IW-NET

Innovation-driven Collaborative European Inland Waterways Transport Network

D1.1 IWT modelling and simulation capability and Revenue Management methods for optimisation

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Executive Summary

IW-NET is the acronym for the project "Innovation-driven Collaborative European Inland Water-ways Transport Network", supported by the European Commission under the “Moving freight by Water: Sustainable Infrastructure and Innovative Vessels” topic of the Horizon 2020 research and innovation programme under grant agreement No 861377.

The key objective of this deliverable is to develop the digital and physical simulation models necessary to assess different scenarios with central focus on the evaluation and design of the Innovation driven Collaborative European Inland Waterways Transport Network (IW-NET) simulation components. The components are designed sufficiently generically to ensure that the Generic IW-NET scenario can be fully represented, taking also into account Living Lab specific requirements.

The document describes a methodology of analysis of business cases through simulation and optimisation models. The main steps include designing and developing a simulation model, designing a simulation experiment, and finally performing simulation analysis.

In this project, the simulation and optimisation models are used to validate the impact of the IWT-NET approach in the Application Scenarios (AS). Simulations based on agent-based modelling (ABM) and discrete event simulation (DES) techniques are used to estimate the performance of the network associated with different application scenarios to identify optimal policies and innovations and to evaluate the efficiency of the different services proposed (e.g., Synchromodality).

The developed models have been used by the project team to assess the impact of some of the innovations of the IW-NET project. As a result, a group of elements has been defined to represent the behaviour of the agents that intervene in a waterway transport system. Both the information necessary for their configuration and the behaviour that characterises them have been defined. These elements constitute a library of objects that enables the creation and evaluation of virtual waterway transport scenarios.

Revenue Management based optimisation methods are adapted, implemented and used in these scenarios in order to highlight potential advantages of these innovative techniques: high quality-of-service for shippers and profit maximization for carriers, via optimal resource utilization and intelligent planning of intermodal transport operations through the extensive and effective use of inland waterway networks. This approach provides flexible management of transport bookings and promotes the development of synchromodality. The mixed approach of combining optimisation and simulation models and methods enables the evaluation of the fine-tuned details of the optimisation solution and comparison with other transport alternatives. Two descriptions are given, one for the application of the optimisation and simulation method related to transport on the Danube River, and another for the application of the simulation approach for traffic management on the Weser River.

Finally, actions for further development of these models are indicated, the research team will continue its investigations to validate and improve the models by integrating new challenges and assessing them in different scenarios. The next steps will be to work together with the other partners in the project to apply the different simulation and optimisation models for the analysis and evaluation of new scenario applications.

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List of Abbreviations

Abbreviation	Description
ABM	Agent-Based Modelling
AI	Artificial Intelligence
AS	Application Scenario
ATT	Average Time of Travel
CEMT	European Conference of Ministers of Transport
CO_2	Carbon Dioxide
CR	Collision Risk
DCPA	Distance to Closest Point Approach
DES	Discrete Event Simulation
EU	European Union
FIFO	First In First Out
GA	Grant Agreement
GHG	Greenhouse Gases
GIS	Geographic Information System
GLEC	Global Logistics Emissions Council
GPS	Global Positioning System
IoT	Internet of Things
IW-NET	Innovation driven Collaborative European Inland Waterways Transport Network
IWT	Inland Waterway Transport
KPI	Key Performance Indicator
NOx	Nitrogen Oxides
OSM	OpenStreetMap
PM	Particulate Matter
RM	Revenue Management
SAFES	Ship Auto Navigation Fuzzy Expert System
TCPA	Time to Closest Point Approach
TEU	Twenty-foot Equivalent Unit
TTW	Tank-To-Wake
WP	Work Package
WSV	German Federal Waterway and Shipping Administration
WTT	Well-To-Tank
WTW	Well-To-Wake

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1 Introduction

1.1 Background

Inland waterway transport plays an important role for the transport of goods in Europe. More than 37,000 kilometers of waterways connect hundreds of cities and industrial regions. The inland waterway transport is a competitive alternative to road and rail transport. In particular, it offers an environment-friendly alternative in terms of both energy consumption and noise emissions. According to Eurostat its energy consumption per tonne kilometre of transported goods is approximately 17% of that of road transport and 50% of rail transport [1]. In addition, inland waterway transport ensures a high degree of safety, in particular when it comes to the transportation of dangerous goods. Finally, it contributes to decongesting overloaded road networks in densely populated regions. Given its environmental strengths, the European Commission aims to promote and strengthen the competitive position of inland waterways in the transport system, and to facilitate its integration into the intermodal logistics chain.

1.2 Objectives

The objective of the IW-NET project is to deliver a multimodal optimisation process across the EU transport system, increasing the modal share of inland navigation and supporting the EC's ambitions to reduce greenhouse gas emissions from transport by two thirds by 2050.Within the project, the objective of this document consists in the description of the modelling, simulation and optimisation capacity developed to evaluate the impact of the different innovations of the project.

