



# Needs

*Dynamic Techno - Economical Scenario  
Simulation Model for Sustainable  
Waterborne Activities and Transport*

Overview of the final version of the generic model  
for application use



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<b>Document information</b>	
Short description	The present document summarises the realised technical developments and status of the simulation model. The developments appeared to be much more interlinked and dependent than originally imagined in steps. As a matter of fact, activities went parallel and could hardly be reported after each other as one would provide input to the other and vice-versa.
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## 1 Management summary

In Work Package 1 of the NEEDS project, a generic techno-economic simulation model has been developed, which can be used to analyse the impact of future developments and policy decisions on the fleet and infrastructure of a geographic region.

This report provides a description of the structure of the generic model but also the specific structure as developed when working on two regional applications.

While the generic framework contains all possible elements to describe a region and its elements, which can basically be defined in ships, ports and route, their interactions and dependencies impose a more complex structure with a greater number of components. Such interactions are now also part of the generic framework, as well as the databases governing the properties of each element of the framework.

This deliverable brings as consequence much more than an architecture with empty elements. It also defines the interactions between each element and the databases giving content of the elements themselves, but also the databases influencing the time histories of the upcoming scenario's (external elements such as environment).

A generic simulation framework was developed with a number of key elements to represent the eco-system of a regional waterborne network. A large amount of generic parameters were defined, such that they can be fixed or varied in time. This offers great possibilities of variations, but will require a careful methodology in its use, as the number of variations and pathways are infinite, as it is the case in real life.



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## 4 Introduction and methodology

The objective of Work Package 1 was to develop a generic model defining a region with all possible elements that can compose the waterborne network. The methodology applied is similar to the one originally thought as concept during the project preparation for each individual elements and databases necessary to perform a simulation. Concerning the interdependency and relations that govern the consequences of a given scenario and the dynamic aspect of such simulation, it was necessary to receive the inputs and the specificity in the regional models to create them. On that part, we originally thought that the development tasks could be much more independent and stepwise, while the development work appeared to be much more combined between the WP1 and the two applications of WP2 and WP3. This explains the change in planning of the deliverables.

As anticipated, the first part of the work consisted in identifying and describing parameters defining the different elements taking place in the modelled eco-system: Energy, Harbour Infrastructure, Ships and Transport.

Entities describing the eco-system are not modelled individually as their number is too large (unless a region would be small enough to do so, which is not applicable for the two cases). The smallest element in the energy infrastructure is an energy bunkering site and energy type. One harbour represents the smallest element in terms of destination and bunkering location. One ship represents the smallest element in terms of transport mean and capacity. Each element, or cluster of elements, is defined with parameters that will be specified as constant entities or time-dependent variables when modelling a specific region.

The next step was to define relevant dependency relations that create the techno-economic model and can make it dynamic. The basic principle of that task was to attribute relations between entities with logical consequences and inter-dependencies.

Another source of dynamic behaviour resides in the variation in environmental conditions. On that aspect we have succeeded in considering a larger number of information than originally expected, especially for the Rhine region where variability over time for water depth and current speed could be integrated.



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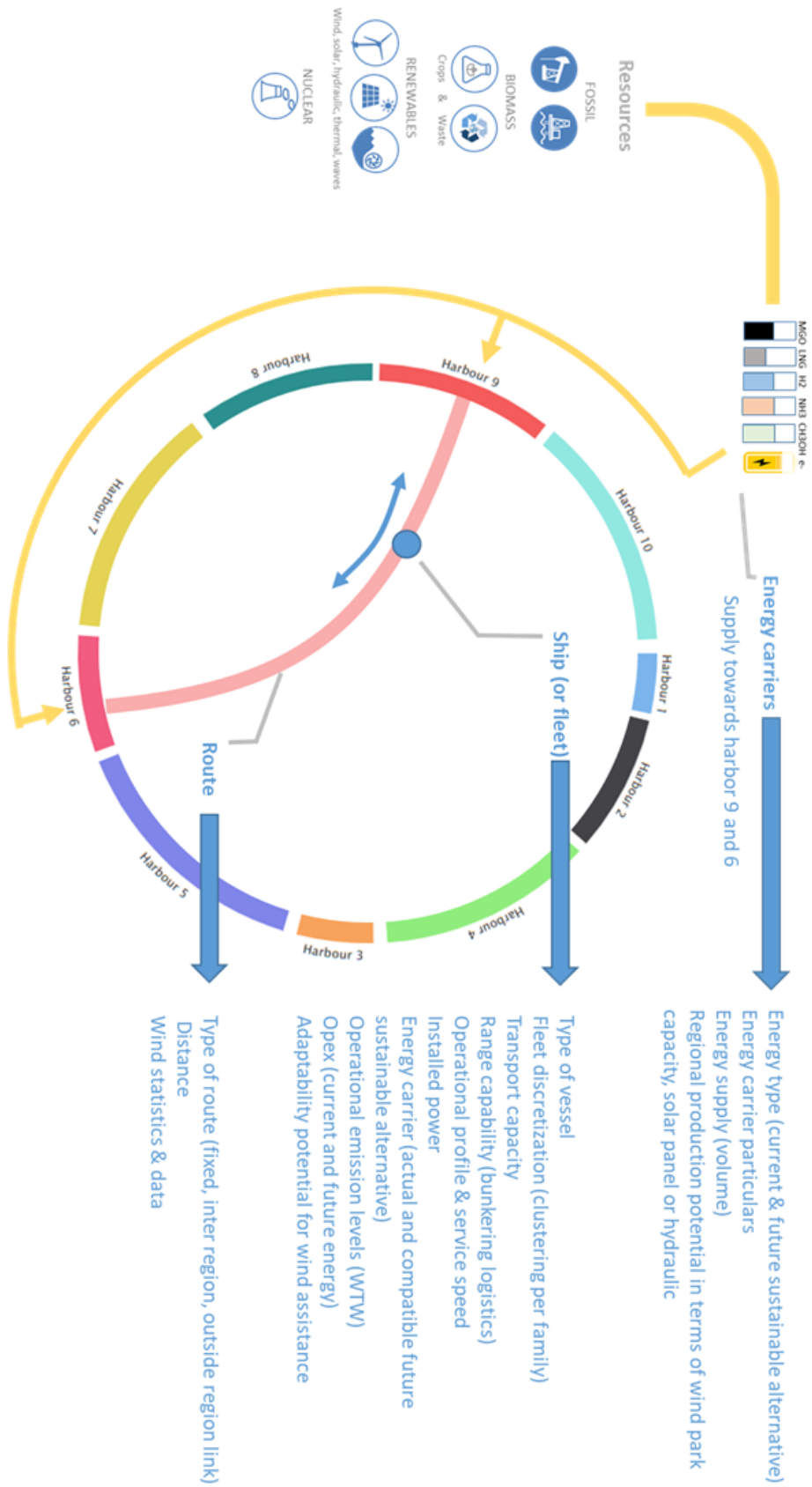


Figure 1: Representation of a regional waterborne eco-system.



## 5 Modelling steps, techniques and structure of the framework

It is important to remind the overall goal of simulation, which is to analyse the influence and consequences of scenarios on GHG emissions at regional level, for entities and variables related to the fleet (ship types, power and energy system, operational conditions, payload, Opex and Capex, logistics), routes and infrastructure (energy carriers requirements at bunkering/charging locations), taking into account the influence of environmental conditions (current and water depth on rivers, waves and wind at sea).

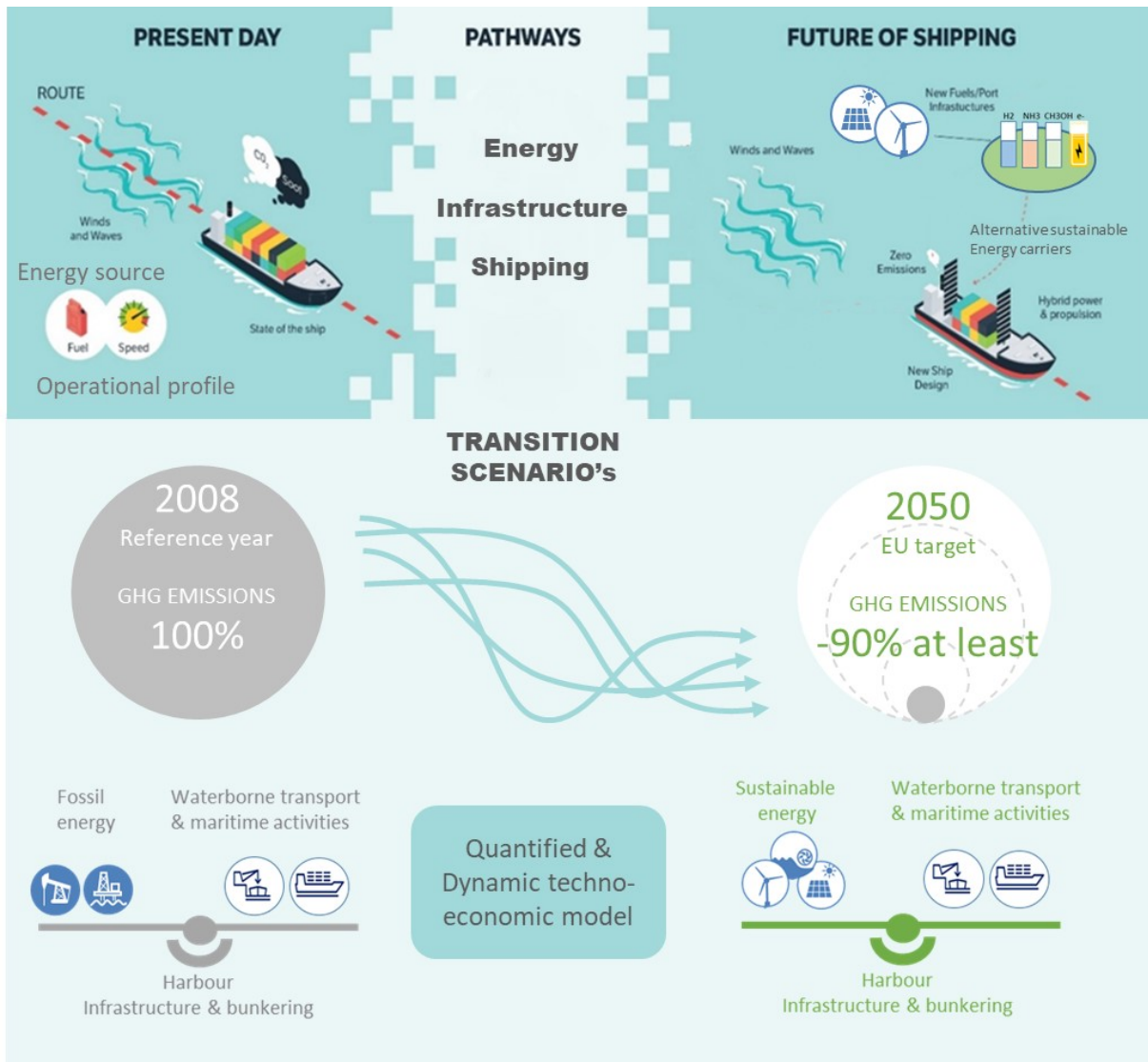


Figure 2: The role of the techno-economic model to evaluate scenarios of the energy transition.

