailed energy consumption data, the second phase applies a mixed-integer programming (MIP) model to optimize bunkering stations. Using aggregated fuel-demand profiles from the simulation, the MIP formulation identifies station sites and capacities that minimize capital expenditures (CAPEX) and operational expenditures (OPEX). The framework places constraints on total station capacity, ensuring that each site can accommodate predicted fuel requirements without excessive oversizing. Stations designated for hydrogen or electricity are tailored to the unique needs of each propulsion method, and vessel routes are set to avoid running out of fuel before reaching the next feasible station.

Figure 1 conceptually summarizes the methodology framework by illustrating how simulation and optimization work together to shape decisions on bunkering station deployment.

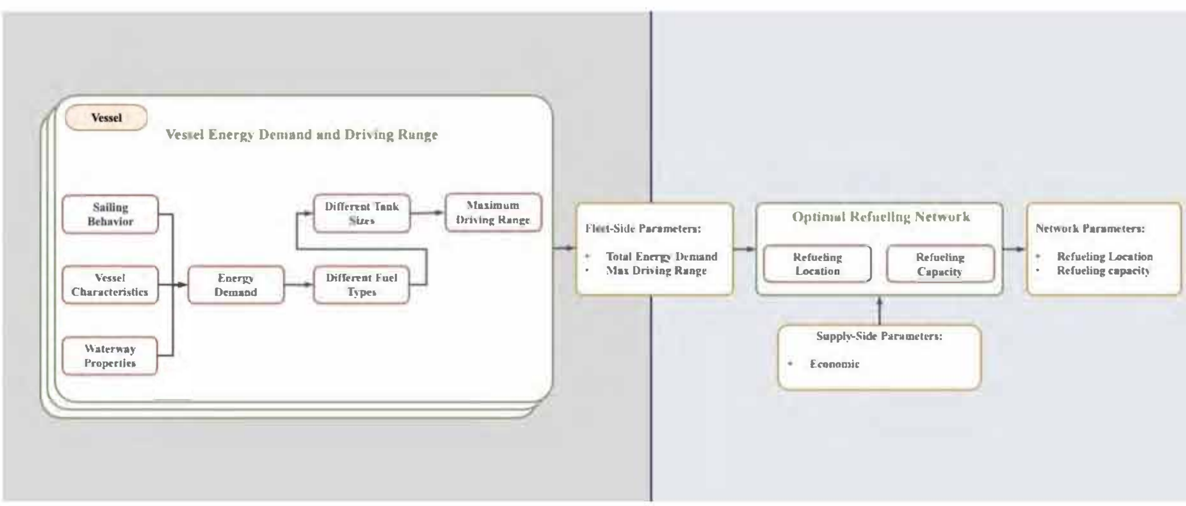

Figure 1-Conceptualization Framework

3 Results

Preliminary Our experiments, conducted on the RIHN corridor—a representative segment of the inland waterway network—demonstrate that an adaptable bunkering network is critical to meeting the diverse operational demands of hydrogen- and battery-powered vessels. Preliminary findings highlight the importance of station networks that can respond dynamically to variations in waterway conditions, vessel characteristics, and traffic demands. In the simulation phase, larger or more heavily loaded vessels showed increased resistance, which raised total fuel consumption. Constricted or shallow waterways further increased drag, underscoring the influence of physical constraints on energy use. Speed variations and opposing currents also intensified consumption, with faster travel or strong head-currents necessitating greater power output. These combined factors enabled the development of precise energy-demand profiles for both hydrogen- and battery-powered vessels, forming a robust foundation for the subsequent optimization phase.

In the simulation phase, our model incorporated detailed vessel parameters—such as dimensions, payload, and engine characteristics—and environmental factors including waterway width, depth, and current speed. For instance, we observed that an increase in fuel tank size extended the vessel's operational range significantly; a 20% increase in tank capacity reduced the frequency of required refueling stops by approximately 15%, which in turn lowered the overall density of required bunkering stations along the corridor. Conversely, vessels equipped with smaller tanks needed more frequent stops, thereby imposing higher demands on the network. Moreover, variations in water level had a pronounced effect on fuel consumption; under low water level conditions, reduced depth increased frictional forces by an average of 10–12%, compelling vessels to refuel more often and necessitating a more dispersed station layout to maintain operational continuity.