The idea behind the IW-NET project is to test improvements with new digitalisation and innovative technologies applied to inland waterway transportation (IWT), with regard to operations, environmental impact and costs.

The use of simulation as a support tool in decision-making has grown in recent decades. It is currently recognized as one of the most widely used research techniques for many sectors due to its versatility, flexibility and analysis potential.

In this project, the simulation and optimisation models are used to validate the impact of the IWT-NET approach in the Application Scenarios (AS). Simulations based on agent-based modelling (ABM) and discrete event simulation (DES) techniques are used to estimate the performance of the network associated with different application scenarios to identify optimal policies and innovations and to evaluate the efficiency of the different services proposed (e.g., Synchromodality).

[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split

1.3 Mapping IW-NET Outputs

The purpose of this section is to map IW-NET's Grand Agreement (GA) commitments, both within the formal Deliverable and Task description, against the project's respective outputs and work to perform.

Table 1: Adherence to IW-NET's GA Deliverable & Tasks Descriptions

IW-NET GA Component Title	Section(s) of present deliverable addressing the IW-NET GA	Description
T1.1 IWT modelling and simulation capability		
ST1.1.1 Simulation Capability for Modal Shift Scenarios	Ch2. Simulation framework Ch5.1. Example of applica-tion in a modal shift sce-nario	Chapter 2 describes a simulation framework as a capability to test synchromodal scenarios. First, it includes a literature review of simulation technologies applied to IWT systems and demonstrates the capability of simulation models. It also defines the elements of IWT that will be used in the simulation model to represent the actions and the flows in the different application scenarios. In Chapter 6, the different scenarios are formulated in the context of three Application Scenarios Areas.
ST1.1.2 Library of Models and Data Sources for IWT analysis Methods	Ch.2. Simulation framework Ch.4. Data Sources for IWT analysis Ch.5. Library of Models and Methods	In Chapter 2 a definition of modelling and simulation elements is defined. In Chapter 4 it is described the datasets and data sources available for simulation models. Chapter 5 contains the descriptions and functionalities of the library of models developed.
ST1.1.3 Revenue Management Methods and Tools	Ch.3. Revenue Management Methods and Tools	In Chapter 3 an overview of revenue management methodological framework and the details of the implemented optimisation models are described.

1.4 Deliverable Overview and Report Structure

The initial chapter contains a general introduction to the project, a description of the general background of the role of inland waterway transport systems and the objectives of the document. It also includes a table to facilitate the relation of the content of the document with the text of the project proposal.

The second chapter describes the simulation framework. It begins with a literature review about simulation applied to IWT to demonstrate the capability of simulation to test synchromodal scenarios. It also defines the elements of IWT that will be used in the simulation model to represent the actions and the flows in the different application scenarios. A generic simulation methodology is also defined. It will be used to create regulatory models and then evaluate the scenarios with the developed models.

The third chapter includes an introduction to Revenue Management (RM) based optimisation approach and its methodological framework. It contains a conceptual description of mathematical optimisation models for intermodal freight transport, under the assumption of a hierarchical decision-making process with respect to different planning horizons. It also provides an overview of the tactical and operational RM based optimisation models, with details regarding RM specific data requirements and formats used for implementation purposes.

The fourth chapter describes the data needed to configure the models. It describes the types of data that are necessary to represent river transport models and a detailed description of the data available to construct transport networks. Several indicators are provided to measure the characterization of transport flows. This includes indicators to measure improvements in cost, operations reliability and emissions. Environmental impact assessment is a key feature of this type of modelling. Several sections are included to describe how to quantify the emission of greenhouse gases and other air pollutants in both inland waterway transport and road transport.

Chapter 5 describes the main functionalities that can be achieved with the library of models developed for the analysis of inland waterway transport. The chapter includes a collection of methods for applying the available models to different types of analysis. The methodology allows the models to be used individually or combined.

The sixth chapter refers to the specific simulations examples of some analysis realized in the project Application Scenarios. It describes applications of these models for the evaluation of different project innovations in selected scenarios. In the first case, the simulation model is used to analyse different container distribution strategies along the Danube River corridor. The second case includes the application of simulation models for traffic routing on the Weser River.

The seventh chapter contains a synthesis of the conclusions of the document and a reference to the next steps and future developments foreseen for the developed models.

At the end of the document, there is the annex section with a brief glossary section with definitions of terms and other annexes with additional information related with simulation Excel files, additional information about the RM tactical and operational models and some simulation-optimisation integration diagrams.

2 Simulation framework

This chapter includes the definition of the simulation framework to evaluate the impact of different project's innovation. These impacts can be evaluated in different supply chain scenarios by using the simulation models. First, the necessary components are defined to create a digital simulation model. Afterwards, these elements are used to create digital models that represent the behaviour of the distribution processes in IWT.