The steps to model a waterborne region and create scenarios are the following:

- Discretise a region and its waterborne transport network in main routes and ship families (clustering).
- Calculate consumption, emissions, and bunker behaviour of each single vessel type.





- Extend this model to an entire fleet (multiplying the elements of a family).
- Define interactions and inter-dependencies between given parameters.
- Prepare a database with the characteristics of the original ship families with alternative power systems (refit or newbuild with upgraded characteristics).
- Model ship operations, routes and ports and run the simulation to obtain the current steady conditions (used as benchmark).
- Apply scenario by defining fixed and varying parameters, defining also parameters left “open” that are calculated (consequences of parameters changing) and re-run the simulation.
- Analyse the consequences of the scenario.
- Optimisation of a transition pathway can be obtained by re-running a scenario, changing / fine-tuning parameters.

The programming language of the tool is in Python, on top of **SimPy**<sup>1</sup>, which is a process-based discrete-event simulation framework, SimPy is released as open-source software under the MIT License.

The main elements composing the simulation model are described below.

## 6 key objects: Ships, Ports, Routes, Scenarios, Region, Pathway

- **Ship**: representation of a real ship, with consumption modelling, bunker and cargo.
- **Port**: representation of a port, with bunker capacity for a given number of ships, storing specific energy carriers with given supply.
- **Route**: geographical connection between ports.
- **Scenario**: external influence over time on a parameter of the simulation.
- **Region**: a group of ports and routes representing a spatially-limited region.
- **Pathway**: a group of scenarios influencing the simulation.

## Main databases

- **Fleet DB**: definition of ship classes with main characteristics.
- **Environmental conditions DB**: hindcast data of the region over a 5-year period, for current, water depth, waves, wind.
- **Power consumption DB**: required power for each ship class, sailing on each route, at any time (any environmental conditions occurring in the 5-year period).
- **Power system DB**: for each ship class, definition of the properties (bunker, cargo, operational profile, efficiency), both for their current power system (diesel) and several pre-defined retrofit alternatives (LNG, hydrogen, electricity, ...).
- **Energy carrier DB**: properties, emission, costs of modelled energy carriers.

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<sup>1</sup> <https://en.wikipedia.org/wiki/SimPy>

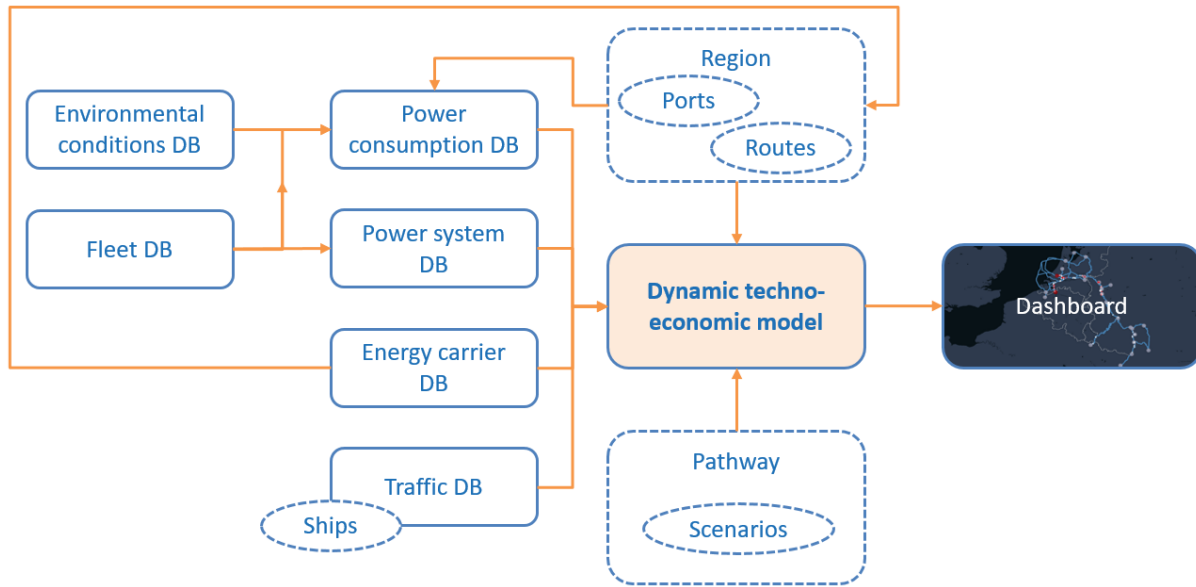


Figure 3: Detailed workflow of the framework.

Beside those elements, which require quite some specialised knowledge in python programming, hydrodynamic performance assessment, marine power systems and data-handling techniques, the results are being made available through a dashboard and a simple web-based visualisation. An upcoming development will also be to allow the input of prepared parameters to play with different scenarios and rerun simulations.



## 6 Key elements of the simulation model

### 6.1 Region definition

A region describes a geographically-limited network of ports and waterways.

Each region contains:

- A graph of the ports and the routes between them. This is a description of the geographic relations between all ports in a region.  
The ports are the nodes on the graph, the routes between them are the connections between the nodes. A shortest path algorithm can be used to find the entire route between two ports, which will return a list of intermediate ports that will be passed along the way.
- An array of ports in the region. The port object is explained in section 6.1.1.

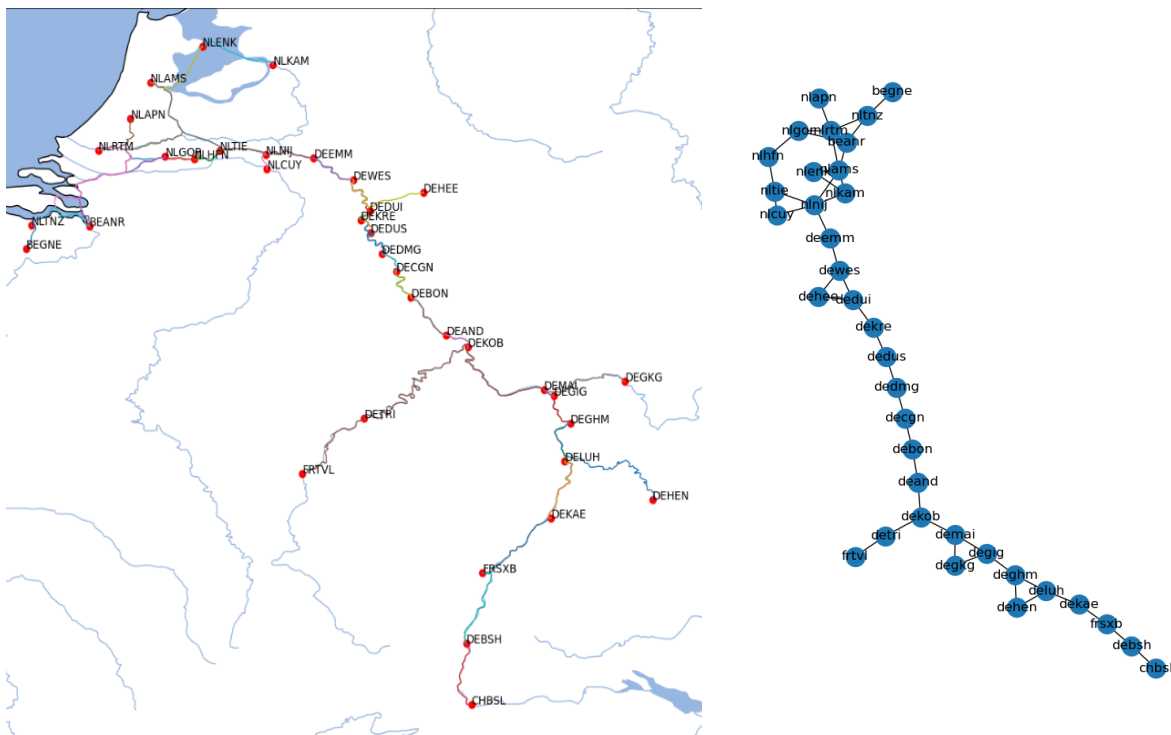


Figure 4: Map and graph of Rhine region with all available ports.





- UN LOCODE<sup>2</sup>
- Ship capacity for bunkering
- A bunker point  
A bunker point holds a list of energy carriers that are available. Per energy carrier the following information is available:
  - The energy carrier price and time-dependent development between 2020 and 2050
  - The bunker speed (how fast energy can be transferred from bunker point to ship)
  - The CO<sub>2</sub> conversion factor of the energy carrier, both Well-to-Tank (WTT) as well as Tank-to-Wake (TTW)

### 6.1.2 The Route object

A route is the representation of the route a ship will sail. It consists of a list of waypoints (longitude and latitude) the ship will pass. In the simulation, a route is unique between two ports. If two ports are not directly linked by a single route, the route will be calculated via an intermediate port that connects both ports.

## 6.2 Power consumption database

For each region, a power consumption database is precomputed with MARIN Gulliver<sup>3</sup> simulation tools. The power consumption database contains the ship speed and energy consumption for a predefined combination of shaft power and start time, for a specific section.

Weather effects and current speed/water depth are incorporated in the ship forces modelling in Gulliver, and are fetched from environmental conditions database.

