Transport models for zero-emission inland shipping

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Abstract—To reduce carbon emissions for inland shipping in the Netherlands, the use of interchangeable batteries is explored. The purpose of this study is to enhance the research into interchangeable batteries so systems can be improved in terms of the capital expenses and the charging costs. First the model of M. Piña Rodríquez [16] is analysed, validated and improved by making the model more realistic and scalable. Subsequently, the model is expanded by integrating smart charging and energy costs, to save expenses and unload the power grid. The final phase of the research is adding route planning, so that the model can determine its own routes instead of having them as predefined inputs. By implementing these changes in the model, it successfully answers the main research question. This demonstrates that optimization of the battery exchange process can lead to substantial reductions in charging costs and capital expenses while avoiding unnecessary waiting times.

I. Introduction

A. Background

Inland shipping is an efficient mode of freight transport, comprising over 20% of all transportation in the Netherlands. [2] Rijkswaterstaat has set ambitious environmental goals, aiming for a 40% reduction in CO_2 emissions from inland shipping by 2030, with the ultimate objective of achieving emission-free transport by 2050. [6] Currently, most inland water vessels rely on diesel propulsion, necessitating a shift in propulsion methods. One promising solution is the usage of battery-driven power systems. [11] These systems involve equipping vessels with one or multiple container-sized batteries onboard to generate power.

In the last decade, progressively more research about the implementation of interchangeable batteries on inland waterway vessels has been done. One way to ensure continuous operation is strategically swapping these batteries as needed to meet the energy demands of transport operations.

Nowadays, the market for electrifying Inland Waterways (IWW) Shipping is relativity small, especially if you compare it to the electric road vehicle market. [7][8] The biggest issue is that the batteries are too expensive and too large for large-scale use. It is expected that the costs of batteries will decrease in the upcoming years. [12] While the research for improving electric shipping takes place, the logistics of this new system can already be developed. So when electric shipping becomes possible for a greater amount of vessels, the logistics plans are ready to be implemented.

Currently there is a company in the Netherlands that is pursuing the concept of interchangeable batteries; Zero-Emission Services, ZES. Their goal is to enable electric sailing for all inland vessels both inside and outside of the Netherlands. M. Piña Rodríguez evaluates the logistical aspects of introducing an interchangeable battery system to inland waterways in her research thesis in collaboration with ZES. [16] The study produces an output that indicates how many exchangeable batteries and docking station locations are required to minimize capital expense for a given vessel demand. It is the basis for an evaluation of the implementation of an exchangeable batteries system in inland waterway shipping.

The paper of M. Piña Rodríguez gives a brief overview of the infrastructure of interchangeable batteries. However, the model could be further improved. For instance, the costs of charging the batteries and waiting times on terminals are not accounted for in the model, while these factors may influence the amount of batteries and docking stations used in the infrastructure.

B. Objective and Research question

The objective of this research is to enhance the transport model in order to implement electric propulsion for inland ships, minimizing charging costs and capital expense while avoiding waiting times.

To achieve the objective the following main research question is defined:

"How can the process of exchanging batteries between docking stations and inland ships be optimized to reduce charging costs and capital expenses, while avoiding waiting times?"

To answer the main research question, the following sub-questions are defined;

- How can the charging costs associated with battery charging be minimized through selection of optimal charging times during the day?
- How can capital expense and charging costs be minimized while avoiding unnecessary waiting times?

The hypothesis for this research is that significant expenses can be saved using smart charging, while also preventing waiting times by implementing route planning. Thus making the process of exchanging batteries more efficient.

C. Research methodology

The main research questions consists of multiple components, which are all to be implemented in the model using development sprints. The goal of the sprints is to structure the research and verify different components gradually. Each sprint has its own objective to help answer the research question. Every sprint is an iteration of the previous sprint, so the model will be expanded during the research and will take the objectives of the previous sprints into account. There are three sprints used in this research:

1) Sprint 0: Verifying the model: This sprint is thoroughly focused on understanding and verifying the model. This step is crucial to lay a solid foundation for the rest of the sprints.

2) Sprint 1: Implementing charging costs: In this sprint, the charging costs are implemented into the model. This addition also incorporates the costs of charging the batteries to allow for cost minimization.

3) Sprint 2: Introducing waiting times and route planning: In the final sprint, route planning is built into the model. This not only allows the model to avoid unnecessary waiting times for ships but also allows for further minimization of the costs.

The final model will be tested for three different networks and will be used to answer the research question.

D. Structure

The paper starts with theory, split into two sections. The first section contains information about the infrastructure and the second contains information about the model used. The Method section elaborates on the three sprints in detail and outlines the overall process. In the Result section, the findings are explained and compared.
Finally, in the Conclusion and Recommendation section the results are used to answer the research question and suggestions for further research are given.

This research study has been conducted as part of the Bachelor End Project for Mechanical Engineering Students at TU Delft in the third year of their Bachelor studies.

II. **Theory**

A. System overview

In this section the key components of the system will be explained: Zero Emission Services, batteries, docking stations and the vessels.

1) Zero Emission Services (ZES): As introduced earlier, Zero Emission Services (ZES) is a company committed to revolutionizing inland shipping by promoting sustainable propulsion methods. ZES is developing a system where electricity is the main power supply for inland vessels. Ship owners are only required to pay the rent of the battery and for the consumed power during the trip, eliminating the need for significant investments of ship owners making it more accessible and appealing to use a more sustainable way of shipping.

The Alphenaar is the first vessel utilizing batteries as its main source for propulsion in the Netherlands. The vessel is used to transport beer for Heineken between Moerdijk and Alphen aan de Rijn, ZES has ambitious plans to have 30 emission-free shipping routes by 2030. [15]

2) Batteries: The battery containers used in this research are the ZESpacks. These are lithium-ion batteries encased in 6 meter long containers, designed for easy loading and unloading to ensure compatibility with the harbour machinery. Each ZESpack has a capacity of 2.000 kW, allowing a vessel to sail for approximately 2 to 4 hours, depending on various operational factors such as speed, load, and environmental conditions. [19] The costs of these batteries are estimated to be € 955.000 each. One of the primary challenges associated with these batteries is their limited availability due to high costs. This means that a charged battery may not always be available when needed. As a result, managing the amount of batteries in the system becomes crucial. Optimizing this can save both time and money by reducing delays while minimizing the number of batteries required. [10]

3) Vessels: The Alphenaar used to be an old diesel-powered vessel that is retrofitted to operate on battery power. [13] The ship has a cargo capacity of 107 TEU and carries two ZESpacks. Using these batteries instead of diesel reduces emissions by 1.000 tonnes CO_2 and 7 tonnes of NO_x per year. [15] In the model, the Alphenaar is simulated with various routes, which will be explained in detail later. According to RWS classification the Alphenaar is in the M6 category (IVa in CEMT classification). [5]

4) Docking Stations: Docking stations are essential for charging the batteries used in the vessels. The docking stations are placed on terminals. The strategic placement of these docking stations is critical for efficient functioning of the system. Each docking station consist of the following components, as seen in Figure 1:

1) **Grid connection station**: Ensures a stable and reliable connection to the electrical grid.
2) **Power distribution container**: Manages the distribution of electrical power to multiple batteries.
3) **Power interface container**: Converts alternating current from the grid to direct current suitable for charging the lithium-ion batteries.
4) **Docking platform for placement of ZES-packs**: Provides the physical space and infrastructure for securing and charging the batteries.
5) **Connector**: A fully-automated plug for energy and data communication between ZES-packs and the docking station.

The smart placement of docking stations along vessel routes can ensure that vessels have timely access to fully charged batteries.