There are several methods to study a system. One of the most common approaches is proposed by Law and Kelton (2013). They classify suitable methods in two main groups: experimenting with the current system, and experimenting with a system model that contains physical and mathematical models. Physical models are useful to study some mechanical properties or engineering aspects of a complex system.

In the IW-NET framework, the most relevant information about the physical world is the time and position of the different containers, transport movements and other elements from the network. But the vast majority of the models built to evaluate the process behaviour is mathematical, representing a system in terms of logical and quantitative relationships that are manipulated and changed to see how the model reacts, and thus how the system would react.

Once a mathematical model is built, it should be examined to see how it can be used to answer the questions of interest in the system it is supposed to represent. If the model is simple enough, it may be possible to work with its relationships and quantities to obtain an exact analytical solution. However, some analytical solutions can be extraordinarily complex and require vast computing resources; inverting a large non-dispersed matrix is a well-known example of a situation in which there is an analytical formula known in principle, but obtaining it numerically in a given case is far from trivial. In this case, the model must be studied by simulation, that is, numerically exercising the model for the inputs in question to see how output performance measures affect them.

A static simulation model is a representation of a system at a particular time or one that can be used to represent a system in which time plays no role; examples of static simulations are Monte Carlo models. On the other hand, a dynamic simulation model represents a customized system that evolves over time, such as a transport system in a factory or a transport network. In the case of IWT, the evolution of time is important, as flow decision taken at the beginning of the day may not be desirable four hours later, due to congestion or some delay in transportation. The dynamics of the system and the connection with real data are very important to determine the behaviour of the system. The simulation models connect the analytical power of the dynamic simulation with the physical information from the real system.

Simulation models can help to create virtual representations of inland waterway traffic conditions in a dynamic way. This means that they enable inland waterway transport managers to test different scenarios before they make crucial decisions. The model proposed in the following chapters is based on a mathematical and logic model of different processes of inland water transportation. The model can be used to test different scenarios and find the most efficient way of running the transport operation.

2.1 Simulation Capability for Modal Shift Scenarios. Literature review

The simulation model must support the assessment of different Application Scenarios with a synchromodal approach, so that it will support modal shift to inland waterways synchromodal options. The opportunities of simulations executed as realistic as possible as in real life are worldwide accepted in the design of existing waterways or waterways under construction. In this section, publications referring to simulation applied to IWT are reviewed.

In Watanabe et al, (2008) a simulation model based on ship motion theory is applied to evaluate safety of inland waterways. The base of the simulation was the software “Marine traffic simulator” developed at Osaka University. “Marine Traffic Simulator” simulates marine traffic flow based on the “Ship Auto Navigation Fuzzy Expert System” (SAFES). On this system, each ship has its own characteristics (principal particulars, speed, manoeuvring parameters, origin and destination as well as waypoints). The physics of manoeuvring follow ship motion theory (ships generally move with a mean forward velocity and their oscillatory motions in waves are superposed upon a steady flow field). In congested areas, the ship avoids collisions with other ships or obstacles by a computerized pilot/captain based on fuzzy-set theory. To realize the traffic simulation, the following procedure is used:

1. Set destination and departure gates/ports of each ship according to the statistics.
2. Determine the creation or deletion of each ship according to the arrival time or completion of the task.
3. Set route including waypoints for each ship.
4. Set parameters of each ship.
5. Determine the steering instruction according to each ship task as well as target ship’s positions and behaviours.
6. Calculate ship velocity and position according to the instruction.

Two parameters are needed: DCPA (Distance to Closest Point Approach) and TCPA (Time to Closest Point Approach). DCPA is the shortest distance between own ship and target ship assuming their speed and direction are kept. To consider differences in ship size, DCPA is made dimensionless by ship length (DCPA’). In the simulation loop, it is assumed that one vessel to be Own Ship and calculate “collision risk” for all other vessels. “Own Ship” chooses the best navigation state by “collision risk (CR)” and the other parameters. They simulated different conditions for safety assessment. First, we simulated for three different densities: Simulation 1 with 157 ships/day, Simulation 2 with 169 ships/day, and Simulation 3 with 214 ships/day). The simulation time is one day. They calculated the average time of travel (ATT) to evaluate efficiency of traffic at each case. We can see the influence of increasing density. To simulate larger area traffic, an algorithm for locks was included in “Inland Waterway Simulator”. Simulations with Locks (time for up-down 450 s) have different tendencies from simulations without lock, due to a traffic jam at the lock.

In Chen et al, (2013) a simulation model is used to analyse traffic flows of ships and road traffic at bridges, locks, narrowing and waterway sections. To simplify the model, the waterway network is converted to the topological structure divided by 11 waterway sections. The ships sailing in the waterway network are summarized into nine classes. The data from GPS based vessel traffic monitoring systems of Huzhou Lock and Wushenmen Lock are collected. In order to get the characteristics of traffic flow in the inland waterway network, 100%, 150%, 200%, 250% and 300% of the 2011 traffic volume in 4 scenarios are investigated. The result of the study shows that the four scenarios are almost the same in the number of ships sailing out per hour, but have a significant difference in waiting times.