The power consumption database is created with the following steps:

- A set of unique sections is created.  
A section is unique by a combination of start port, end port, ship type and loading condition.
- For each unique section, a number of Gulliver calculations is performed
  - The ship type linked to the section will start sailing from the start port, and will follow a list of waypoints to the end port. The loading condition and resulting resistance curve is applied. The ship will sail at a predefined shaft power ratio, and the resulting ship speed and energy consumption are recorded.
  - The Gulliver simulation will be started at a range of start times (to incorporate fluctuating environmental conditions) and a range of shaft power ratios (to assess the influence of ship speed variation)
  - The range of start times is as follows:

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<sup>2</sup> <https://unece.org/trade/cefact/unlocode-code-list-country-and-territory>

<sup>3</sup> <https://www.marin.nl/en/publications/voyage-scenario-simulation-with-gulliver>



*Rhine region: Start: 1-1-2015, end 1-1-2020, interval between starts  $\approx$  36 days.*

*Greek region: Start: 1-1-2015, end 1-1-2020, interval between starts  $\approx$  36 days.*

- The range of shaft power ratios is as follows: [0.01, 0.15, 0.3, 0.6, 0.9, 1.0]
  - The minimum water depth encountered in the section is recorded.
- Each unique combination of section, start time and shaft power ratio is recorded in the power consumption database.

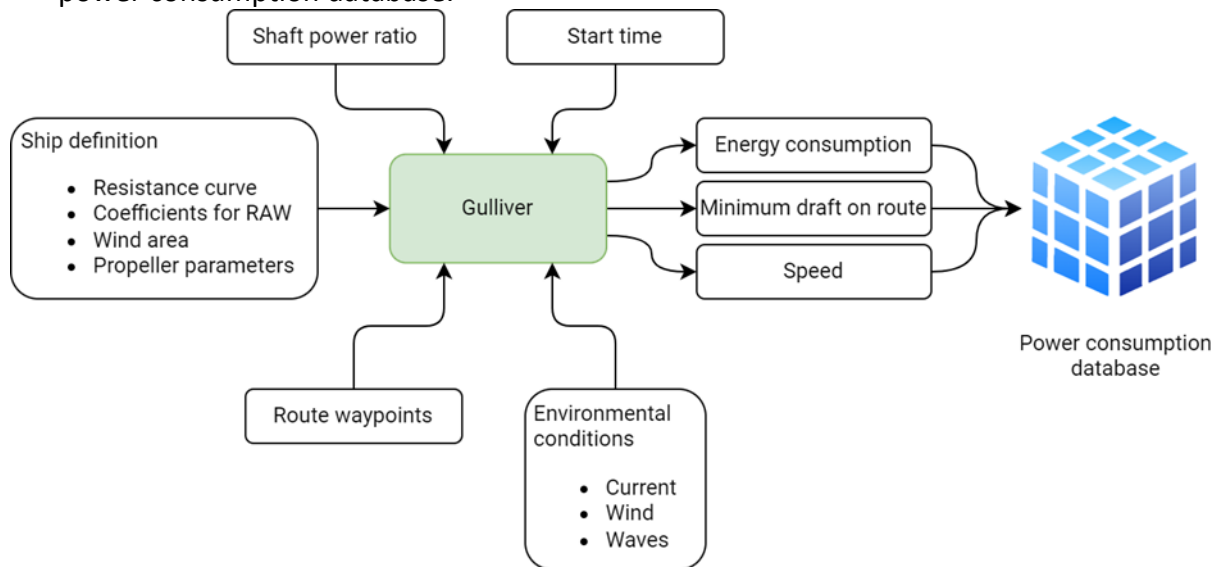


Figure 7: Workflow for the generation of the Power consumption database.

### 6.3 Power system database

The power system database contains the ship parameters that are influenced by the on-board power system. It is used to change key properties of a retrofitting ship, or to define properties of a newly-built ship. For each ship class and type of power system, the following characteristics are indicated:

- The Tank-To-Shaft efficiency of the propulsion train.
- The payload.
- The equipped power.
- The sailing profile.
- The bunker capacity.

Each ship class of the fleet has initial characteristics, with a diesel combustion engine. They represent the baseline situation with typical characteristics of the existing fleet. The database also describes, for each ship class, multiple alternatives with different power systems (LNG, hydrogen, electric batteries, etc.). Naturally, alternative power systems come with compromises on the payload, installed power, bunker capacity when comparing to the diesel solution.



In practice, different choices can be made when selecting an alternative power system. The size of this system and the bunker capacity (and therefore the autonomy) greatly influence the available payload. As an example, installing 20 containers of battery on an electrified inland ship greatly reduces the payload when comparing to its diesel-ICE twin with a 50 m<sup>3</sup> fuel tank. To take into account that not all ship owners will make the same compromise between performance and cargo capacity, the power system database contains three options per type of alternative power system. For the sake of clarity, the characteristics of these 3 options are compared to the characteristics of the diesel-ICE ship:

- A large power system: little to no compromise on the performance, at the cost of an acceptable loss on the payload.
- An intermediate power system: a limited reduction of installed power, sailing speed and payload.
- A compact power system: significant reduction of the installed power and sailing speed. Little to no compromise on the payload.

When retrofitting/building a ship with a given energy carrier, the selection of the power system size is done randomly between the 3 options described above.

In order to create such database, we use the SPEC<sup>4</sup> (Ship Power and Energy Concepts) tool developed by MARIN. It relies on a dataset MARIN made publicly available in the course of their involvement in the European Sustainable Shipping Forum, as task leader of a study in the Sustainable Alternative Power for Ships working group. Such database is publicly available on a dedicated portal<sup>5</sup>.

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<sup>4</sup> <https://www.marin.nl/en/news/webinar-on-ship-power-and-energy-concepts-tool>

<sup>5</sup> <https://sustainablepower.application.marin.nl/>







## 6.4 Energy carrier database

The energy carrier database contains for every energy carrier type:

- The bunker speed in kWh per hour.
- The base fuel price and expected price development.
- The TTW and WTW conversion ratio.
- The calorific value.
- The fitting costs and time required to install a system running on the specific energy type. These costs are divided into costs for the bunker capacity (tanks etc.) and costs for the energy conversion (engines etc.). For each specific combination of installed power and bunker capacity, such costs can be calculated.
- A matrix describing which energy carriers require a retrofit, and which ones can act as a drop-in energy carrier.

For each energy carrier, there are multiple mixes available, from grey to green.



Table 1 Example of parameters for each energy type in the Energy carrier database

Fuel	Transfer method	Contained energy	Bunker speed	CO <sub>2</sub> emissions kg/GJ		Energy price €/kWh						
				WTT	TTW	2020	2025	2030	2035	2040	2045	2050
Diesel (MDO)	Stat2Ship	MJ/kg 30.09	kWh/h 335476	14.26	75.1	0.17	0.06	0.06	0.06	0.06	0.07	0.07
Diesel (20%FAME UCO, 30% HVO rapeseed)	Stat2Ship	31.13	350242	-10.3	72.1	0.17	0.07	0.07	0.07	0.07	0.07	0.07
eDiesel (renewable electricity + Flue CO2)	Stat2Ship	30.36	335476	-68.3	75.1	0.2	0.18	0.17	0.11	0.1	0.1	0.09
LNG	Stat2Ship	28.37	202500	13.7	57.3	0.09	0.04	0.04	0.04	0.04	0.04	0.04
Electricity	Charging	0.33	188	11.6	0	0.1	0.09	0.09	0.09	0.09	0.09	0.09
Electricity	Swapping	0.33	36000	11.6	0	0.1	0.09	0.09	0.09	0.09	0.09	0.09
Green Electricity	Charging	0.33	188	0	0	0.13	0.12	0.12	0.12	0.12	0.12	0.12
Green Electricity	Swapping	0.33	36000	0	0	0.13	0.12	0.12	0.12	0.12	0.12	0.12
Fossil Hydrogen	Stat2Ship	6.6	156	75.6	0	0.27	0.11	0.11	0.11	0.11	0.11	0.11
CCS Hydrogen	Stat2Ship	6.6	156	39.7	0	0.32	0.13	0.13	0.13	0.13	0.13	0.13
Renewable Hydrogen	Stat2Ship	6.6	156	0	0	1.12	0.47	0.47	0.47	0.47	0.47	0.47
Hydrogen Diesel4%	Stat2Ship	7.46	13569	3.5	18	1.08	0.45	0.45	0.45	0.45	0.45	0.45
Hydrogen Diesel4%	Stat2Ship	7.46	13569	60.6	18	0.26	0.11	0.11	0.11	0.11	0.11	0.11
eLNG (renewables + fluegas CO2)	Stat2Ship	28.37	83100	-50.4	57.3	0.21	0.09	0.09	0.09	0.09	0.09	0.09
Methanol	Stat2Ship	14.533	148500	27.35	69.7	0.16	0.05	0.05	0.05	0.05	0.05	0.05
Methanol (black liquor)	Stat2Ship	14.533	148500	-33.1	69.7	0.18	0.1	0.1	0.05	0.05	0.05	0.05
Methanol (renewable electricity + flue gas (C2 = H2O))	Stat2Ship	14.533	148500	-62.1	69.7	0.19	0.1	0.1	0.05	0.06	0.06	0.06
Methanol Diesel5%	Stat2Ship	15.26	148500	-55.8	70	0.18	0.09	0.09	0.05	0.05	0.05	0.05
Methanol Diesel35%	Stat2Ship	19.79	148500	-20.5	71.7	0.17	0.08	0.08	0.05	0.05	0.05	0.05



Fuel	Fitting costs €/kWh - €/kW				Install time	Type	
	Energy carrier	Energy converter	Energy distribution	Days		Energy converter	Energy distribution
Diesel (MDO)	0.11	350	0	60	4 stroke - medium speed	Direct propulsion	
Diesel (20%FAME UCO, 30% HVO rapeseed)	0.11	350	0	60	4 stroke - medium speed	Direct propulsion	
eDiesel (renewable electricity + Flue CO2)	0.11	350	0	60	4 stroke - medium speed	Direct propulsion	
LNG	0.4	350	0	60	4 stroke - medium speed	Direct propulsion	
Electricity	700	0	1200	60	None	Battery electric propulsion	
Electricity	700	0	1200	60	None	Battery electric propulsion	
Green Electricity	700	0	1200	60	None	Battery electric propulsion	
Green Electricity	700	0	1200	60	None	Battery electric propulsion	
Fossil Hydrogen	30	2500	1200	60	LT PEMFC	FC electric propulsion	
CCS Hydrogen	30	2500	1200	60	LT PEMFC	FC electric propulsion	
Renewable Hydrogen	30	2500	1200	60	LT PEMFC	FC electric propulsion	
Hydrogen Diesel4%	16.04	350	0	60	4 stroke - medium speed	Direct propulsion	
Hydrogen Diesel4%	16.04	350	0	60	4 stroke - medium speed	Direct propulsion	
eLNG (renewables + fluegas CO2)	0.4	350	0	60	4 stroke - medium speed	Direct propulsion	
Methanol	0.18	350	0	60	4 stroke - medium speed	Direct propulsion	
Methanol (black liquor)	0.18	350	0	60	4 stroke - medium speed	Direct propulsion	
Methanol (renewable electricity + flue gas C12 = H2O)	0.18	350	0	60	4 stroke - medium speed	Direct propulsion	
Methanol Diesel5%	0.18	350	0	60	4 stroke - medium speed	Direct propulsion	
Methanol Diesel35%	0.16	350	0	60	4 stroke - medium speed	Direct propulsion	



Most of the fuel prices have been given as input by SPB. For the fuel types that did not have a price, the SPEC database was used. The prices of the SPEC database were scaled with the price of SPB for a fair comparison. More details on how the prices were derived can be found in the Database\_Fuel.xlsx in the tab Costs.