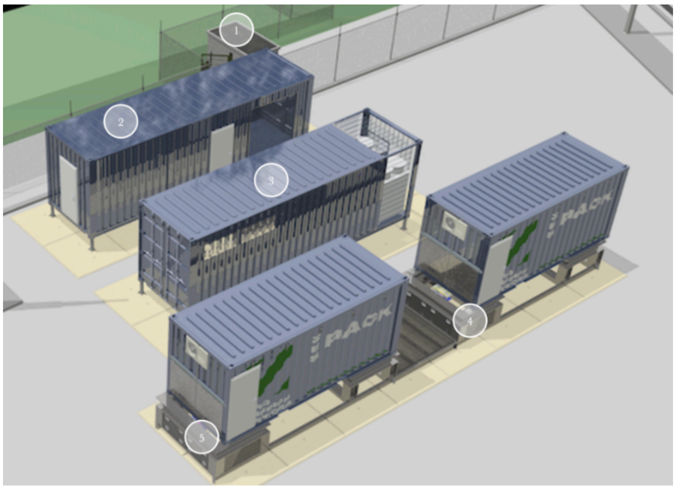

Fig. 1. Docking Station [16]

B. Model

The model is formulated as a Mixed Integer Linear Programming (MILP) [18] problem which includes both continuous and integer variables subject to linear constraints. This mathematical formulation is implemented in Python, the program Gurobi is used for solving the MILP. Gurobi effectively solves MILP problems by performing pre-processing steps to simplify the model, such as removing redundant constraints or variables, tightening variable bounds, and transforming the problem into a more efficient bound. In section 3 the model will be explained in more detail.

III. **Methods**

This section presents the methodology over the three sprints introduced earlier.

A. The model

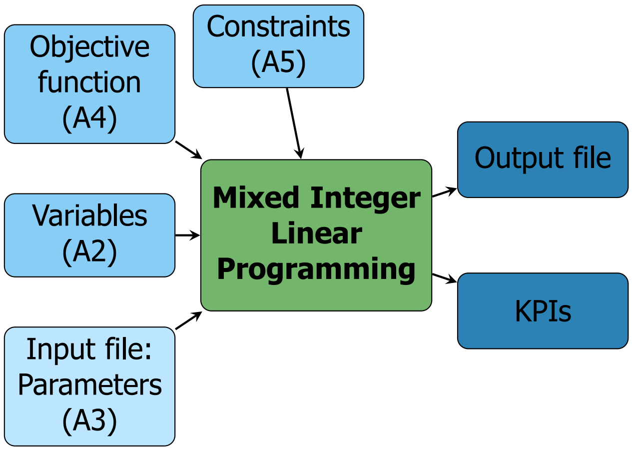

Fig. 2. Model visualisation

In Figure 2 the model is visualised. The mathematical model can be found in Appendix A and the explanation of the model can be found in Appendix B. In the following sections the modifications to the mathematical model are described.

B. Sprints

Sprint 0: Verifying the model

During this sprint, the primary goal was to understand the existing model, verify its functionality, and resolve any issues with the model. The most significant problem identified was that batteries could drain without being used. For our implementation this is was not realistic and introduced unnecessary uncertainty into the model. The issue was traced back to the constraint checking the battery level (1). The improved constraint is as follows:

$$l_{b,p} = l_{b,p-1} + \sum_{t \in T} pw\_var_{b,t,p} \cdot k_{b,t,p} - \sum_{v \in V} m_{b,v,p} \cdot pv\_var_{v,p} \quad (1)$$

This correction ensures that batteries only drain when they are used by vessels. Additionally, constraints 2 and 3 were introduced to prevent batteries from draining at terminals:

$$l_{b,p} - l_{b,p-1} \leq M_4(1 - x_{b,t,p}) \quad (2)$$

$$l_{b,p} - l_{b,p-1} \geq -M_4(1 - x_{b,t,p}) \quad (3)$$

Where:

- $l_{b,p}$ is the battery level of a battery b at time step p.
- $pw\_var_{b,t,p}$ equals one when battery b is being charged in terminal t at time step p and equals zero otherwise.
- $k_{b,t,p}$ is a binary variable that equals one if battery b is charged at terminal t at time step p and equals zero otherwise.
- $m_{b,v,p}$ is a binary variable that equals one if battery b is used at a vessel v at time p and equals zero otherwise.
- $pv\_var_{v,p}$ is the power consumption of vessel v at time step p.
- $x_{b,t,p}$ is a binary variable that is one if battery b is at terminal t at time step p an zero otherwise.
- M_4 is a large number corresponding to the largest battery capacity.

These constraints ensure that battery levels remain constant when the battery is not in use by a vessel, thereby preventing unintended battery drainage. During the debugging phase another significant issue was identified. Due to an coding error, batteries were allowed to ”teleport” unrealistically between vessels. This error was corrected, ensuring that batteries remain associated with their respective vessels throughout the simulation.

Sprint 1: Implementing charging costs

The goal of this sprint is to implement the cost of charging in the model. The price of electricity depends on the supply and demand at a certain time period. The influence of charging costs will be modelled by integrating electricity pricing, optimizing the process of charging batteries during off-peak hours.

Starting from the model from sprint 0, the following changes are made to the model:

- Charging: In the model from sprint 0 all batteries had to be fully charged before leaving a terminal. By removing this constraint the model can decide how much battery power is actually needed and thereby reducing charging costs.
- Charging costs: To calculate the cost of charging an average of the hourly rates are taken from the past year. [1] These costs can be found in Table V in Appendix C.

- Objective function: The objective function is adapted to account for charging costs and the resulting objective function is as follows:

$$
\begin{aligned}
obj_1 = &\sum_{t \in T} u_t \cdot cds_t + \sum_{b \in B} n_b \cdot cb_b \\
&+ \sum_{p \in P} CC_p \cdot \beta \cdot \sum_{t \in T} \sum_{b \in B} pw\_var_{b,t,p} \cdot k_{b,t,p}
\end{aligned} \tag{4}
$$

where:
- CC_p is the charging cost for each time period.
- β is investment horizon in days.

Sprint 2: Introducing waiting times and route planning

Prior to this sprint, routes of vessels were restricted to match the sailing profiles provided in the input perfectly. In the final sprint, two new requirements for the model arose; a variable sailing profile and minimizing the number of vessels at a terminal. A variable sailing profile would allow the model to strategically choose arrival times, charging power and power consumption to minimize costs. In the original model, congestion at terminals was not accounted for. To avoid unrealistic scenarios of multiple vessels swapping batteries at the same moment and to integrate waiting times, a new constraint was desired. However, allowing multiple vessels at the same terminal couldn't be implemented as a simple constraint. Instead, this requirement was added as an objective; the model would first minimize the numbers of vessels at a terminal to ensure that no more than one vessel is at a terminal at any given time unless required.

$$
obj_2 = min\left(\sum_{t \in T} \sum_{p \in P} nvt\_aux_{t,p}\right) \tag{5}
$$

where $nvt\_aux_{t,p}$ is the amount of ”waiting” vessels at a terminal. If three vessels are at a terminal, this value would be two.

To implement a variable sailing profile, a more major change had to be made. In the previous models, all information about a vessel was lost the moment it went into ”sailing mode” ($sp_{v,t,p}$ being zero for all t for a given vessel v at time step p). To keep track of the location of sailing vessels, a collection of ”nodes” had to be introduced. The function of a node could be described as a canal between two terminals. To achieve the desired behaviour, the following rules were implemented:

- When a vessel is at a terminal, it can always travel to a node, when this node is connected to the terminal.
- When a vessel is at a node, it can travel to an adjacent terminal when the vessel has travelled the required distance.
- Direct travel between terminals is impossible
- Direct travel between nodes is impossible.