Hofbauer (2020) includes a literature review dealing with external costs of IWT. In a meta-analysis, the papers were assigned to the seven external cost categories: accident, noise, congestion, habitat damage, air pollution, climate change and well-to-tank emissions. The most investigated external cost categories are climate change, air pollution and accidents.

2.2 Simulation Environment

The idea behind the simulation approach followed within IW-NET is the technical perspective, that the developed models should allow the inclusion of information from both digital elements as well as physical sources. In certain simulation models, the information of some components (i.e., the position of a truck, or the storage capacity of one facility) could be obtained from a real physical entity, through APIs available in the cloud.

As mentioned by Law and Kelton 2013, although there are few firm rules on how the modelling process should be approached, one point on which most authors agree is that it is always good practice to start with a model that is only moderately detailed, which can later become more sophisticated if necessary. Robertson (2002) explains that a model must contain sufficient detail to only capture the essence of the system for the purposes for which the model is designed. Therefore, it is not necessary to have a one-to-one correspondence between the elements of the model and elements of the system. A model with excessive detail may be too expensive to program and execute. As is shown in the next image (Figure 1) the model proposes to increase the complexity iteratively. The first model contains many assumptions. Afterward adding real constraints, reducing the assumptions and the model becomes more realistic.

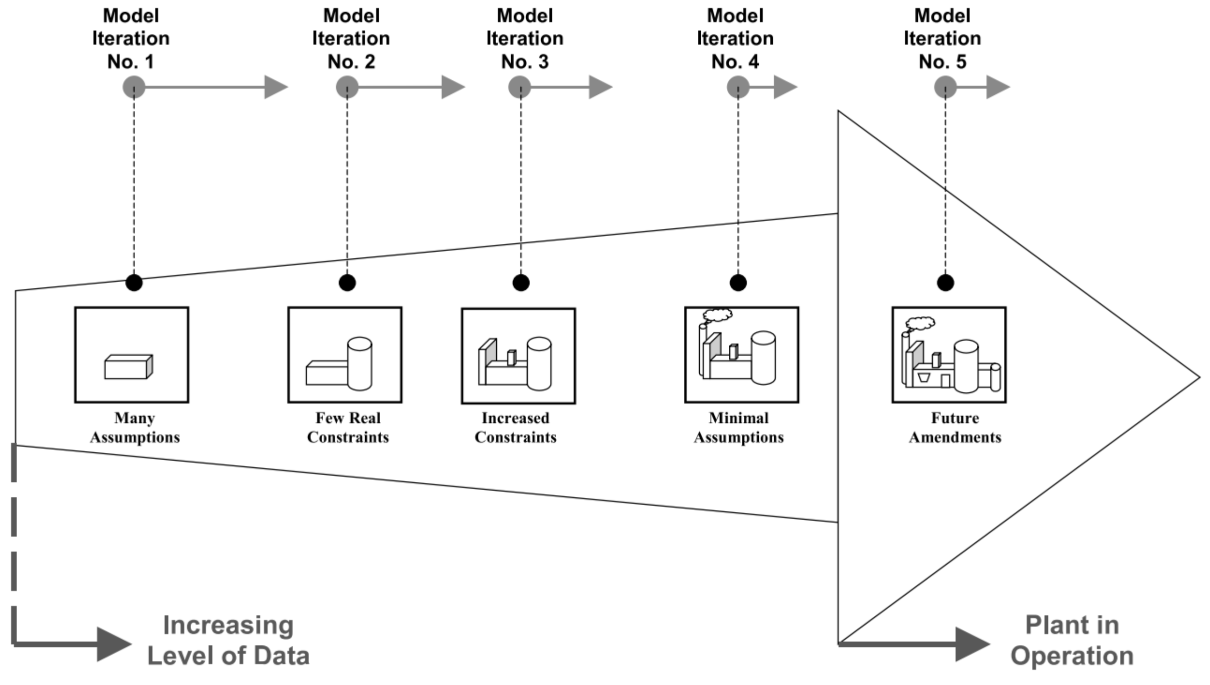

Figure 1: The iterative model building process (Robertson, 2002)

2.3 Simulation Elements

The main objective of the simulation in the application scenarios in IW-NET is to represent the dynamic behaviour of the main components of the inland waterway transportation systems. In the simulation environment, global representation is done through different elements that are the main components of the simulation model. These elements can represent very diverse things: ships, units of equipment, products, orders, etc. An element is a component of the model design that can have behaviour, memory (history), timing, contacts, etc. Every element's internal state and behaviour can be implemented in several ways such as by a series of variables or by the status of the agent in the state graph. The behaviour can be, roughly speaking, passive (e.g., there are elements that only react to the arrival of messages), or active, when the element internal dynamics (waiting times or system dynamics processes) causes it to act.