The bunkering speeds were provided by SPB, except for hydrogen. The latter was taken from the DNV report 11I1RCRW-2 titled "RH2INE-Kickstart-Study-Scenario-building-Hydrogen-Bunkering-Scenarios".

The costs of the power system database have been based on the SPEC database. Report [https://eibip.eu/wp-content/uploads/2018/08/D7.1\\_Move-it-Final-Report\\_System-Integration.pdf](https://eibip.eu/wp-content/uploads/2018/08/D7.1_Move-it-Final-Report_System-Integration.pdf) was used to validate the retrofit costs of diesel.

A default power system installation time of 60 days for any energy source is currently implemented. More specific values can be specified per technique.



## 6.5 Traffic database (ships)

### 6.5.1 The fleet

The traffic database defines the fleets that will be simulated by the simulation model in a certain region.

Each entry in the regional fleet database describes a 'fleet', i.e., a ship type sailing on a specific sailing schema (which is a combination of route, loading condition and sailing speed). By changing the number of ships per 'fleet', a subset of the entire regional fleet can be simulated.

Table 2 Example of Rhine traffic database

Ship Type	Port A	Port B	#ships	Empty outbound	Speed between ports [kn]		Port Waiting time [h]	Port cons. [kWh/day]	Operational hours / year
					A-B	B-A			
PushB4	Rotterdam	Duisburg	9	TRUE	5.17	9.55	8	1	8064
C3L/B	Rotterdam	Antwerp	40	FALSE	5.40	5.40	48	1	8064
MTS 135m	Rotterdam	Karlsruhe	22	TRUE	5.65	6.03	10	1	7898
C3L/B	Amsterdam	Karlsruhe	17	TRUE	5.34	5.61	17	1	8064
C3L/B	Rotterdam	Basel	9	FALSE	5.32	5.35	64	1	8064
MVS 110m	Antwerp	Thionville	16	FALSE	4.79	4.81	9	1	4318
C3L/B	Amsterdam	Antwerp	9	FALSE	5.84	5.83	36	1	8064
C3L/B	Rotterdam	Krotzenburg	5	FALSE	5.15	5.13	27	1	8064
MTS 135m	Amsterdam	Rotterdam	6	TRUE	5.40	7.20	6	1	7898
MVS 135m	Antwerp	Mainz	7	FALSE	5.15	5.15	36	1	7898
MVS 110m	Breisach	Cuijk	12	FALSE	5.32	5.32	15	1	4318
C3L/B	Antwerp	Duisburg	4	FALSE	5.57	5.57	36	1	8064
MVS 110m	Rotterdam	Duisburg	15	FALSE	5.62	5.62	26	1	4318
MTS 86m	Rotterdam	Ludwigshafen	16	FALSE	5.54	5.54	8	1	3971
MTS 110m	Rotterdam	Kampen	4	FALSE	7.11	7.11	9	1	4318
MVS 110m	Rotterdam	Strassbourg	4	FALSE	5.47	5.47	15	1	4318
MVS 105m	Amsterdam	Heilbronn	4	FALSE	5.16	5.16	12	1	4013
MVS 110m	Duisburg	Antwerp	3	FALSE	5.67	5.67	12	1	4318
MVS 105m	Rotterdam	Alphen a/d Rijn	10	FALSE	5.11	5.11	18	1	4013
MTS 110m	Terneuzen	Rotterdam	3	FALSE	5.47	5.47	9	1	4318
MVS 67m	Wesel	Enkhuizen	1	FALSE	5.47	5.47	6	1	3778
MVS 86m	Rotterdam	Herne	2	FALSE	5.15	5.15	9	1	3971
MVS 110m	Dusseldorf	Antwerp	1	FALSE	5.63	5.63	12	1	4318
MVS 110m	Antwerp	Gent	2	FALSE	5.58	5.58	9	1	4318
MVS 86m	Rotterdam	Duisburg	1	FALSE	5.65	5.65	12	1	3971

If all fleets in the Rhine traffic database are simulated, a total of 222 ships are sailing simultaneously. According to SPB/EICB (based on the Prominent project), the emissions of this total fleet would be indicative to make an extrapolation to assess the impact on the total emissions from inland shipping.



Table 3 Example of the Greek traffic database

Ship type	Port A	Port B	Port C	Port D	Port E	Port F	Speed				
							A-B [knots]	B-C [knots]	C-D [knots]	D-E [knots]	E-F [knots]
Medium Ropax 6	GRPIR	GRAEG	GRAGG				14.2	13.3			
Medium Ropax 8	GRSKU	GRKIM					15.2				
Medium Ropax 8	GRAXD	GRSAM					16.5				
Medium Ropax 3	GRIGO	GRCFU					14.2				
Medium Ropax 5	GRCFU	GRIGO					11.9				
Medium Ropax 8	GRPKE	GRKYL					16.3				
Medium Ropax 6	GRAEG	GRPIR					13.9				
Large Ropax 5	GRLAV	GRAGO	GRMYR	GRKVA			16.8	16.7	17.3		
Medium Ropax 8	GRKIS	GRPOA	GRDIK	GRGYT			16.6	16.3	16.7		
Large Ropax 2	GRRHO	GRKGS	GRVTH	GRPIR			21.6	21.7	21.7		
Medium Ropax 6	GRJSY	GRPAS	GRSER	GRKRE	GRKMS	GRADL	14.5	14.4	14.4	14.3	14.5
Large Ropax 3	GRCHQ	GRPIR					20.1				
Large Ropax 3	GRPIR	GRHER					19.3				
Large Ropax 4	GRJTR	GRJNX	GRPAS	GRPIR			23.9	23.9	24.4		
Large Ropax 4	GRKAR	GREYD	GRJMK	GRJSY	GRPIR		24.3	24.2	24	23.8	
Large Ropax 7	GRJTY	GRAIG	GRDON	GRJNX	GRPAS	GRPIR	21.4	21	21.1	21.4	21.8
Large Ropax 7	GRJMK	GRTIN	GRJSY	GRPIR			21.6	21.6	22.2		
Large Ropax 4	GRJTR	GRIOS	GRJNX	GRPAS	GRPIR		23.4	23.2	23.3	23.5	
Catamaran 2	GRSKG	GRJSI	GRSKO	GRALO	GRKYM		30.3	31.6	28.3	32	
Catamaran 2	GRADL	GRKRE	GRSER	GRPIR			34.8	31.4	34.1		

### 6.5.2 The Ship object

The ship object contains the logic and data required for the actions (such as moving, bunkering and retrofitting) of the ships. The following attributes of a ship are required when creating a ship:

- Name
- Ship type
- Fleet the ship belongs to
- Power system
  - Setting a power system results in setting a new fuel type, the installed power, the bunker capacity and the propulsion train efficiency
- Start port
- End port
- Loading condition and speed on outbound and inbound journey
- Port waiting time (loading and unloading)
- Daily port consumption
- Build year
  - At the start of the simulation, the age of the existing ships is determined randomly to represent a realistic fleet (now by default between 0 and 30 years).



## 7 Defining a pathway (scenarios)

A pathway is a set of scenarios that are applied on the parameters in the simulation model on the same time. A pathway is a user input to the simulation. If no scenarios are defined (and hence no pathway exists), a business-as-usual simulation will be run.

### 7.1 The Scenario object

A scenario object describes the change of an attribute of the model over time. It therefore requires four inputs:

- The attribute that is changing.
- The quantity or value of the change.
- The period over which the change happens (start and end time).
- The objects on which it will act (ships, ports).

There are three types of attributes in the model, each type requiring a specific scenario type:

- Type attributes, representing properties that change in type, such as the type of power system of a ship.
- Continuous attributes, representing uncountable properties defined by float numbers, such as the price of an energy carrier.
- Discrete attributes, representing countable properties, such as the number of ships in the simulation.

### 7.2 The discrete scenario

As the name implies, the discrete scenario is used for changing an attribute in the model that can only have discrete (integer) values, such as the number of ships in the model. A discrete scenario requires the following input parameters:

- The attribute to change, for instance 'quantity'
- The target, for instance 'ships'
- The value to change, for instance the number of ships to add
- The start time, the time since the start of simulation from which the change will happen (optional, if not filled out it will start at the start of the simulation)
- The change period, the time that the change will take
- The number of steps: changes are applied in steps. If the number of steps is one, the attribute of all target objects will change at once at the start of the change period. If the number of steps is 2, the first half of the ships will be added at the beginning, the next half will be added halfway the change period. The higher the number of steps, the more gradual the change will be.

### 7.3 The switch scenario

The switch scenario is also used for changing an attribute in the model that can only have discrete values, such as the power system of ships, but in comparison to the discrete scenario,



where a value is gradually increasing for all objects at once, here the value is set immediately, but gradually over the objects.

A switch scenario requires the following input parameters:

- The attribute to change, for instance 'power system'.
- The target, for instance 'ships'.
- The new value of the attribute, for instance "Electric A".
- The start time, the time since the start of simulation from which the change will happen (optional, if not filled out it will start at the start of the simulation)
- The change period, the time that the change will take.
- The number of steps: changes are applied in steps. If the number of steps is one, the attribute of all target objects will change at once at the start of the change period. If the number of steps is 2, the first half of the ships will get a new power system at the beginning, the next half will change halfway the change period. The higher the number of steps, the more gradual the change will be.