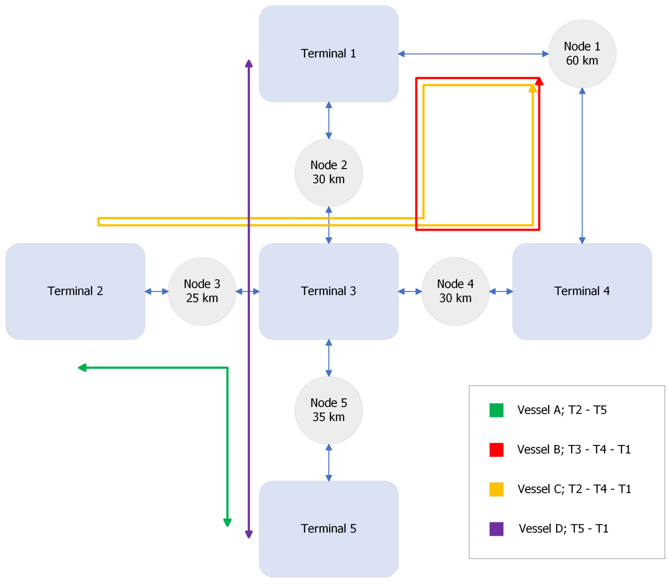

Fig. 3. Network 2 - A network containing a terminal prone to congestion

The implementation of nodes can be seen in Figure 3. The nodes and terminals form a new set called R. As mentioned above, travel from nodes to terminals is governed by the distance travelled by vessels. To keep track of this distance, the following variables and parameters were introduced:

- $reach_{v,p}$, the travelled distance of a ship at a node.
- $speed_{v,p}$, the speed of a vessel.
- $sp\_var_{v,r,p}$ a binary variable keeping track of the ships location.
- $pv\_var_{v,p}$, the power consumption of a ship when sailing.

$$
reach_{v,p} = reach_{v,p-1} + speed_{v,p} \cdot \Delta p \tag{6}
$$

$$
speed_{v,p} = \frac{pv\_var_{v,p}}{pv\_max_v} \cdot ts_v \tag{7}
$$

For simplicity, the power consumption and speed of a vessel are taken to be linear. Furthermore, the reach of a vessel resets at a terminal. To keep track of the distance needed to travel between node and terminal, the required stops and arrival times, two parameter matrices were defined:

1) DM_{r_1,r_2}, the distance matrix defining the distance between all locations.
2) $LT_{v,r,p}$, the logistic tensor containing all required stops and arrival times.

The distance of two locations that are not connected is chosen to be $M_3 = |P|max(ts_v)$, so a vessel can only sail to another location when the distance is less than M_3. The variable $pv\_var_{v,p}$ is a free continuous variable when a ship is at a node, otherwise it is equal to zero. $sp\_var_{v,r,p}$ is a free binary variable, except at locations and times when a ship is required to be at a terminal, defined by the logistic matrix. Vessels are required to remain at a terminal for at least one hour, due to the time needed to swap batteries. [17] Using these new variables and parameters, the solver is now able to strategically distribute arrival times and departure times of ships to minimize charging costs while avoiding congested terminals and thus waiting times.

C. Testing

During each new sprint the model from the previous sprint is used and expanded. For the testing, the model established at the end of the third sprint is used. The testing is carrier out using different networks, each in a different configuration (e.g. with smart charging enabled). All networks are tested on a base configuration where both smart charging and route planning are disabled. The specifics of these networks and configurations are listed below. Overall, for the vessels a top speed of 20km/h and a maximum power requirement of 800kW were taken. These specifications were estimated based on brake power to speed characteristics of diesel powered M6 barges found in literature. [9] For the batteries, a capacity of 2.000kWh was chosen based on the ZESpacks. [19] For docking stations, a charging capacity of 1.000kW was chosen. Capital costs for docking stations were taken from Table I).

Network 1: Simple network

In the simple network the vessels will sail the same route as in the model of M. Piña Rodríguez. [16] Because of computational constraints, three vessels

Number of docking spots	Charging capacity per spot [kW]	Capital expense [€]
2	1.000	1.350.000
2	500	1.080.000
1	750	840.000
1	1.000	950.000

TABLE I
Capital expense of different docking stations. [16]

are used instead of four. The network is shown in Appendix D. This network is used to simulate the effects of smart charging and route planning on a simple network. To illustrate the benefits of both smart charging and route planning, for one, five and ten years, the following configurations are tested;

- **Base configuration:** Smart charging & route planning disabled.
- **Smart charging enabled:** This test assessed the impact of smart charging without having route planning enabled.
- **Smart charging disabled & route planning enabled:** This test assesses the impact of route planning without using smart charging.
- **Smart charging & route planning enabled:** To test the additional benefit of route planning, smart charging and route planning were enabled.

In the configurations where smart charging is disabled, the charging costs are not taken into account in the objective. This can result in higher charging costs when route planning is enabled compared to a configuration where route planning is disabled.

Network 2: Network prone to congestion

Network 2, along with the sailing profiles of the vessels, is displayed in Figure 3. This network is designed for a more accurate assessment of the effects of route planning on networks that are more prone to congestion at terminals, like at terminal 3 in Figure 3. The vessels are not required to stop at terminal 3, and the model minimizes the maximum number of ships at a terminal for each time step. Four vessels were used in this network. Aside from a baseline simulation and testing several configurations, some additional scenarios were tested:

- **Base configuration**
- **Smart charging enabled**
- **Smart charging & route planning enabled**

- **More batteries per docking station:** In this scenario, the number of battery spots per docking station was increased to three. Based on the information in Table I, a worst-case scenario for the costs of an extra third docking spot was estimated at €400.000, based on the cost increase from one to two spots.
- **More charging spots at terminal 3:** For this scenario, only the docking station at terminal 3 was expanded to three charging spots to explore potential benefits.
- **Ignoring congestion at terminals:** This scenario allowed more than one vessel at a terminal to evaluate the effect of congestion on costs.
- **Less charging capacity:** The charging capacity of docking stations was reduced to 500kW to investigate the impact on the system.

Network 3: Realistic Network

Finally in the last network, the effects of the sailing profile and smart charging are tested on a realistic network. The sailing profile is based on real-life terminals in the Netherlands. Sailing distances are calculated using The Blue Road Map, an online tool that provides available inland waterway transport options for container shipments. [4] The Blue Road Map is an online tool that gives the possibility for available inland waterway transport options for containers. By using this platform for the routing it is made sure that the routes chosen are routes that are actually sailed by vessels.The network used is shown in Figure 4. The costs are compared over different investment horizons. Due to computational constraints, this network was run using three vessels.

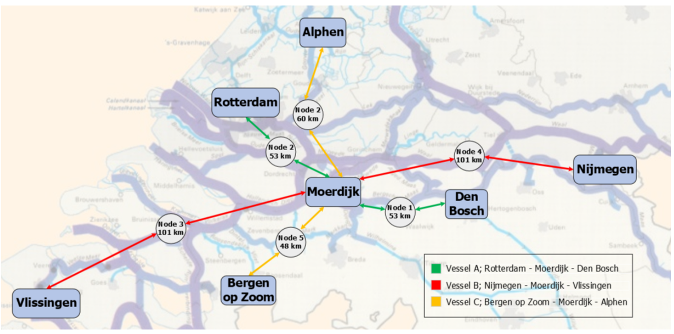

Fig. 4. Realistic network

There are three different ships used in this network. To make the model more realistic different types of ships are simulated. These ships have a power consumption of 700kW, 800kW and 1.000kW. The same four configurations as used for the simple network are used to observe the influence of smart charging and route planning on the realistic network.

D. Determination of the optimal solution

In MILP programming, an optimal solution is guaranteed to be the optimal solution when the MIP gap is 0%. The MIP gap is defined as the difference between the upper bound (primal objective bound) and the lower bound (dual objective bound) with respect to the upper bound. [14]

$$MIP\ gap = \frac{|z_p| - |z_d|}{|z_p|} \tag{8}$$

For this optimization problem, a gap of 0% is not feasible. Due to the size of the model, running times would be too long for the available resources and time frame of this research. To reduce the running times to an acceptable amount, a nonzero gap was selected. After analysing the convergence behaviour of network 2 using four vessels (Figure 5), it was found that the optimal solution converged well before 5% MIP gap. With this in mind, a general MIP gap of 5% was chosen for the models.