A digital simulation model allows creation of a representation of the physical world and its behaviour in a computer. The simulation model is dynamic and thus evolves over time. The rules of behaviour included in the model refer to changes in the temporal states of the processes and the participating elements. For example, when a barge arrives at an arrival port, its contents can be transferred to the stock of the warehouse in the hinterland, and a delivery notification could be sent to the sender or the recipient. The programmed dynamic rules are responsible for defining the quantity and time used in each of these processes.

For the dynamic simulations, a commercial simulation tool called AnyLogic [2] has been used. AnyLogic is the leading simulation modelling software for business applications, utilized worldwide by several companies. AnyLogic simulation models enable analysts, engineers, and managers to gain deeper insights and optimize complex systems and processes across a wide range of industries.

The main simulation elements that have been implemented in AnyLogic as components of the IW-NET IWT simulation models are described below.

2.3.1 IW-NET Waterway

The waterway network defines the geographic scope of the simulation. The network of waterways or fairways provides important data and constraints for the investigation of traffic flows. It therefore consists of a series of fairway sections with their detailed characteristics, like length and CEMT (European Conference of Ministers of Transport) class, as well as the specific type of the section including encounter regulations, navigability and locks.

Navigation restrictions due to water depths, clearance heights under bridges and the like can be considered if required. The network nodes define locations of ports or terminals as starting points and destinations of ship voyages. A GIS-based visualisation is preferred to discuss results with practitioners more realistically. In addition, the fairway sections (links) and nodes must provide spatial information as geographical objects, such as coordinates and lines. From a technical perspective, the waterway network is represented by a graph that consists of nodes and links, often called edges, between the nodes. This representation is also used for the routing of vessels from its source to any destination node in the network.

Table 2: Simulation network node data schema

Nodes	**Description**
mandatory fields	
Id	Unique identifier
Latitude	The geographical position in terms of latitude
Longitude	The geographical position in terms of longitude
optional fields	

[2] https://www.anylogic.com/

Type	e.g., node, terminal, berth, lock gate, reporting point
Location info	Text can be used to display additional information, e.g., the name of a terminal, the country that the node belongs to
River km	The kilometric point of the river

Table 3: Simulation network link data schema

Links (Edges)	**Description**
mandatory fields	
Id	Unique identifier
Source	Id of the start node
Target	Id of the end node
Bidirectional	Routing constraint for one-way sections
Geojson	Standard line-string used to display the exact course of fairway section and to calculate the length
optional fields	
Type	e.g., fairway, lock, canal
Location info	Text can be used to display additional information, e.g., the name of a river, lock or canal
CEMT class	The CEMT class indicates the maximum size of a vessel suitable for a particular waterway
Speed	Speed limit
Length	Length of the section
Regulation	Identifying the type of traffic regulation
Water level	The water level is expressed in cm and its calculation methodology depends on the country where the edge element is located on

The network component is integrated in the AnyLogic simulation tool and supports the dynamic routing of vessels. The routing method considers various constraints and objectives, such as CEMT classes, speed or minimum length in a flexible way. Thus, the routing algorithm can be used to find the shortest route between arbitrary nodes and the solution contains all available information from the underlying network.

In the case of inland waterway transport, one of the characteristic properties is the importance of the water level, due to the respective draught of a vessel. In the model the water level is a characteristic of each link attribute in the model, allows to make more accurate calculations about fuel consumption and GHG emissions. As an example, Figure 2 shows the correlation between vessel fuel consumption and water depth. In addition, the water level can change during the periods of time considered, so vessels may find restrictions when entering a specific waterway section at a certain time (with regard to speed, weight, draught...) if the water level is below or above its nominal value.

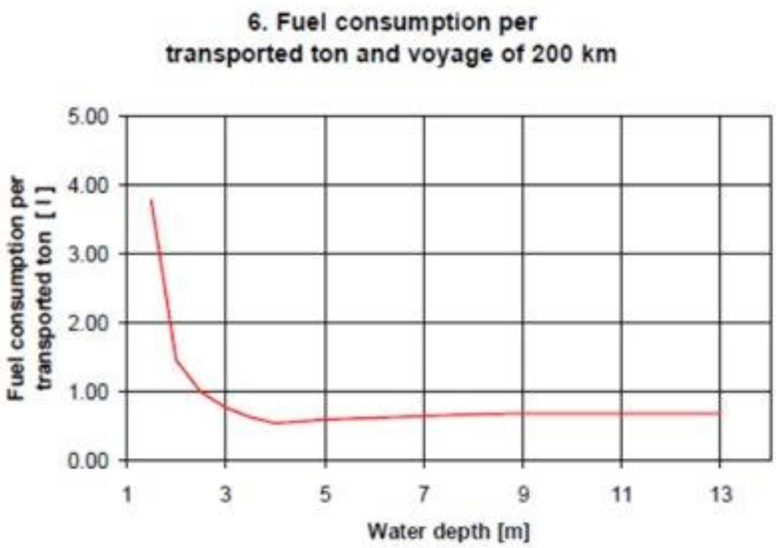

Figure 2: Correlation between vessel fuel consumption and water depth[3]