#### 7.4 The continuous scenario

The continuous scenario is used for attributes that can have a continuous value, such as the price of a specific energy carrier. A continuous scenario requires the following parameters:

- The attribute to change, for instance 'fossil diesel price'.
- The target, for instance 'ports'.
- The delta of the attribute, for instance "0.5".
- The start time, the time since the start of simulation from which the change will happen (optional, if not filled out it will start at the start of the simulation)
- The change period, the time that the change will take.
- The number of steps: changes are applied in steps. If the number of steps is one, the attribute of all target objects will change at once at the start of the change period. If the number of steps is 2, the price of fossil diesel in all ports will be increased with half the delta at the beginning of the simulation, and the second half of the delta is added to the MDO price halfway the simulation. The higher the number of steps, the more gradual the change will be.





## 8 Simulation and power system selection logic

The simulation model is a software routine written in the Python programming language. It is built on top of the package Simpy.

A simulation is invoked by running the main script file of the model. The following steps are consequently performed:

- The NEEDS environment is created, in which all the objects (ports, ships and so on) will interact. This environment is a slightly modified version of a Simpy environment. The NEEDS environment additionally allows for changing the starting date of the simulation and enabling the power system selection logic in the simulation routine.
- The power consumption database, energy carrier database, power system database and traffic database are loaded into memory.
- Based on user input, either the Rhine region or the Greek region is instantiated. Upon instantiation, all ports in the region are loaded in memory from the port database and are equipped with a bunker station containing a list of energy types (diesel, methanol, LNG, electricity and so on) with corresponding prices and bunker speeds. The information on energy types is loaded from the energy carrier database. Each port also has a limited capacity in number of ships that can bunker at the same time. This capacity can be changed.
- A graph is created using the Python package NetworkX<sup>6</sup>. This graph describes the geographic relations between ports and allows to find the 'shortest route' between multiple ports, using Dijkstra's shortest path algorithm<sup>7</sup>. The distance between ports is calculated using the waypoints of the routes between the ports, which are loaded from the route database.
- The traffic database is used to instantiate the ships. Every row in the traffic database describes a unique 'fleet'. A fleet is defined as a combination of a ship type sailing a specific sailing schema (a route in a certain loading condition at a certain speed). For each fleet a number of individual ships is created. The number corresponds to the predefined fleet dimension.
- When a ship is created, the part of the power consumption database that applies to the ship type is loaded, and from this data a power-, water depth- and speed-interpolator is created. Every ship is then placed on a random point along its route.
- A list of predefined scenarios, forming a pathway, is loaded from user input. This pathway is then loaded into the NEEDS environment.
- Now, all conditions have been set to start a simulation. The simulation logic is explained in the next chapter.
- The end time of the simulation is coming from user input. The simulation will run until the end time, or until all ships have stopped sailing (for whatever reason), whichever comes first.
- Once the simulation is finished, the output of all the steps in the simulation are saved to a CSV file, together with the list of scenarios.

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<sup>6</sup> <https://networkx.org/>

<sup>7</sup> [https://en.wikipedia.org/wiki/Dijkstra's\\_algorithm](https://en.wikipedia.org/wiki/Dijkstra's_algorithm)



## 8.1 Simulation logic

The main actors in the simulation are the ships. Each individual ship moves from one loading port to another and consumes a certain amount of power to do this. When the power of the ship (the bunker level) is running low, the ship will bunker, to be able to continue operations.

Each ship follows the flow diagram shown below in a loop until the end of the simulation has been reached, or until the ship runs out of power before it can bunker.

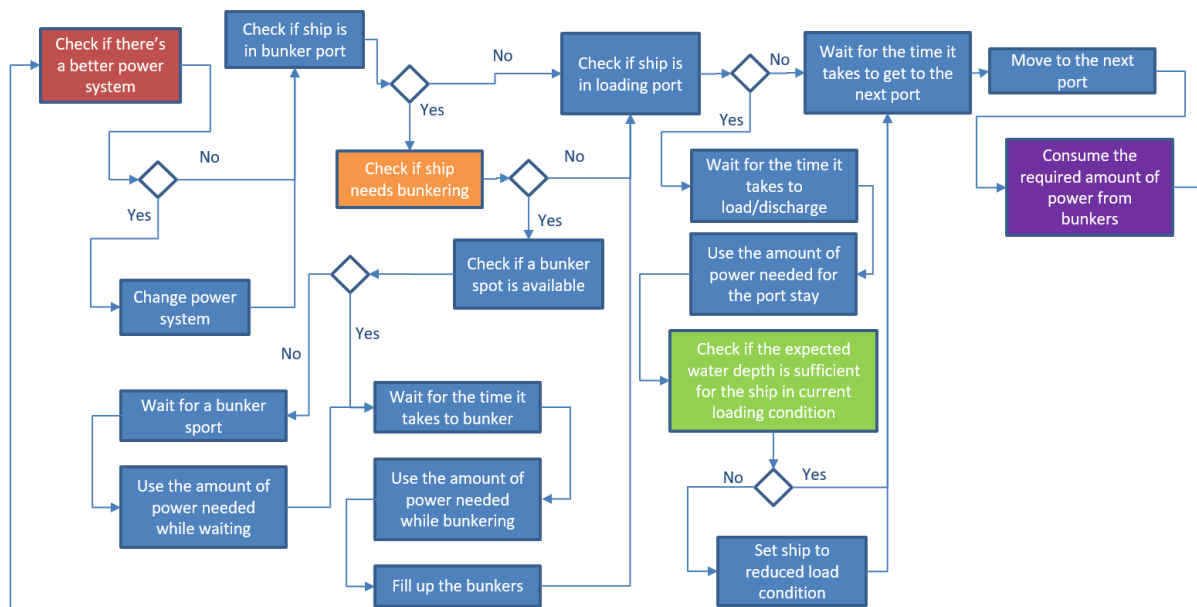


Figure 9: Simulation logic.

Four blocks in this diagram will be explained more thoroughly. The red block represents the power system selection logic. This will be explained in detail in chapter 8.5. The orange block represents the bunker prediction logic of the ship. This will be explained in detail in section 8.2. The green block represents the water depth check, which will be explained in section 8.3. The purple block represents the power consumption calculation, which will be explained in section 8.4.

## 8.2 Bunker prediction logic

The *bunker prediction logic* predicts the power the ship will consume to reach the upcoming ports, and depending on this prediction, decides if the ship should bunker in the current port. By default, the ship will always try to bunker in a loading port, since this is the most efficient place to bunker. It could however be that, even when the ship has full bunkers, it cannot make it to the next planned loading port without bunkering in between. The bunker prediction logic therefore also predicts if the ship will make it to the next planned bunker port when bunkers are full. If not, it will calculate which port it can reach on full bunkers. This port is then added to the list of allowed bunker ports.



When the ship has bunkered in this 'temporary' bunker port, the port is removed from the list of allowed bunker ports. This is once again done to make sure the ship is bunkering mainly in the loading ports.

As a side note, it must be noted that ship-to-ship bunkering is currently not included in the simulation framework. In this iteration of the model, implementing this feature would require considerable effort and the effect would be limited (not (yet) applicable for most alternative power systems).

### 8.3 Water-depth check

The power consumption database not only contains the power needed to sail a certain section, but it also contains the minimum water depth the ship will encounter on that section. This data is used to determine if a ship can sail through with the intended loading condition, or if it should reduce its payload.

This is specifically important for the Rhine region during summertime. Due to high fluctuations in water level over the year, it is possible that in some periods the maximum draft of inland ships on certain sections of the river is restricted. For maritime regions, this check systematically succeeds.

Before a ship leaves a loading port, it will calculate the expected minimum water depth it will encounter on the next sections until the next loading port.

If the ship intends to sail in full loading condition but the water depth is less than the draft of the ship in this loading condition, it will sail until the next loading port in 'reduced load' condition. This will result in a lower transport capacity and a different power requirement.

The inverse also holds: if the ship intends to sail in reduced loading condition because the last voyage also was in reduced loading condition, it will check if it can sail in full load condition. If the water depth allows this, the ship will sail until the next loading port in 'full load' condition.

### 8.4 Power consumption calculation

To calculate the power required to sail a certain section, the power consumption database is used.

The goal of the ship is to sail from the start loading port to the end loading port at a given speed that has been predefined in the traffic database. The loading condition at which this will happen also follows from the traffic database.

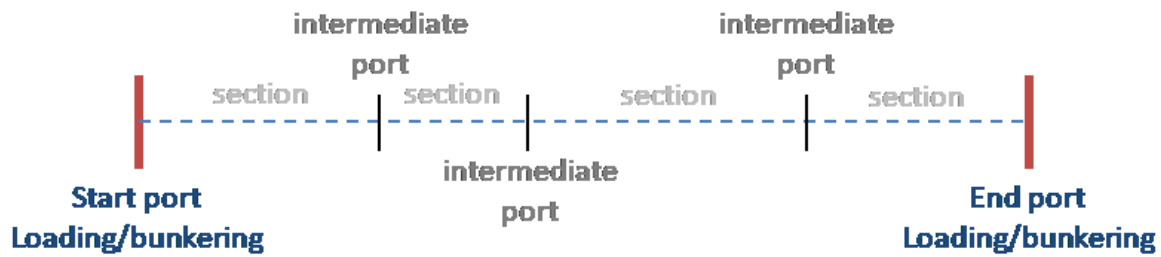


Figure 10: Discretisation of the route a ship sails between start and end ports.

The ship will sail various sections on its way from start to end port. Each section has different environmental conditions (higher currents, different water depth, different wind and wave conditions. etc...), so the shaft power required to sail all the sections at the same speed will differ for each section.

However, in reality the ship will sail with a fixed shaft power, resulting in varying speed per section. This is also how the ships in the simulation behave. Before a ship leaves port, a small routine will define the shaft power required to arrive in time in the end port, regardless of the varying environmental conditions.

Once this shaft power requirement is calculated, the ship can calculate the energy required to sail a section. This is energy requirement follows from the power interpolator that has been created for each section. This power interpolator is a 3D field that outputs the required energy for any combination of shaft power and starting time in the section. An example is shown in Figure 11.