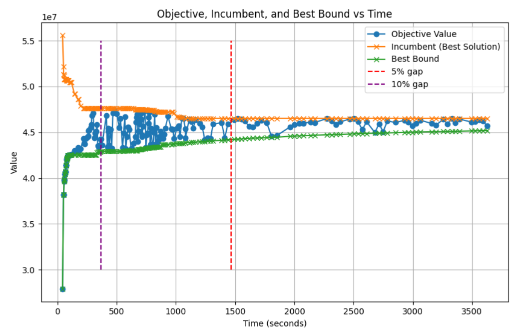

Fig. 5. Convergence of best solution using network 2 with 4 vessels

E. Resources

To manage runtimes effectively, servers were set up to run the codes. Three virtual machines (VMs) were used through the Google Compute Engine™ infrastructure. Two VMs for normal loads were set up utilizing Intel Xeon Platinum 8481C CPUs at

2.70GHz and using 32GB of RAM. An extra server for more computationally intensive optimizations was set up using an Intel Cascade Lake Xeon CPU at 3.10GHz and also using 32GB of RAM. For both VMs, 8 virtual CPUs or threads were available.

IV. **Results**

In this section and the appendices, 'Varex' refers to charging costs for one year and 'Capex' refers to the capital expense of batteries and docking stations.

A. Network 1: Simple network

The goal of testing this network was to demonstrate the effects of smart charging and route planning, this is modelled for the following investment horizon: one year, five years and ten years. In Table II the capital- and variable expenses for 10 years are shown for the different configurations. The results of one, five and ten years can be found in Tables VI, VII and VIII in Appendix D, these are not discussed in this section because they are nearly the same as the results for ten years. It's clear that the configuration with both smart charging and route planning is the most profitable due to the lower variable expenses of charging. This can be explained by the fact that when using route planning, vessels will aim to charge their batteries during the cheapest time periods, as shown in Table IX in Appendix D. They can achieve this by either waiting at terminals or speeding up to arrive earlier.

KPI	Base configuration	Smart charging, no route planning	No smart charging, route planning	Smart charging, route planning
Capex per vessel[€]	3.261.000	3.261.000	3.261.000	3.261.000
Varex per vessel[€]	894.937	771.012	895.648	755.429

TABLE II
Costs of configurations compared to base configuration for Network 1 over 10 years

B. Network 2: Network prone to congestion

An extensive summary of the results of the different configurations can be found in Tables X and XI in Appendix E. Below in Table III the most important results are shown.

Different configurations compared to base configuration				
KPI	Base configuration	Smart charging	Smart charging & route planning	
Total difference costs [€]	-	-11.856.560	-13.778.000	
Costs of scenarios with smart charging & route planning enabled				
KPI	Ignoring terminal congestion	More battery spots all DS	More battery spots terminal 3	Less charging capacity
Total difference costs [€]	-125.800	733.680	3.920	2.371.560

TABLE III
Most important results from Network 2 over 10 years

- **Base configuration:** When running the model with this configuration, a very quick convergence of the best solution was seen, Figure 6. Due to long running times, the optimization was stopped at a 17,7% gap.

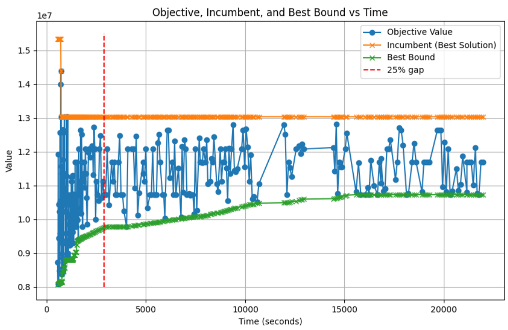

Fig. 6. Convergence of the base configuration, network 2

- **Smart charging enabled:** With smart charging enabled, a very significant decrease in charging costs was observed (see Table X in Appendix E). In total, a decrease in total costs of €11.856.560 (19,7%) was realized over 10 years.
- **Smart charging & route planning enabled:** Over a period of 10 years, additional savings added up to €13.778.000 in total. This is a further increase of savings by 16,2%, increasing the total savings to 22,9% compared to the base configuration. Not only did the charging costs decrease, the capital

expense decreased as well due to the fact that one less docking station was needed.

- **More batteries per docking station:** Increasing the number of battery spots at each docking station resulted in a total expense increase of €733.680. Although this configuration realized an annual reduction of €46.632 in total energy expenses, the added costs of the docking stations outweighed these savings. A three-spot docking station would need to cost less than €1.566.580 to break even over 10 years for this network.
- **More charging spots at terminal 3:** When terminal 3 was assigned a docking station with three charging spots, a near break-even situation was observed in the worst-case scenario. Assuming a three-spot docking station costs €400.000 more than a two-spot station, the total costs over 10 years increased by just €3.920. Annual charging cost savings are amounted to €39.608, suggesting a net positive investment after 11 years.
- **Ignoring terminal congestion:** Ignoring terminal congestion reduced costs by €125.800, indicating that congested terminals limit the optimization of charging times.
- **Less charging capacity:** Using docking stations with a 500kW charging capacity significantly increased costs by €2.371.560. This was due to reduced charging optimization and the need for an extra docking station and battery. Even increasing the power to 750kW while keeping capital expenses equal resulted in an increase of €623.760 in total costs, showing the importance of charging rates in a system with terminals prone to congestion.

C. Network 3: Realistic network

The goal of testing the realistic network is to show the effects of the model on real life sailing routes. In Tables XIII, XIV and XV in Appendix F results for one year, five years and ten years are shown.
In Table IV the most important results are shown. The results match the expectations, implying that the model can be applied to a realistic network.

- **Base configuration**: Just as with network 2, the model converged very quickly on the best solution. Due to long running times, optimization was stopped at 24% MIP gap. Convergence behaviour was very similar to the behaviour depicted in figure 6.
- **Smart charging enabled:** When smart charging was enabled, the charging costs decreased significantly, €1.205.790 costs can be saved in total over 10 years.
- **Route planning enabled:** One less docking station was needed when using route planning so the Capex decreased with €1.350.000. This shows that with route planning costs can be saved on the capital expense.
- **Smart charging enabled, route planning enabled:** Using both route planning and smart charging saves €5.543.730 in charging costs over 10 years. This result shows route planning increases the efficiency of smart charging, increasing savings by a factor of 4,6. The combination of smart charging and route planning resulted in a cost reduction of 17,7% compared to the base configuration.

KPI	Smart charging, no route planning	No Smart charging, route planning	Smart charging, route planning
Difference in Capex [€]	0	-1.350.000	0
Difference in Varex [€]	-120.579	-49.392	-554.373
Total difference [€]	-1.205.790	-2.293.920	-5.543.730

TABLE IV
Cost of configuration compared to base configuration for Network 3 over 10 years

V. **Conclusion and Recommendations**

The main goal was to expand the research done in the logistic side of the implementation of an exchangeable battery system to IWW shipping. In this chapter, the conclusions of the research are given, by answering the main and sub research questions. The chapter will end with recommendations for further research.

A. Conclusion

The main research question was: "How can the process of exchanging batteries between docking stations and inland ships be optimized to reduce charging costs and capital expenses, while avoiding waiting times?". The main research question can be answered by answering the two sub questions and then summarizing the findings.

How can the charging costs associated with battery charging be minimized through selection of optimal charging times during the day?

The results showed that smart charging, where vessels charge their batteries during the cheapest time periods, significantly reduces charging costs. For the realistic network, a reduction in costs of 3,4% was seen when implementing smart charging without route planning.

How can capital expense and charging costs be minimized while avoiding unnecessary waiting times?

To avoid congestion and therefore waiting times, route planning of vessels was implemented. In addition to avoiding congestion at terminals, a significant synergy between route planning and smart charging was observed. Due to route planning, vessels have more freedom to choose convenient arrival and departure times to optimize battery charging. When enabling both smart charging and route planning, a reduction in costs of 15,7% was observed for the realistic network. When testing the more congestion prone network 2 with four vessels, charging capacity and extra charging spots were identified to be potentially important factors in cost saving.

Final Conclusion

The enhanced model provides a more realistic representation of the operational logistics for battery swapping in IWW shipping. It indicates significant cost savings achievable through strategic planning of charging times and strategic route planning. By addressing these factors, the model successfully answers the main research question, demonstrating that optimization of the battery exchange process can lead to substantial reductions in waiting times, charging costs, and capital expenses.