2.3.2 IW-NET Port /Terminal

The port elements include different processes for truck, train, and vessel handling. This includes activities such as mooring, loading, and unloading. In addition, the handling of push boats with the necessary coupling and uncoupling processes is supported by the port elements. Ports or terminals have individual attributes for length of berth, railways, and number of truck gates, which limit their throughput and performance. As the internal cargo handling procedures are generally out of the scope of IW-NET, the length of stay of inland vessels will be determined using statistical distributions and typical KPIs in conjunction with load volumes.

Table 4: Main attributes of a port in the model

Port	
Port id	Unique identifier of the port
Port name	The name of the port, descriptive
Lat	The geographical position in terms of latitude
Lon	The geographical position in terms of longitude
Country	The name of the country that the inland port is placed in it

2.3.3 IW-NET Lock

Lock modelling will consider features such as predefined opening hours, processing durations, waiting times and split locking of push boats and lighters. Process times will be calculated based on their actual statistical distribution.

Each lock has an individual scheduling strategy, based on typical lockage time distributions for upstream and downstream lockage. Their capacity is limited due to the dimension of the lock chambers and opening hours.

[3] *Source: Thomas Guesnet (DST Duisburg) at a CCNR workshop in 2011 (Workshop "Inland Navigation CO2-Emissions", presentation "Energy efficiency of inland water ships – and how to improve it")*

Table 5: Main attributes of a lock

Locks	
Lock id	Unique identifier of the lock
Lock name	The name of the lock
Country	The name of the country where the lock is located
River-km	The river km where the lock is located
Lock chambers L x W (m)	The dimension of the lock in terms of the length and width (measured in meters)
Capacity	The number of barges that the locks can take at the same time
Lat	The geographical position in terms of latitude
Lon	The geographical position in terms of longitude
Processing time	The average time needed to complete an operation (gates opening and closing, locking...)

2.3.4 IW-NET Traffic Regulation

Similar to the lock modelling approach, some simulation scenarios must consider local traffic regulations that have a significant impact on the scenario. As implemented for the example of encounter traffic, certain sections of the waterway network can be modelled with information on the respective traffic rules. The traffic regulation element can be omitted if the network under study does not contain any regulated waterway sections or their influence is deemed negligible with respect to the outcome of the simulation.

Table 6: Main attributes of a traffic regulation section

Traffic Regulation	
Id	Unique identifier of the regulation element
Fairway section	Section with traffic regulation scheme
Limitation type	"No passing" or "vessel type dependent passing"
Coordination strategy	Applied strategy to be evaluated in the simulation scenario

2.3.5 IW-NET Transport Vehicles and Services

The "Transport vehicle" elements are responsible for the transport actions in the model. In a synchromodal framework, they are the vessels, barges, trains, trucks, transporters, that convey or handle containers in the distribution network. A general "Transport vehicle" has some basic attributes that are shown in Table 7.

Table 7: Main attributes of a transport vehicle

Transport vehicle	
Id	Unique identifier of the vehicle
Type	Identification of type of transport: vessel, barge, truck, train, van…
CEMT class	The CEMT class indicates the minimum class of the waterway allowed
Path id	Unique identifier of path followed by the mover. (Through the links between the nodes)
Capacity	Attribute to indicate the capacity of the transport
Filling rate	Attribute to indicate the filling rate of the transport
Next stop	The actual next stop planned for the vehicle movement
Actual status	The actual status of the transport

In order to manage the behaviour of the different vehicles within the simulation model, next stop and actual status attributes are updated according to certain rules that can be defined in a state chart.

2.3.5.1 State charts

A state chart or status diagram shows all the possible status of the transport (idle, entering a Node, searching for destination…) and the logic conditions to evolve from one status to the next. A simple state chart for modelling a voyage of a vessel is shown in Figure 3. The states and transitions can vary between different simulation models, depending on the requirements and level of abstraction.