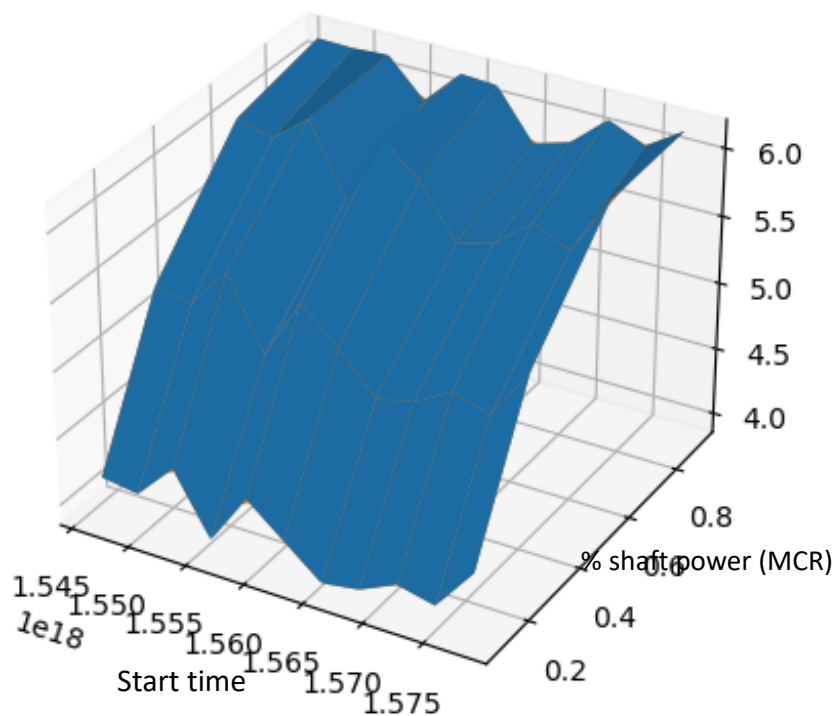


Figure 11 Envelope of the energy consumption as function of operational parameters start time and % shaft power.



Once the required energy for a section is calculated, it can be multiplied by the TTS (tank to shaft) efficiency of the power system that is installed. The resulting number is the energy consumed from the bunkers of the ship on the section.

## 8.5 Power system selection logic

When a ship is in a bunker port, it will check if it is still using the most appropriate power system. This check is performed with the power system selection logic. It is possible to disable the power system selection logic in the simulation. In this case, the ships will keep on sailing on the original power system that they started the simulation with, until the power system is changed by external influences (such as a scenario). When the power system selection logic is enabled, the flow diagram shown in Figure 12 will be followed every time the ship is in a bunker port.

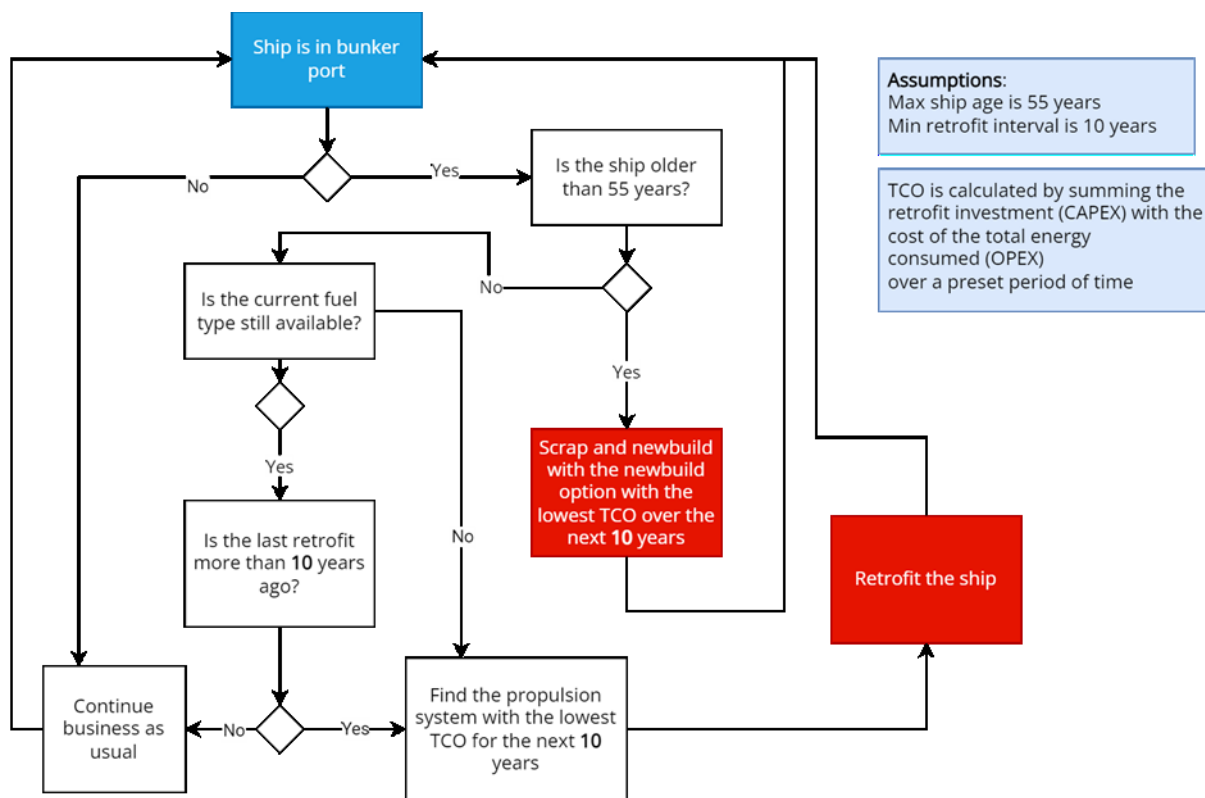


Figure 12 Power system selection logic.

The TCO (total cost of ownership) calculation is performed once a ship is ready for a retrofit. With the current default values, this means that the ship should at least be 10 years in the running since the last retrofit, and it shouldn't be older than 55 years.

For all possible power systems, the retrofit costs (CAPEX (capital expenditures)) are then calculated based on the installed power and the bunker capacity for the specific power system. For the operational expenditures (OPEX) an extrapolation to 10 year is made of the



power consumption since the beginning of the simulation, and it is corrected for the efficiency of the different power systems.

In order to have sufficient statistics to extrapolate to a 10-year period, the power system selection logic only runs after the ships have sailed at least 3 months.

The current calculation of the TCO ignores the productivity loss induced by the retrofit (reduced payload, lower speed, slower bunkering, ...) compared to the baseline (diesel ICE). This may be considered in a next iteration for a more realistic retrofit behaviour during the simulation.



## 9 Post-processing and dashboard

At this stage of the development, the post-processing was realised in Python and on demand. We are currently developing a standard default visualisation and analysis of the calculated data, as well as post-processing for derived quantities. Several concept outputs are being tried and are presented to users to define if it should come as standard output or not. An example of the visualisation of CO<sub>2</sub> eq. emission per section of the waterways, depending on the month (thus on the water depth), is shown here after.

Presentation on the dashboard will focus on four data cross-sections:

- Evolution in time
- Distribution among ports
- Distribution in the transport network
- Distribution among the fleet

A workflow has been created to post process the raw model output data into databases that reflect the different data cross-sections to make them easily and fast accessible.

The dashboard will be defined at the moment the simulation will be run for the scenarios of the selected regions and will use input of the realisation of the next work packages. Experience of this first part taught us that the use of the tool and the study of its output is the main source of inspiration and specifications for what the user wants to obtain as default analysis, post-processing and visualisation.

A first mock-up was made on a web portal, which still requires further development.

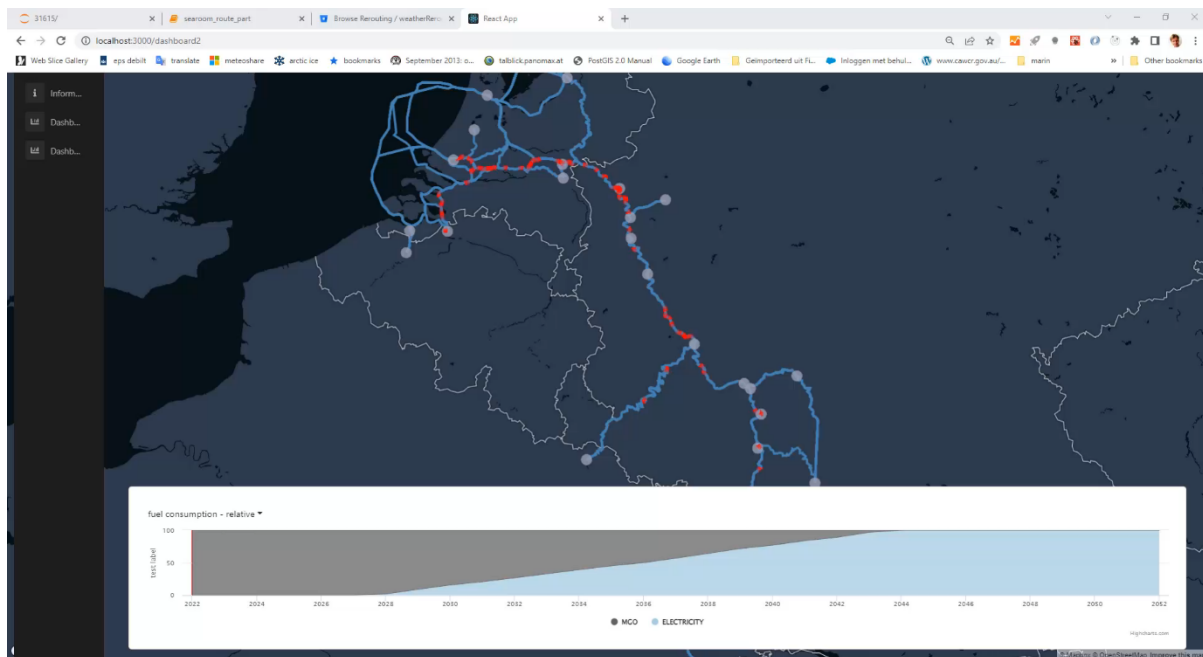


Figure 13: First mock-up of the web-based dashboard and interface, for the Rhine region.