B. Recommendations

Due to the lack of computational power and time, it was not possible to include more than three or four vessels in the simulations. However, to achieve the goal of Green Deals [6], the number of vessels using electricity instead of diesel should be significantly higher. To obtain a fully reliable output and implement this in the inland waterways in the Netherlands, it's important to run this model with multiple vessels.

In Appendix A, the power-to-speed relation for the vessels was assumed to be linear for simplicity. However, the power-to-speed relationship of diesel-powered ships are known to be exponential and have been extensively studied. [3] [9] Future research should investigate the implementation of nonlinear engine behavior to enhance the realism of this model. Additionally, power-to-speed curve-fit data for inland waterway shipping is available in literature. [20] Furthermore, the total drivetrain efficiency has not yet been accounted for. According to the EV development roadmap proposed by the US Department of Energy, EV motors are targeted to achieve an efficiency of 97% and a power density of 50 kW/L. Although the efficiency of electric motors might be high, the overall drivetrain efficiency is expected to be lower due to factors such as the energy storage efficiency of Lithium-ion batteries, which ranges from 85% to 90%. Addressing these recommendations in future research will give a solid foundation for a more realistic model that can accelerate the transition to sustainable inland waterway transport.

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Appendix

A. Mathematical model

1) **Sets**:

Set	**Definition**
$b \in B$	set of batteries
$v \in V$	set of Vessels
$t \in T$	set of terminals
$n \in N$	set of nodes
$r \in R = T \cup N$	set of all terminals and nodes
$p \in P$	set of time periods

2) **Variables**:

$n_b = \begin{cases} 1 & \text{if battery } b \text{ is being used} \\ 0 & \text{otherwise} \end{cases}$

$u_t = \begin{cases} 1 & \text{if terminal } t \text{ is being used as a DS} \\ 0 & \text{otherwise} \end{cases}$

$x_{b,t,p} = \begin{cases} 1 & \text{if battery } b \text{ is at terminal } t \text{ at period } p \\ 0 & \text{otherwise} \end{cases}$

$y_{b,v,p} = \begin{cases} 1 & \text{if battery } b \text{ is at vessel } v \text{ at period } p \\ 0 & \text{otherwise} \end{cases}$

$k_{b,t,p} = \begin{cases} 1 & \text{if battery } b \text{ is being charged at terminal } t \text{ at period } p \\ 0 & \text{otherwise} \end{cases}$

$m_{b,v,p} = \begin{cases} 1 & \text{if battery } b \text{ is being used at vessel } v \text{ at period } p \\ 0 & \text{otherwise} \end{cases}$

$sp\_var_{v,r,p} = \begin{cases} 1 & \text{if vessel } v \text{ is at terminal/node } r \text{ at period } p \\ 0 & \text{otherwise} \end{cases}$

$sp\_var\_aux_{v,r1,r2,p} = \begin{cases} 1 & \text{if vessel } v \text{ is travelling from terminal/node } r1 \text{ to terminal/node } r2 \text{ at period } p \\ 0 & \text{otherwise} \end{cases}$

$l_{b,p} \in [0, cap_b]$ Battery level of battery $\forall b \in B, \forall p \in P$

$pw\_var_{b,t,p} \in [0, pw_t]$ Charging rate at terminal t $\forall b \in B,\ \forall t \in T,\ \forall p \in P$

$pv\_var_{b,v,p} \in [0, pw_t]$ Power usage of vessel v $\forall b \in B,\ \forall v \in V,\ \forall p \in P$

$reach_{v,p} \in [0, 24 * ts_v]$ The reach of vessel v at time step p

$speed_{v,p} \in [0, ts_v]$ Velocity of vessel v at p

$speed\_aux_{v,r,p} \in [0, 1]$ If a vessel is having a velocity a terminal/node at a time period

$nvt_{t,p} \in [0, |V|]$ The amount of vessels at terminal t at time step p

$nvt\_aux_{t,p} \in [0, |V| - 1]$ The amount of vessels waiting at terminal t at time step p.

3) **Parameters**:

a) General:

$$\begin{aligned} \beta = &\quad \text{Investment horizon in days} \\ M1 = &\quad 2 \cdot |P| \\ M2 = &\quad 1/max(pv\_max_v) \\ M3 = &\quad |P|max(ts_v) \\ M4 = &\quad max[cap_b] \\ M5 = &\quad 1/max(pw\_max_t) \end{aligned}$$

b) Terminals:

cd_t : Capex for installing a specific DS in terminal t [€]
ch_t : Number of charging points of a DS installed at terminal t
pw_max_t : Maximum charging rate of each charging spot at terminal$t$[kW]
CC_p : The price of electricity at p [kWh]
DM_{r_1,r_2} : A distance matrix for the distances between terminals and nodes, it's a R x R matrix.

c) Batteries:

cb_b : Capex of battery b [€]
cap_b : Maximum battery capacity of battery b [kWh]
mbl : The minimum percentage of the battery level
$Lb0$: The initial value of the battery

ut_aux : Initial battery location at a terminal
uv_aux : Initial battery location on a vessel
k_aux : Initial battery usage at a terminal
m_aux : Initial battery usage on a vessel

d) Vessels:

$LT_{v,r,p}$: Logistic tensor: If vessel v has to be at r at time step $p,$ then $LT_{v,r,p} = 1,$ and 0 otherwise.
pv_max_v : Maximum power of vessel v [kWh]
chv_v : Number of batteries that can be fitted in vessel v (docking spots)
ts_v : Topspeed of vessel v [km/h]

e) Initial conditions:

$Uv0_{b,v}$: Initial location of batteries on vessels
$k0_{b,t}$: Initial charging of batteries
$m0_{b,v}$: Initial usage of batteries
$sp0_{v,r}$: Initial locations of vessels

4) **Objective function**:

$$obj_1 = min(\sum_{t \in T} u_t \cdot cds_t + \sum_{b \in B} n_b \cdot cb_b + \sum_{p \in P} CC_p \cdot \beta \cdot \sum_{b \in B} \sum_{t \in T} pw\_var_{b,t,p}) \tag{1}$$

$$obj_2 = min(\sum_{t \in T} \sum_{p \in P} nvt\_aux_{t,p}) \tag{2}$$

5) **Constraints**:

$$n_b \cdot M_1 \geq \sum_{t \in T} \sum_{p \in P} x_{b,t,p} + \sum_{v \in V} \sum_{p \in P} y_{b,v,p} \quad \forall b \in B,\ p > 0 \tag{3}$$

$$u_t \cdot M_1 \geq \sum_{b \in B} \sum_{p \in P} x_{b,t,p} \cdot n_b \quad \forall t \in T \tag{4}$$

$$\sum_{b \in B} m_{b,v,p} \leq 1 \quad \forall v \in V,\ \forall p \in P,\ p > 0 \tag{5}$$

$$\sum_{b \in B} m_{b,v,p} \geq pv_{v,p} \cdot M_2 \quad \forall v \in V,\ \forall p \in P,\ p > 0 \tag{6}$$

$$l_{b,p} = l_{b,p-1} + \sum_{t \in T} pw\_var_{b,t,p} \cdot k_{b,t,p} - \sum_{v \in V} m_{b,v,p} \cdot pv\_var_{v,p} \quad \forall b \in B,\ \forall p \in P,\ p > 0 \tag{7}$$

$$l_{b,p} - l_{b,p-1} \leq M_4(1 - x_{b,t,p}) \tag{8}$$

$$l_{b,p} - l_{b,p-1} \geq -M_4(1 - x_{b,t,p}) \tag{9}$$

$$l_{b,p} \leq cap_b \cdot n_b \tag{10}$$

$$l_{b,p} \geq cap_b \cdot n_b \cdot mbl \tag{11}$$

$$\sum_{v \in V} y_{b,v,p} + \sum_{t \in T} x_{b,t,p} = n_b \quad \forall b \in B,\ \forall p \in P,\ p > 0 \tag{12}$$

$$x_{b,t,p} \leq x_{b,t,p-1} + \sum_{v \in V} y_{b,v,p-1} \cdot sp\_var_{v,t,p} \quad \forall b \in B,\ \forall t \in T,\ \forall p \in P,\ p > 0 \tag{13}$$