During the optimization phase, the model balanced the projected energy demand across the network with the imperative to minimize total costs. In high-demand regions near major ports or along busy routes, establishing multi-fuel stations enabled both hydrogen and battery-powered vessels to refuel without excessive detours, thereby enhancing operational flexibility. The strategic placement of these stations at central nodes effectively limited infrastructure redundancy, as a single station could handle significant traffic volumes. In contrast, in lower-demand areas, the model demonstrated that smaller, cost-effective stations were sufficient to serve local routes without overburdening capital investment. This differential approach ensured that resources were allocated in line with local energy consumption profiles while preventing both fuel shortages and underutilization of capacity. The results further underscored the contrasting fueling profiles of hydrogen- and battery-powered vessels.

Difference in energy density and refueling frequency dictated that battery-powered vessels necessitate a denser network of smaller stations, whereas hydrogen vessels could be effectively supported by fewer, strategically placed, higher-capacity stations.

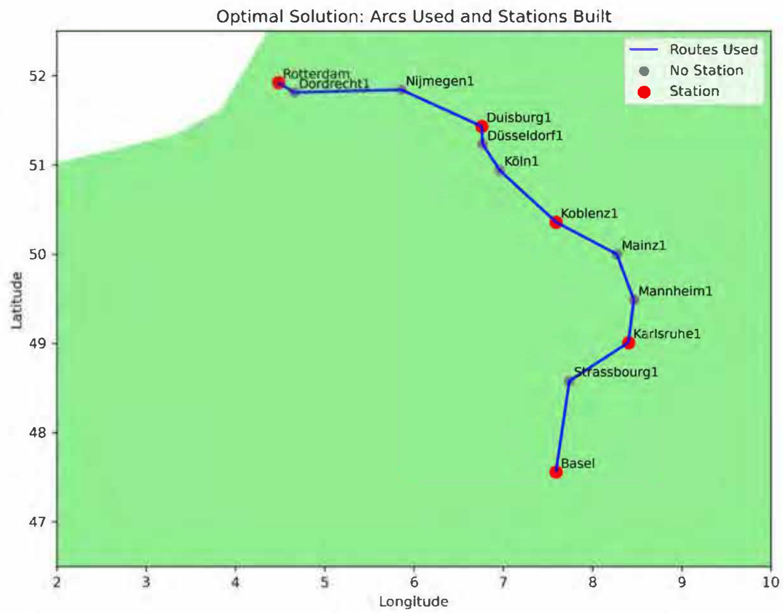

Figure 2-IWT corridor

Sensitivity analyses were conducted to further examine the influence of additional factors. Vessel size and sailing speed were found to be critical; larger vessels, due to their increased displacement and frictional resistance, exhibited higher energy consumption per kilometer compared to smaller ones. Similarly, higher sailing speeds led to exponentially greater fuel requirements, compelling the optimization model to adjust station capacities and locations to ensure vessels could complete their voyages without interruption. Moreover, our study also investigated the role of upstream fuel suppliers in the network. Integrating the presence of fuel suppliers into the model allowed for more efficient distribution of hydrogen or electricity to bunkering stations. The strategic placement of suppliers at key nodes significantly reduced detour lengths and refueling wait times, thereby easing capacity constraints at individual stations. In scenarios with active supplier integration, total operational costs were reduced by approximately 8–10% compared to networks designed without direct supplier access, as the improved logistics minimized both fuel handling losses and downtime during refueling.