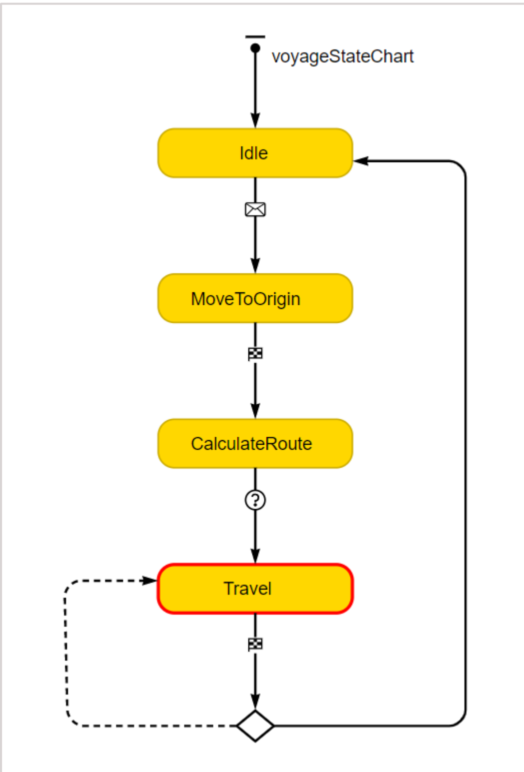

Figure 3: Travelling behaviour state chart

2.3.5.2 Vessel types

In an IWT context, vessels/barges are the most common type of Transport Vehicles. These inland vessels must also be classified into different size-types. There are different categorizations such as the CEMT classification of 1992 that is shown in the following image (Figure 4).

Class	L (m)	B (m)	T (m)	H (m)
I	38.50	5.05	1.80-2.20	4.00
II	50-55	6.60	2.50	4.00-5.00
III	67-80	8.20	2.50	4.00-5.00
IV	80-85	9.50	2.50	5.25-7.00
Va	95-110	11.40	2.50-4.50	5.25-9.10
Vb	172-185	11.40	2.50-4.50	5.25-9.10
VIa	95-110	22.80	2.50-4.50	7.00-9.10
VIb	185-195	22.80	2.50-4.50	7.00-9.10

Figure 4: CEMT 1992 classification of ships [4]

There is a broad diversity of different types of barges that can be used for inland waterway transport. Some of the barges proposed to be analysed in the project are the following ones (Figure 5).

Overview barge estimation costs									
Vessel type	Project ID	Lenght	Breadth	Side height	Mean draught lightship	Lightship displacement	No of cargo holds	Steel building estimated costs (mil euro)	Complete building estimated costs (mil euro)
Europa 2b	1	76.50	11.45	3.20	0.52	375,921	1	1,428,500	1,503,500
Europa 3a	2	90.00	11.45	3.25	0.51	442,707	1	1,682,287	1,757,287
IW-NET 3 unit abreast	3	81.00	9.50	3.20	0.50	341,653	1	1,298,281	1,373,281
IW-NET NEWS Evolution v2	4_v2	85.92	11.45	4.10	0.54	475,724	10	1,807,751	1,882,751
IW-NET Containers transverse v2	5_v2	89.80	16.28	4.00	0.48	624,949	6	2,374,806	2,449,806
IW-NET 3 unit abreast long	6	94.77	9.50	3.20	0.49	397,974	1	1,512,301	1,587,301
IW-NET NEWS Evolution long	7	97.32	11.45	4.10	0.51	512,253	6	1,946,561	2,021,561
IW-NET 3 unit abreast long/shallow	8	94.77	11.45	3.20	0.47	458,444	1	1,742,087	1,817,087

Figure 5: Barge classes as analysed in WP3. Source: WP3 T3.1, T3.2

There is a set of characteristics of the ship that must be considered in the simulation model. According to section 2.3 definitions in IWT simulation, the following configuration procedure must be carried out:

1. Set destination and departure gates/ports of each ship.
2. Determine the creation or deletion of each ship according to the arrival time or completion of the task.
3. Set route including waypoints for each ship.
4. Set parameters of each ship.
5. Determine the steering instruction according to each ship task as well as target ship's positions and behaviours.
6. Calculate ship velocity and position according to the instruction.

In the dynamic simulation model, there are alternative road transport options based on transport by truck. In the model, truck movements are created on demand as soon as their transportation capacity is needed. Therefore, their modelled process starts with a transport request, followed by the pickup of containers from the port of origin and ending with the delivery at the destination port.

[4] CEMT

2.3.5.3 Transport services

Transport services are used to define the schedules and destinations offered by the different transport companies or IWT service providers to move goods by inland waterways. A transport service is defined by a set of consecutive ports that are visited by a specific vessel. In general, the sequence of ports is repeated over time and arrival and departure times to/from every port must be specified.

Table 8: Main attributes of a transport service

Transport services	
Service Line id	Unique identifier of the service line
Port id	Set of ports covered by the service
Frequency type	Identification of the type of frequency of the transport: Daily, Weekly, Non-Stop, OnlyOneTrip, etc.
Arrival time	The scheduled arrival time to the port (discretised in time intervals)
Departure time	The scheduled departure time from the port (discretised in time intervals)
Vessel id	Unique identifier of the vessel

2.3.6 IW-NET Order

An order is the element of information that causes products to move. In a multimodal transport scenario, the order is associated with a set of containers, which must be transported from a point of origin to one (or several) destinations. Table 9 lists the main attributes related to an order.