$$y_{b,v,p} \leq y_{b,v,p-1} + \sum_{t \in T} x_{b,t,p-1} \cdot sp\_var_{v,t,p-1} \quad \forall b \in B,\ \forall v \in V,\ \forall p \in P,\ p > 0 \tag{14}$$

$$\sum_{b \in B} x_{b,t,p} \leq ch_t \quad \forall t \in T,\ \forall p \in P \tag{15}$$

$$\sum_{b \in B} y_{b,v,p} \leq chv_v \quad \forall v \in V,\ \forall p \in P \tag{16}$$

$$k_{b,t,p} \leq x_{b,t,p} \quad \forall b \in B,\ \forall t \in T,\ \forall p \in P \tag{17}$$

$$m_{b,v,p} \leq y_{b,v,p} \quad \forall b \in B,\ \forall v \in V,\ \forall p \in P \tag{18}$$

$$x_{b,t,0} = Ut0_{b,t} \quad \forall b \in B,\ \forall t \in T \tag{19}$$

$$y_{b,v,0} = Uv0_{b,v} \quad \forall b \in B,\ \forall v \in V \tag{20}$$

$$k_{b,t,0} = k0_{b,t} \quad \forall b \in B,\ \forall t \in T \tag{21}$$

$$m_{b,v,0} = m0_{b,v} \quad \forall b \in B,\ \forall v \in V \tag{22}$$

$$pw\_var_{b,t,p} \geq k_{b,t,p} \quad \forall b \in B,\ \forall t \in T,\ \forall p \in P \tag{23}$$

$$pw\_var_{b,t,p} \cdot M_5 \leq k_{b,t,p} \quad \forall b \in B,\ \forall t \in T,\ \forall p \in P \tag{24}$$

$$l_{b,0} \leq l_{b,|P|-1} \quad \forall b \in B \tag{25}$$

$$sp\_var_{v,r,0} = sp0_{v,r} \quad \forall v \in V,\ \forall r \in R \tag{26}$$

$$sp\_var_{v,r,p} \geq LT_{v,r,p} \quad \forall v \in V,\ \forall r \in R,\ \forall p \in P \tag{27}$$

$$speed_{v,p} \cdot pv\_max_v = ts_v \cdot pv\_var_{v,p} \quad \forall v \in V,\ \forall p \in P \tag{28}$$

$$reach_{v,p} \cdot sp\_var_{v,r,p} = 0 \quad \forall v \in V,\ \forall r \in T,\ \forall p \in P \tag{29}$$

$$reach_{v,p} \cdot sp\_var_{v,r,p} = (reach_{v,p-1} + speed_{v,p} \cdot \Delta p) \cdot sp\_var_{v,r,p} \quad \forall v \in V,\ \forall r \in N,\ \forall p \in P,\ p > 0 \tag{30}$$

$$reach_{v,0} = \left(1 - \sum_{t \in T} sp\_var_{v,t,0}\right) \cdot speed_{v,0} \cdot \Delta p \quad \forall v \in V \tag{31}$$

$$sp\_var\_aux_{v,r_1,r_2,0} = 0 \quad \forall v \in V,\ \forall t \in T,\ \forall p \in P\ ,\ p > 0,\ \forall r \in R \tag{32}$$

$$sp\_var\_aux_{v,t,r,p} \leq sp\_var_{v,t,p-1} \quad \forall v \in V,\ \forall t \in T,\ \forall p \in P\ ,\ p > 0,\ \forall r \in R \tag{33}$$

$$sp\_var\_aux_{v,t,r,p} \leq sp\_var_{v,r,p} \quad \forall v \in V,\ \forall t \in T,\ \forall p \in P\ ,\ p > 0,\ \forall r \in R \tag{34}$$

$$sp\_var\_aux_{v,t,r,p} \geq sp\_var_{v,t,p-1} + sp\_var_{v,r,p} - 1 \quad \forall v \in V,\ \forall t \in T,\ \forall p \in P\ ,\ p > 0,\ \forall r \in R \tag{35}$$

$$DM_{t,r} \cdot sp\_var\_aux_{v,t,r,p} \leq M_3 - 1 \quad \forall v \in V,\ \forall t \in T,\ \forall p \in P\ ,\ p > 0,\ \forall r \in R \tag{36}$$

$$sp\_var\_aux_{v,n,t,p} \leq sp\_var_{v,n,p-1} \quad \forall v \in V,\ \forall n \in N,\ \forall p \in P\ ,\ p > 0,\ \forall t \in T \tag{37}$$

$$sp\_var\_aux_{v,n,t,p} \leq sp\_var_{v,t,p} \quad \forall v \in V,\ \forall n \in N,\ \forall p \in P\ ,\ p > 0,\ \forall t \in T \tag{38}$$

$$sp\_var\_aux_{v,n,t,p} \geq sp\_var_{v,n,p-1} + sp\_var_{v,t,p} - 1 \quad \forall v \in V,\ \forall n \in N,\ \forall p \in P\ ,\ p > 0,\ \forall t \in T \tag{39}$$

$$DM_{n,t} \cdot sp\_var\_aux_{v,n,t,p-1} \leq M_3 - 1 \quad \forall v \in V,\ \forall n \in N,\ \forall p \in P\ ,\ p > 0,\ \forall t \in T \tag{40}$$

$$reach_{v,p-1} \geq DM_{n,t} \cdot sp\_var\_aux_{v,n,t,p} \quad \forall v \in V,\ \forall n \in N,\ \forall p \in P\ ,\ p > 0,\ \forall t \in T \tag{41}$$

$$\sum_{r \in R} sp\_var_{v,r,p} = 1 \quad \forall v \in V,\ \forall p \in P \tag{42}$$

$$DM_{n_1,n_2} \cdot sp\_var\_aux_{v,n_1,n_2,p} \cdot \leq 0 \quad \forall v \in V,\ \forall n_1, n_2 \in N,\ \forall p \in P\ ,\ p > 0 \tag{43}$$

$$\sum_{b \in B} m_{b,v,p} \geq M_2 \cdot pv\_var_{v,p} \quad \forall v \in V,\ \forall p \in P \tag{44}$$

$$speed\_aux_{v,r,p} \leq sp\_var_{v,r,p} \quad \forall v \in V,\ \forall r \in R,\ \forall p \in P,\ p > 0 \tag{45}$$

$$speed\_aux_{v,r,p} \leq sp\_var_{v,r,p-1} \quad \forall v \in V,\ \forall r \in R,\ \forall p \in P,\ p > 0 \tag{46}$$

$$speed\_aux_{v,r,p} \geq sp\_var_{v,r,p} + sp\_var_{v,r,p-1} - 1 \quad \forall v \in V,\ \forall r \in R,\ \forall p \in P,\ p > 0 \tag{47}$$

$$speed\_aux_{v,r,0} = 0 \quad \forall v \in V,\ \forall r \in R \tag{48}$$

$$speed\_aux_{v,n,p} \cdot speed_{v,p} = speed\_aux_{v,n,p} \cdot speed_{v,p-1} \quad \forall v \in V,\ \forall n \in N,\ \forall p \in P,\ p > 0 \tag{49}$$

$$nvt_{t,p} = \sum_{v \in V} sp_{v,t,p} \quad \forall t \in T,\ \forall p \in P \tag{50}$$

$$nvt\_aux_{t,p} \geq nvt_{t,p} - 1 \quad \forall t \in T,\ \forall p \in P \tag{51}$$

B. Explanation of the Mathematical model

The mathematical model of the system can be found in Appendix A, in this model all the sets, variables, parameters, initial values, objective functions and constraints can be found. To fully understand the model it's important to understand the objective functions and the constraints.