Furthermore, when certain stations were assumed to be near capacity or temporarily offline—due either to maintenance or unexpected traffic surges—the optimization engine dynamically rerouted vessels or adjusted fuel volumes accordingly, thereby avoiding disruptions in the supply chain. This capacity to adapt under realistic constraints, including sudden shifts in traffic or partial infrastructure outages, verified that strategic planning can significantly enhance network resilience. The interplay between these factors—tank size, water level, vessel dimensions, sailing speed, and supplier integration—was pivotal in shaping the final configuration of the bunkering network.

Overall, the synergy between simulation and optimization enabled a holistic approach to the deployment of bunkering stations. The simulation phase accurately captured the physical forces influencing fuel consumption, while the optimization phase used these data to propose an arrangement that minimizes costs without compromising vessel operations. Multi-fuel stations emerged as particularly advantageous in busy corridors, where they not only streamline infrastructure investments but also provide the flexibility to adapt to evolving energy requirements. The detailed sensitivity analyses on the RIHN corridor provide robust evidence that a well-calibrated balance of these factors—coupled with strategic supplier integration—can significantly enhance network efficiency and operational reliability. These findings suggest that robust, well-placed bunkering networks are essential to accelerate the adoption of zero-emission fuels, thereby mitigating greenhouse gas emissions and reducing the reliance on conventional diesel-powered inland shipping.

References

A. Guimarães, T. *et al.* (2019) 'The two-echelon multi-depot inventory-routing problem', *Computers and Operations Research*, 101, pp. 220–233. Available at: https://doi.org/10.1016/j.cor.2018.07.024.

Cokyasar, T. (2021) 'Optimization of battery swapping infrastructure for e-commerce drone delivery', *Computer Communications*, 168, pp. 146–154. Available at: https://doi.org/10.1016/j.comcom.2020.12.015.

Hir, M.P. *et al.* (2023), 'Zero-emission fueling infrastructure for IWT: optimizing the connection between upstream energy supply and downstream energy demand', *Modelling and Optimisation of Ship Energy Systems*

Jiang, M. *et al.* (2023) 'Corridor Scale Planning of Bunker Infrastructure for Zero-Emission Energy Sources in Inland Waterway Transport', in *Lecture Notes in Civil Engineering*. Springer Science and Business Media Deutschland GmbH, pp. 334–345. Available at: https://doi.org/10.1007/978-981-19-6138-0_30.

Kirichek, A. *et al.* (2024) 'Paving the Way Towards Zero-Emission and Robust Inland Shipping', *Modelling and Optimisation of Ship Energy Systems 2023* [Preprint]. Available at: https://doi.org/10.59490/moses.2023.675.

Pourmohammad-Zia, N. and van Koningsveld, M. (2024) 'Sustainable Urban Logistics: A Case Study of Waterway Integration in Amsterdam', *Sustainable Cities and Society*, p. 105334. Available at: https://doi.org/10.1016/j.scs.2024.105334.

Prause, F., Prause, G. and Philipp, R. (2022) 'Inventory Routing for Ammonia Supply in German Ports', *ENERGIES*, 15(17). Available at: https://doi.org/10.3390/en15176485.

Qin, H. *et al.* (2021) 'A review on the electric vehicle routing problems: Variants and algorithms', *Frontiers of Engineering Management*, 8(3), pp. 370–389. Available at: https://doi.org/10.1007/s42524-021-0157-1.

Saif, A. and Elhedhli, S. (2016) 'Cold supply chain design with environmental considerations: A simulation-optimization approach', *European Journal of Operational Research*, 251(1), pp. 274–287. Available at: https://doi.org/10.1016/j.ejor.2015.10.056.

Turan, B., Minner, S. and Hartl, R.F. (2017) 'A VNS approach to multi-location inventory redistribution with vehicle routing', *Computers and Operations Research*, 78, pp. 526–536. Available at: https://doi.org/10.1016/j.cor.2016.02.018.

Zhang, N. *et al.* (2022) 'Robust location and sizing of electric vehicle battery swapping stations considering users' choice behaviors', *Journal of Energy Storage*, 55. Available at: https://doi.org/10.1016/j.est.2022.105561.