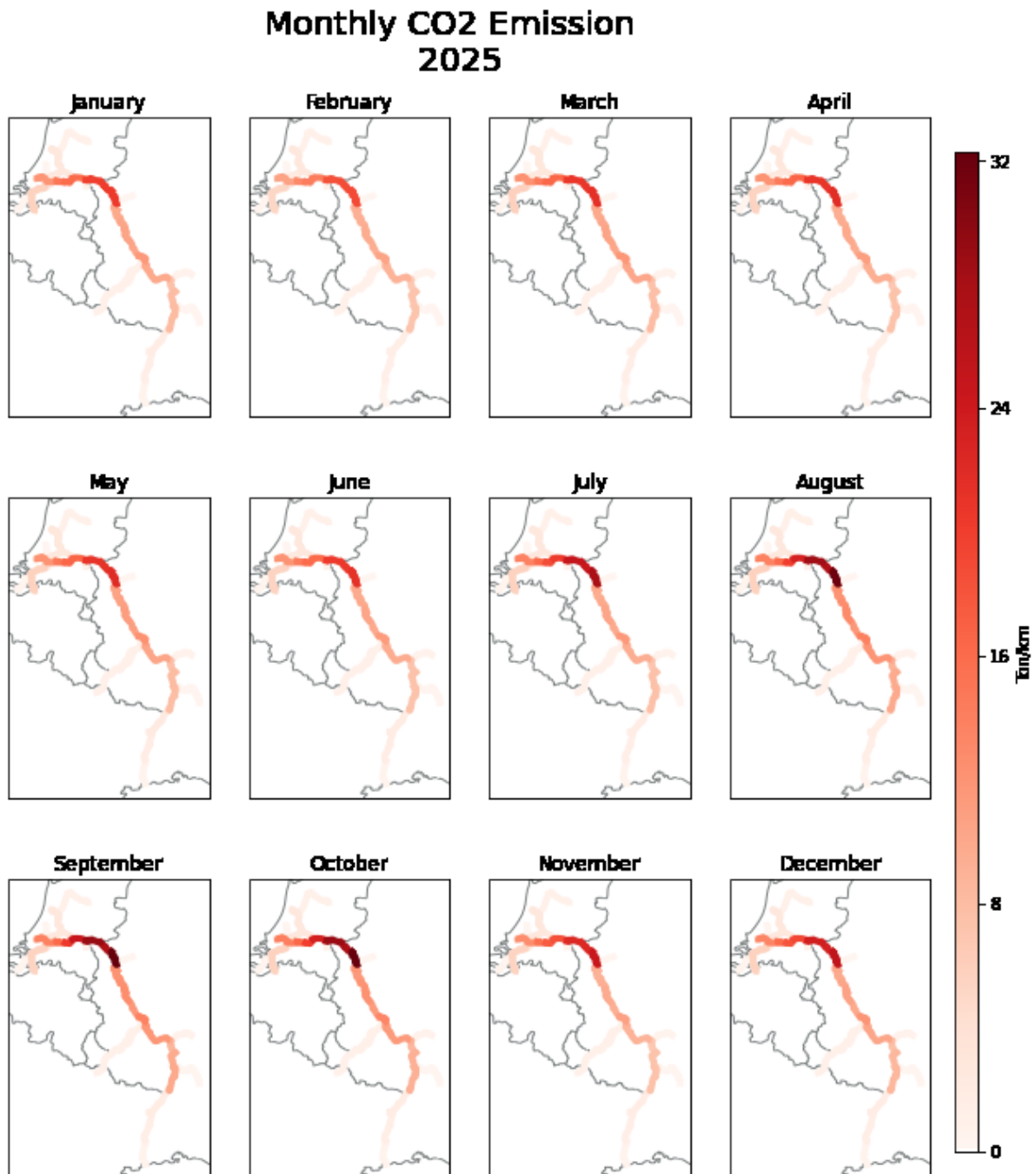


Figure 14: Example of possible visualisation of emission along the routes as function of the months

A large part of the regional definitions and input, as well as the relations and mechanisms for decision-making and inter-dependency between variables, will have to be generated by expert users in the final version of the delivered framework. Those aspects are basically part of the specific regional framework and its modelling. This means that all elements will have to be set-up and prepared in the phase defining and modelling a given region and fleet, prior to launching scenarios.





However, several variables will be possibly brought as user-specify input prior to run or re-run a specific scenario simulation. Such input will be developed in the dashboard interface.

The list of user-defined variables will be for example time-dependant evolution of price, or availability of certain energy in the scenario. The list is however not yet finalised. After running and completing the scenarios for the two selected regions, the list of variables specified by users interface will be created.



## 10 First simulations to illustrate the framework potential

A number of complete simulations are presented in the chapter to illustrate the potential of the generic framework. These examples were performed for the Rhine regional case, which will be used further in WP3. The custom-made preparations of this case are currently more advanced than the inputs for the Greek regional case (WP2), which are being refined at the time of writing. Therefore, only results of the Rhine case are presented here.

The fleet discretisation of the Rhine region was provided and documented by SPB/EICB. Simple and straightforward variations were done to evaluate the final generic model. Although they might not be realistic, they aim to study and check the stability of the framework, the relation between parameters, and the consequences of hypotheses on the final results.

The following hypotheses were made as input for the simulations:

- The fleet consists of 222 ships, starting with conventional ICE engine and using diesel.
- Selected alternative ship is battery-electric powered, e- used is renewable electricity.
- The fleet converts gradually step-wise from 2029 on.
- Alternative power/engine is battery-electric for all ships, electricity is produced from renewable electricity.
- Any harbour along the route have battery charging capacity (or swapping battery capacity) and unlimited available renewable electricity supply (no constraint).

At that point, 3 different variations for the region were made, creating 3 different simulations:

***First simulation: batteries on board ships are charged in harbours ...***

- that have a given (limited to 10 places) amount of chargers.
- with corresponding charging speed (188 kWh/h), resulting in long charging and waiting time.

***Second simulation: batteries on board ships are charged in harbours ...***

- that have an unlimited amount of chargers.
- with corresponding charging speed (188 kWh/h), resulting in long charging time.

***Third simulation: batteries are swapped in harbours ...***

- that have an unlimited amount of charged battery packs available.
- with corresponding swapping speed (36,000 kWh/h), resulting in short swapping time (similar to diesel bunkering time).

Before talking about the long-time trend, monthly fluctuations in the transport capacity shown in the figures reflects two parameters influencing it:

- Time and spatially varying current and water depth (fluctuations in the time history). Certain water depths do not allow the ships to sail and increased in current velocity slows down the fleet sailing upstream. Those seasonal changes are observed in the model.
- Vessels being retrofit, which are out of service for few months period. In that case, ships are simply out of operation for the duration of the retrofit.



## First simulation: battery charging with limited amount of charging points per harbour

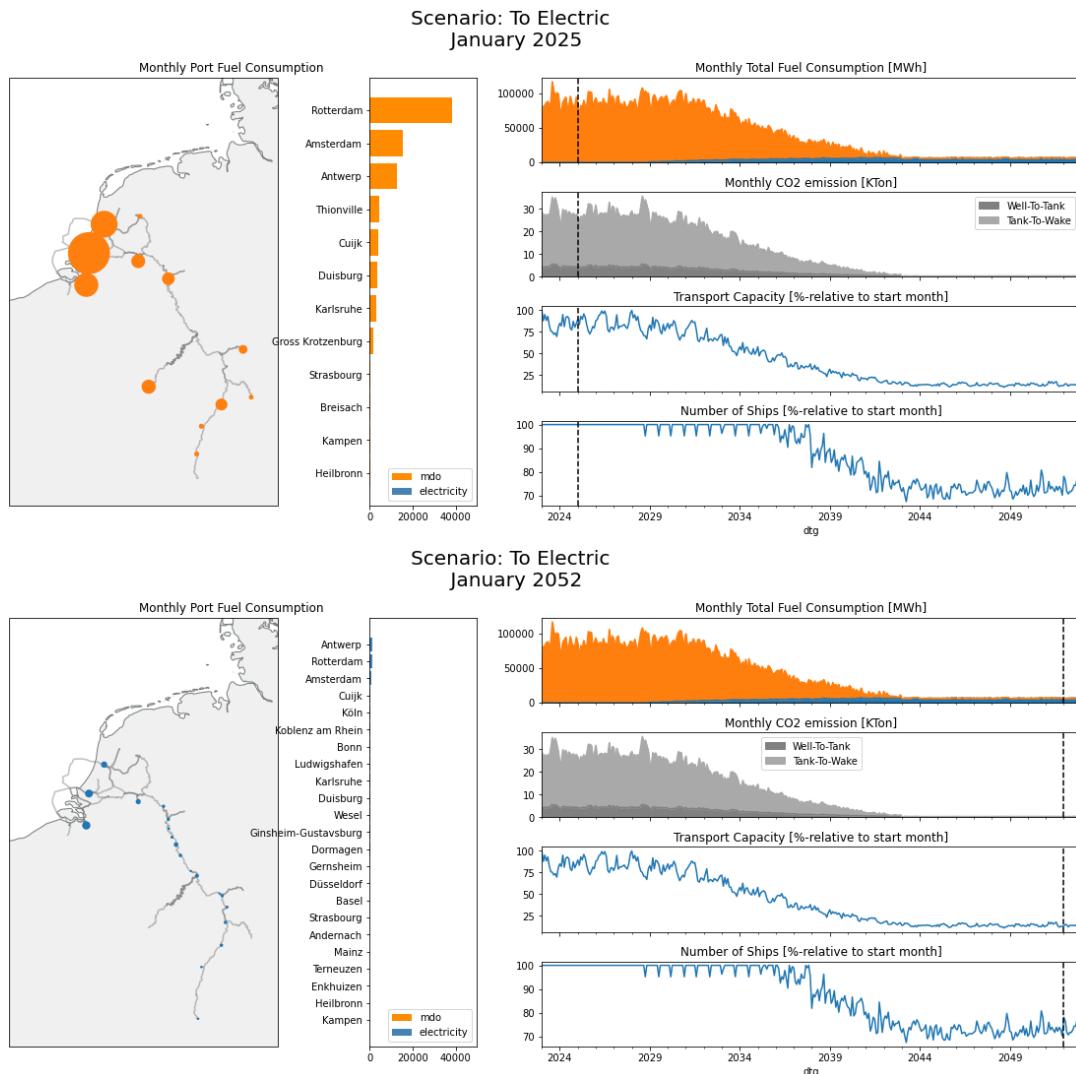


Figure 15: First simulation: battery charging with limited amount of charging points per harbour.