1) **Objective functions**:
   1) This objective will minimize the total capital and charging costs, so the model will choose the iteration with the lowest expenses. Whenever the model is used without taking into account the moment for charging, the last added factor can be removed from the objective.
   2) This objective will minimize the number of vessel at a terminal at the same moment, avoiding congestions at terminals and therefore waiting times. This objective is prioritized over the other objective, meaning that the solver will first optimize this objective and then objective 1 without compromising on this optimization.
2) **Constraints**:
   3) A battery is used when the battery is on a vessel or at a terminal for at least one timestep. Initial conditions are omitted, as these are predefined.
   4) A terminal is used whenever a used battery is at a terminal at a time step during the simulation.
   5) It's not possible to use more than one battery at the same time step at a vessel.
   6) $pv_{v,p}$ can only be a number greater than zero if a battery is used at a vessel at that time step.
   7) The battery level at the current time step is the previous battery level plus the charging rate when a battery is charged, or, minus the power used by a vessel when a battery is used at a vessel.
   8) The battery level at two consecutive time steps will be the less or equal than $M_4 \cdot (1 - x_{b,t,p})$.
   9) The battery level at two consecutive time steps will be the greater or equal than $-M_4 \cdot (1 - x_{b,t,p})$. This constraints combined with the previous will make sure the battery will not drain at a terminal.
   10) The maximum battery level can't be greater than the maximum capacity if the battery is used in the system.
   11) Battery levels can't be below the minimum capacity (10% in this research). When the battery is not used, the battery level will be zero.
   12) When a battery is used in the model, it has to be at a terminal or on a vessel at all time steps.
   13) A battery can only be at a terminal if it was already at that terminal or was on a vessel that was at that terminal in the previous time step.
   14) A battery can only be at a vessel if it was already on that vessel or it was at the terminal where the vessel was in the previous time step.
   15) There can only be as many batteries on a terminal as spots there are on the docking station.
   16) There can only be as many batteries on a vessel as places there are on the vessel.
   17) A battery can only be charged when it's at a terminal.
   18) A battery can only be used as power supply when it's at a vessel.
   19) t/m 22): Initial locations and states of the batteries.
   23) pw_{var} cannot be zero when a battery is being charged.
   24) If the battery is not being charged, pw_{var} is zero.
   25) The battery level at the start of a day ($p = 0$) has to be the less or equal to the battery level at the end of a day ($|P| - 1$), this makes it possible to extrapolate results from a single day to a longer time period.
   26) The starting positions of the vessels are defined here.
   27) A vessel has to be at a terminal at a certain time step defined by $LT_{v,r,p}$
   28) The speed of a vessel is defined using the top speed, the maximum power and the current power consumption.
   29) When a vessel is at a terminal, the reach will be reset to zero.
   30) The reach of a sailing vessel is defined by the reach of the previous time step plus the speed of the vessel. Reach can only be accumulated when a vessel is at a node.

31) The reach at time step zero, is zero when a vessel starts at a terminal.
32) $sp\_var\_aux_{v,r_1,r_2,0}$ is always zero at time step zero.
33) $sp\_var\_aux_{v,t,r,p}$ can only be one when the vessel was at terminal t at the previous time step.
34) $sp\_var\_aux_{v,t,r,p}$ can only be one when the vessel is at terminal/node r at the current time step.
35) $sp\_var\_aux_{v,t,r,p}$ is one if vessel v is traveling from t to r
36) It is only possible for a vessel to travel from t (terminal) to r (terminal or node) when the distance between them is less than M_3.
37) $sp\_var\_aux_{v,n,t,p}$ can only be one when the vessel v was at node n at the previous time step.
38) $sp\_var\_aux_{v,n,t,p}$ can only be one when the vessel v is at terminal t at the current time step.
39) $sp\_var\_aux_{v,n,t,p}$ is one if vessel v is traveling from n to t.
40) It is only possible for a vessel to travel from n (node) to t (terminal) when the distance between them is less than M_3.
41) The reach of a vessel at $p-1$ has to be equal or greater than $DM[n,t]$ when traveling from n to t at p.
42) A vessel can only be at one location at a time step.
43) It's not possible for a vessel to travel from n_1 (node) to n_2 (node).
44) Whenever $pv\_var_{v,p}$ is greater then zero, one battery is used in the vessel.
45) $speed\_aux$ can only be one if vessel v is at node/terminal r at the current time step.
46) $speed\_aux$ can only be one if vessel v is at node/terminal r at the previous time step.
47) $speed\_aux$ can only be one if vessel v is at node/terminal r at the current and the previous time step.
48) $speed\_aux$ is zero at time step zero.
49) The speed of a vessel must be consistent when travelling at a node.
50) $nvt_{t,p}$ is equal to the number of vessels at a terminal at a time step.
51) $nvt\_aux_{t,p}$ is the amount of vessels waiting at a terminal, so $nvt\_aux_{t,p}$ equals $nvt_{t,p}$ minus one.

From constraint 32 onward, a lot of constraints were put in place for the linearization of previously established constraints. These constraints used auxiliary variables like sp_var_aux. As the name implies, these variables were added to help enforce the desired behaviour of variables like sp_var, while maintaining linear behaviour of the model.

C. Charging costs per hour

Time	Price [€/kWh]
00:00	0,28080
01:00	0,273115798
02:00	0,217332
03:00	0,264846182
04:00	0,240806
05:00	0,258714
06:00	0,294046
07:00	0,305178
08:00	0,3001565
09:00	0,30421
10:00	0,300096
11:00	0,267624286
12:00	0,2916865
13:00	0,2876935
14:00	0,290537
15:00	0,283398
16:00	0,281341
17:00	0,3208475
18:00	0,3220575
19:00	0,346802
20:00	0,3457735
21:00	0,322844
22:00	0,3019715
23:00	0,280615

TABLE V
Charging costs per hour

D. Simple network

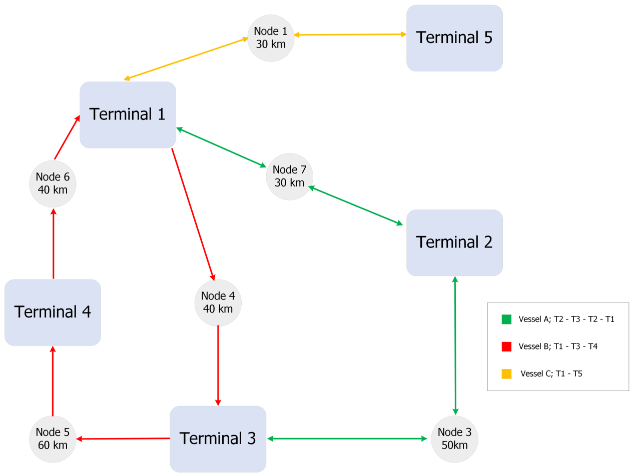


Fig. 7. Route simple network, with nodes added.

1 year				
Configuration	No Smart charging, route planning disabled	Smart charging enabled, No route planning	No smart charging, route planning enabled	Smart charging, route planning enabled
Capex per vessel [€]	3.261.000	3.261.000	3.261.000	3.261.000
Varex per vessel [€]	894.937	768.929	895.648	755.429
Total batteries	6	6	6	6
Total docking stations	3	3	3	3
GAP	13,80%	4,22%	4,40%	4,73%
Time to solve (sec)	6.584	326	917	1268
Pearson Correlation	-0,20	0,42	-0,04	0,54

TABLE VI
Simple network: 1 Year

5 years				
Configuration	No Smart charging, route planning disabled	Smart charging enabled, No route planning	No smart charging, route planning enabled	Smart charging, route planning enabled
Capex per vessel [€]	3.261.000	3.261.000	3.261.000	3.261.000
Varex per vessel [€]	894.937	768.929	895.648	755.429
Total batteries	6	6	6	6
Total docking stations	3	3	3	3
MIPgap	13,80%	4,91%	4,40%	4,73%
Time to solve (sec)	5.488	466	932	1.268
Pearson Correlation	-0,20	0,42	-0,04	0,54

TABLE VII
Simple network: 5 Years

10 years				
Configuration	No Smart charging, route planning disabled	Smart charging enabled, No route planning	No smart charging, route planning enabled	Smart charging, route planning enabled
Total Capex per vessel [€]	3.261.000	3.261.000	3.261.000	3.261.000
Varex per vessel [€]	894.937	771.012	895.648	755.429
Total batteries	6	6	6	6
Total docking stations	3	3	3	3
MIPgap	13,80%	4,97%	4,40%	4,99%
Time to solve (sec)	6.243	448	918	2.760
Pearson Correlation	-0,20	0,40	-0,04	0,54

TABLE VIII
Simple network: 10 Years

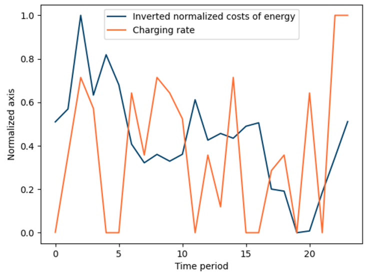
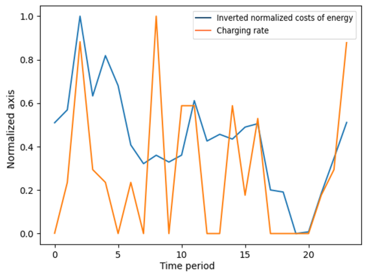
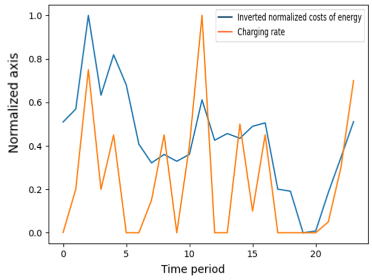
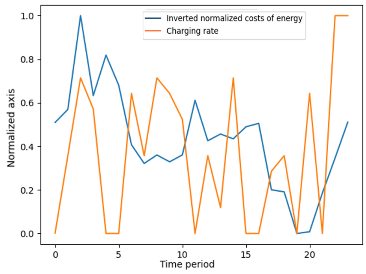
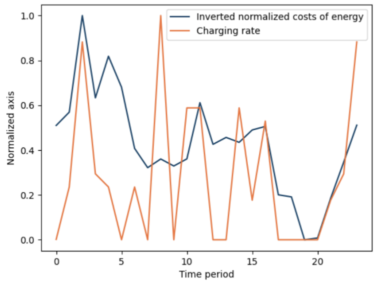
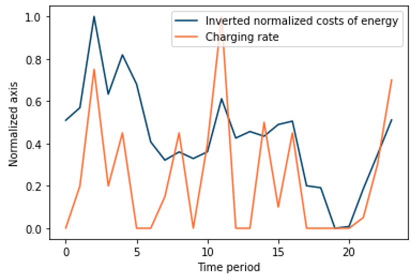
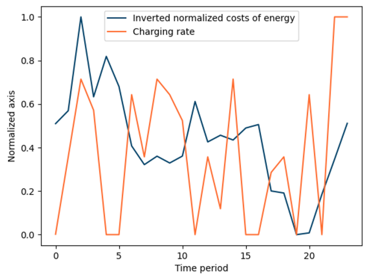
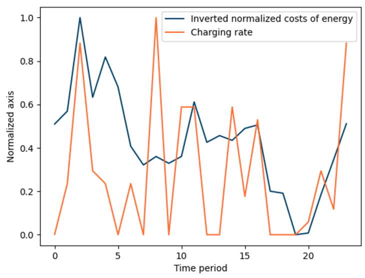
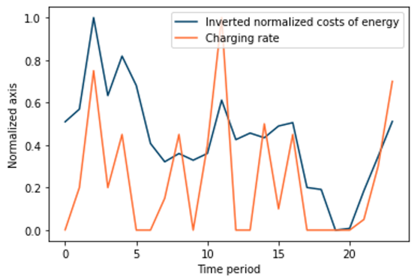
Years	Not smart, Route planning enabled	Smart, Route planning disabled	Smart, Route planning enabled
1			
5			
10			

TABLE IX
Charging rate compared to costs of energy per time period

E. Network prone to congestion

Network prone to congestion			
KPI	Base configuration	Smart charging enabled	Smart charging and route planning enabled
Battery per vessel	2	2	2
DS per vessel	1	1	0,75
Capex per vessel [€]	3.260.000	3.260.000	2.922.500
Varex per vessel [€]	1.179.526	883.112	868.826
Pearsons correlation	-0,126	0,394	0,582
MIPgap	17,7%	5%	5%
Investment horizon	10 years	10 years	10 years
Total costs over horizon (10 years) [€]	60.221.040	48.364.480	46.443.040
Difference in Capex (per year) [€]	-	0	-
Difference in Varex [€]	-	-1.185.656	-1.242.800
Total difference over 10 years [€]	-	-11.856.560	-13.778.000

TABLE X
Results of different configurations applied to network 2

Network prone to congestion					
KPI	Smart charging and route planning enabled	Ignoring terminal congestion	more battery spots all DS	More battery spots terminal 3	Less charging capacity
Battery per vessel	2	2	2	2	2,25
DS per vessel	0,75	0,75	0,75	0,75	1
Capex per vessel [€]	2.922.500	2.922.500	3.222.500	3.022.500	3.228.750
Varex per vessel [€]	868.826	865.681	857.168	858.924	897.490
Pearsons correlation	0,582	0,549	0,648	0,647	0,498
MIPgap	5%	5%	5%	5%	5%
Investment horizon	10 years	10 years	10 years	10 years	10 years
Total costs over horizon (10 years) [€]	46.443.040	46.317.240	47.176.720	46.446.960	48.814.600
Difference in capex (per year) [€]	-	0	1.200.000	400.000	1.225.000
Difference in Varex [€]	-	- 12.580	- 46.632	- 39.608	114.656
Total difference over 10 years [€]	-	- 125.800	733.680	3.920	2.371.560

TABLE XI
Results of different scenarios applied to network 2, all with smart charging and route planning enabled

F. Realistic Network

Vessel 1	Vessel 2	Vessel 3
Rotterdam	Nijmegen	Den Bosch
Moerdijk	Moerdijk	Moerdijk
Den Bosch	Vlissingen	Alphen aan de Rijn

TABLE XII
Real routes: The sailing profiles for network 3

Realistic network				
KPI	Basis	Smart charging enabled, route planning disabled	Smart charging disabled, route planning enabled	Smart charging enabled, route planning enabled
Total Capex [€]	3.710.000	3.710.000	3.260.000	3.710.000
Varex per vessel[€]	888.519	630.046	754.650	618.094
Batteries per vessel	2	2	2	2
DS per vessel	1,333	1,333	1	1,333
Gap	5,00%	5,00%	27,6%	5,00%
Pearson correlation	-0,179	0,597	-0,084	0,716

TABLE XIII
Realistic network - Year 1

Realistic network				
KPI	Basis	Smart charging enabled, route planning disabled	Smart charging disabled, route planning enabled	Smart charging enabled, route planning enabled
Total Capex [€]	3.710.000	3.710.000	3.260.000	3.710.000
Varex per vessel [€]	888.519	763.502	754.649	618.094
Batteries per vessel	2	2	2	2
DS per vessel	1,333	1,333	1,333	1,333
Gap	5,00%	5,00%	25,00%	5,00%
Pearson correlation	-0,179	0,180	-0,402	0,716

TABLE XIV
Realistic network - Year 5

Realistic network				
KPI	Base configuration	Smart charging, route planning disabled	No smart charging, route planning enabled	Smart charging enabled, route planning enabled
Battery per vessel	2	2	2	2
DS per vessel	1,3333	1,333	1	1,333
Capex per vessel [€]	3.710.000	3.710.000	3.260.000	3.710.000
Varex per vessel [€]	803.695	763.502	787.231	618.904
Pearson correlation	-0,183	0,180	-0,402	0,716
Gap	5%	5%	24%	5%
Investment horizon	10 years	10 years	10 years	10 years
Total costs over horizon (10 years)[€]	35.240.850	34.035.060	34.103.910	29.697.120
Difference in Capex (per year) [€]	-	0	0	0
Difference in Varex [€]	-	-120.579	-113.694	-554.373
Total difference over 10 years [€]	-	-1.205.579	-1.113.694	-5.543.730

TABLE XV
Results of different scenarios applied to realistic network over 10 years