The simulation appears then to work fine, despite a very surprising results, which is the 30% reduction of the operational fleet over time and the 80% reduction of transport capacity. Analysis of the results showed that the selected capacity of chargers per harbour is simply not sufficient to allow the operational fleet to be charged simultaneously. A default value of 10 available chargers per harbour was given when creating the framework, and not adapted since then. The result of such limitation appears clearly in the simulation: a large part of the fleet (mainly the large vessels having the largest battery capacity thus the longest charging time) is waiting to recharge. The ships with the largest transport capacity being also the ones with the largest charging capacity requirement are immobilised for more than a week to recharge their batteries. This results then in a huge drop in total transport capacity.

This case illustrates the dependency between different parameters and how the simulation can illustrate the effect of limitations of key variables and the consequences.



## Second simulation: battery charging without constraint on amount of charging points per harbour

Scenario: To Electric, Unlimited Port Charging  
January 2052

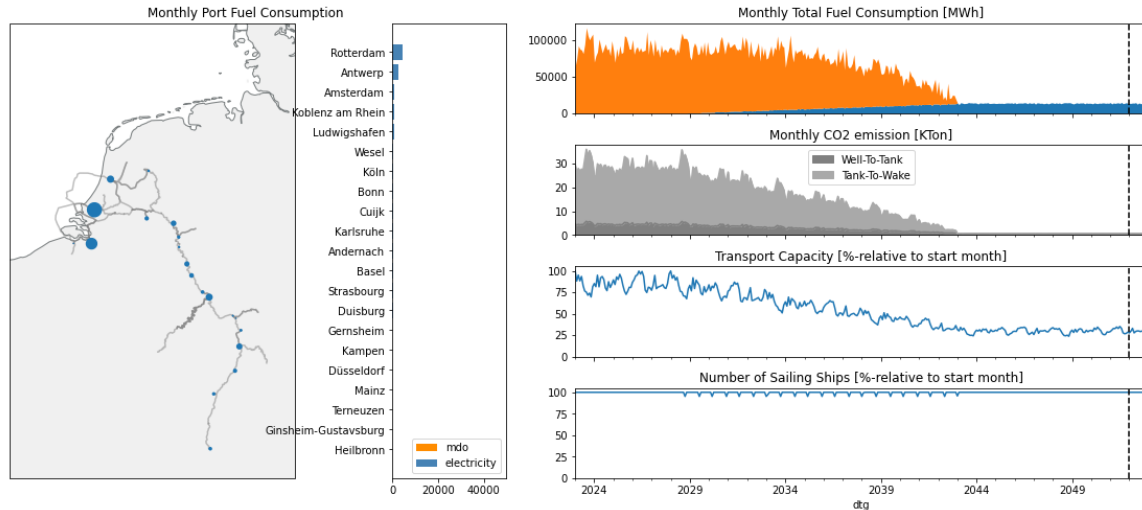


Figure 16: Second simulation: battery charging without constraint on amount of charging points per harbour.

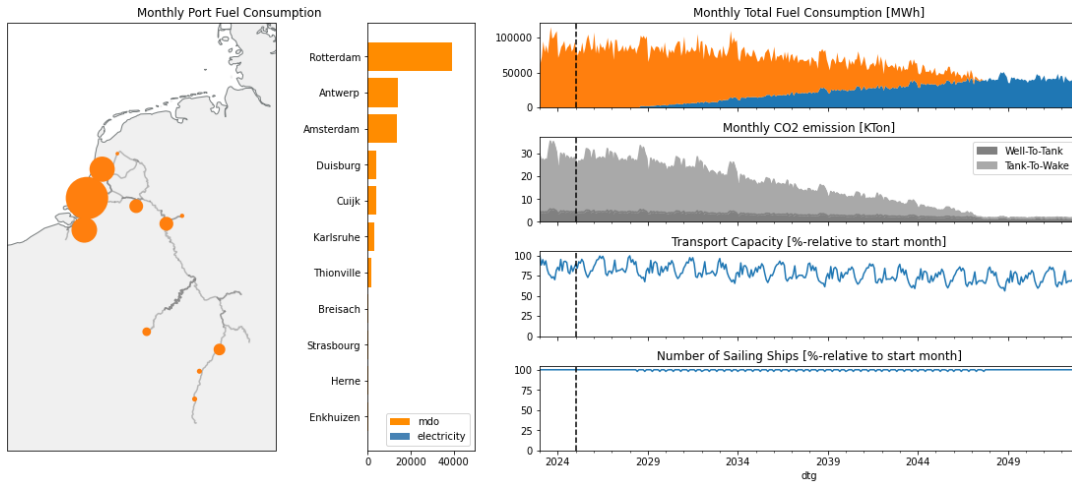
For this solution, we have given unlimited charging station to any harbour. Ships remain operational but are just not transporting goods because the waiting for charging is very long (talking about one week). In that case, the effect of charging time creates a drop of 75% in transport capacity. Such aspect illustrates the fact that charging time is a clear bottleneck with the size of battery capacity, thus implies alternative solutions such as battery swapping to keep the fleet being operational.

This is realised in the last solution with a transformation of the fleet to electric, with unlimited supply of renewable electricity for batteries that are swapped in the vessel. The remaining loss of transport capacity over the years is because vessels refit with battery – electric propulsion (or new built) are simply losing cargo capacity. The goal of drastic emission reduction is however reached.

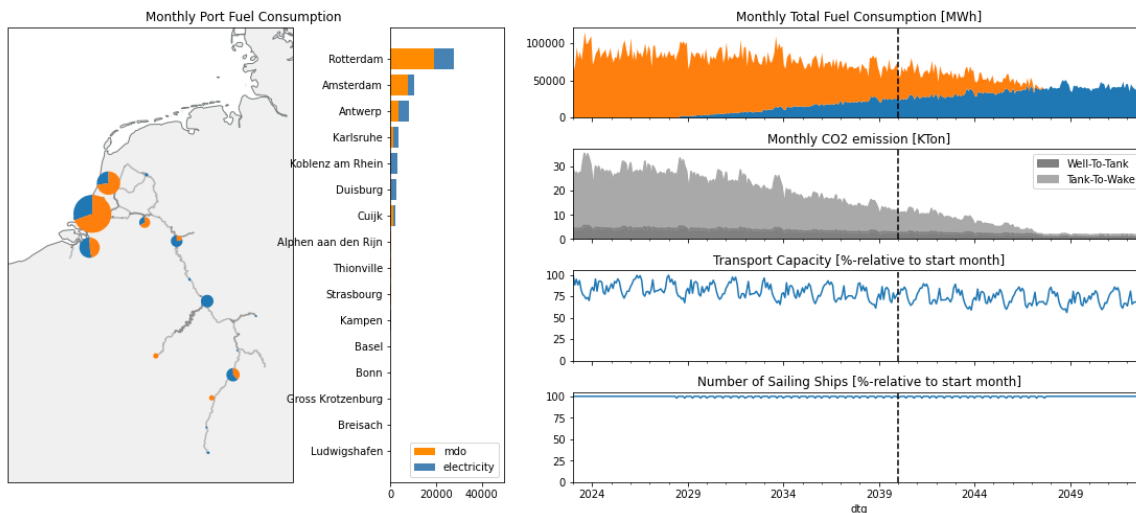


## Third simulation: battery swap without constraint on amount of swapping points per harbour

Scenario: To Electric, Battery Swapping  
January 2025



Scenario: To Electric, Battery Swapping  
January 2040



Scenario: To Electric, Battery Swapping  
January 2052

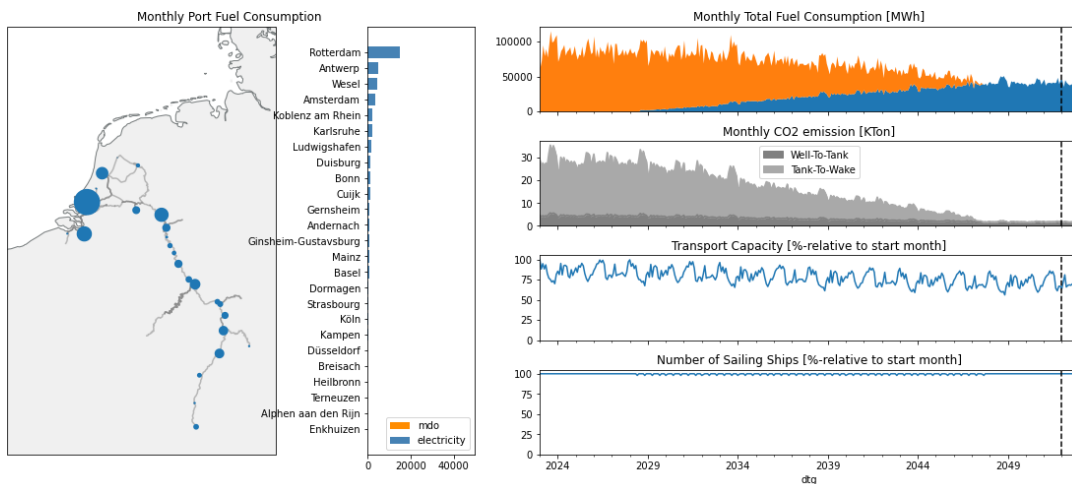


Figure 17: Third simulation: battery swap without constraint on amount of swapping points per harbour.



## 11 Conclusions

This WP1 deliverable describes the different elements of the generic simulation framework and the way they are linked to form a dynamic eco-system. The simulation procedure and its logics are also described.

This report also illustrates the technical capabilities of the generic framework and highlights that the characteristics of a given region also partly affects the structure of the framework, in particular the database of fixed or time-dependent parameters. Each regional eco-system requires a custom-made framework. All elements are generic, but creating a region with its fleet, infrastructure and operations demands a custom-made preparation.

The joint development of the generic framework, together with the work packages on the regional modelling of the Rhine (WP3) and Greece (WP2) cases, has also helped structure this framework. To improve the simulation time and allow time-dependent variable to influence the scenarios, a part of the simulations is done during the pre-processing stage, with elements and parameters characterising the region. A large part of the performance, consumption, emission, energy use or routes are treated in an early stage and saved in databases that are used at a later stage of the simulation. Nevertheless, the type of pathway and the options remain tuneable prior to the simulation, or even in post-processing.

As a conclusion, a generic simulation framework was developed with a number of key elements to represent the eco-system of a regional waterborne network. A large amount of generic parameters were defined, such that they can be fixed or varied in time. This offers great possibilities of variations, but will require a careful methodology in its use, as the number of variations and pathways are infinite, as it is the case in real life.