Table 9: Main attributes of an order

Order	
Order id	Unique identifier of the order in the simulation model
Container list	Set of containers included in the order
Sender id	Unique identifier of the sender/origin of the order
Receiver id	Unique identifier of the receiver/destination of the containers
Max. Delivery time	Maximum delivery time window
Min. Delivery time	Minimum delivery time window
Booking time	Time at which the client requests the order
Costumer type	Customer type, they can be regular or spot customers
Due time in destination	Contractual due time

2.3.7 IW-NET Container

The container element is defined as the load reference unit for moving products. From the perspective of simulation, it is the minimum unit that can be transported, handled or delivered. Some information that is needed in the simulation model to move a container through the waterway is represented in Table 10.

Table 10: Main attributes of a container

Container	
Container id	Unique identifier of the container
Origin id	Unique identifier of origin
Destination id	Unique identifier of the destination port/gate
Sender id	Unique identifier of the sender of the container. The initial owner of the products.
Receiver id	Unique identifier of the receiver of the container.
Max. Delivery time	Maximum delivery time window
Min. Delivery Time	Minimum delivery time window
GPS latitude	Latitude GPS coordinates
GPS longitude	Longitude GPS coordinates
Costumer type	The customer type they can be regular or spot customers
Order id	Unique identifier of the order
Reservation time	The time at which the client requests the container
Optimizer result	The result of the optimizer. If the request is rejected the value is 0. If the request is accepted the value is 1. For the rejected requests there is a negotiation phase. If after the negotiation the request is accepted, the value is 2 and if not, the value is 3 (RM)
Port sequence	The sequence of ports that the container has to visit
Service sequence	The sequence of services the container has to take [RM]
Alternative modes	The alternatives transport modes. 1 if the cargo has to be delivered by a truck, 0 otherwise

In this chapter, the properties and behaviour of the main elements used in the simulation models have been described. The following chapter describes the main concepts, some properties and the *modus operandi* of RM based optimisation models at different levels of decision-making. The integration between simulation and optimisation models enables the investigation of different planning strategies and thus the optimal allocation of transport orders to modes of transport and vehicles

3 Revenue Management methods and models

This chapter describes the methodology and models used to design and implement revenue management optimisation and decision-making for inland waterway transportation system.

3.1 Methodological framework

Revenue Management (RM) optimisation methods and tools attempt to answer a general type of question, faced by many transportation companies: given the operating constraints and available assets, and given the information and knowledge about market conditions, potential customers, and demand, what is the best set of services to offer, during what periods, and at what prices, in order to maximize expected profits and ensure a high quality-of-service to customers? Operational research offers a scientific approach to tackle this kind of problem, through a methodological framework composed of the following elements:

- *Mathematical modelling*, which allows formulating operational and tactical planning problems as probabilistic mixed integer programs (objective function and constraints, integrating probability distributions based on insights about uncertainty related to demand, travel times, vehicle capacities, etc.).
- *Optimisation* techniques and algorithmic approaches aimed at finding optimal solutions and ensuring the best trade-off between the quality of solutions obtained and computational times.
- *Validation* methods, focusing on enhancing the consistency of the decisional process, through the design of a decision support system, guaranteeing the feasibility and applicability of different dedicated solutions to different specific scenarios.

Those elements need to be incorporated within a methodological framework which is deployed throughout the IW-NET project, and which is based on a twofold approach:

- A top-down approach, which consists of translating general RM ***concepts*** into practical **application scenarios** through the **development** and **implementation** of **models**, optimisation **methods** and **tools**.
- A bottom-up approach, where the purpose is to nourish the reasoning and **abstraction process** with the feedback collected and consolidated by ground data from the real-world case studies, through the **analysis** of data, information, and knowledge available in the system. The **validation** process, formalized and managed at different stages of **implementation**, will also enable the analysis of the opportunities provided by the technical and technological innovations devoted to the consolidation of the value chain for the economic development of the IWT sector.

3.2 The conceptual RM approach in freight transportation

This section describes the main concepts used to make decisions in a hierarchical setting, from a tactical and operational point of view, to improve resource utilization and customer satisfaction in inland waterway transportation systems.

3.2.1 Decision-making and revenue management in transportation

The road network supports 77.4% (Eurostat, 2020[5]) of the freight transport and 92.3% (EU-stats2, 2017[6]) of the inland passenger transport (passenger cars, buses). In addition to congesting the road network, road transport is a considerable source of GHG emissions, not to mention noise pollution and the high risk of accidents. In this context, the inland waterway freight transport, or barge transportation, is an opportunity for reducing gaseous emissions and traffic on roads. However, barge transportation faces some drawbacks with respect to truck transportation. One of them is the fact that barge transportation cannot directly satisfy transport demands that are away from the inland waterway network. To cope with this difficulty, barge transportation needs, on one hand, to be integrated within an effective and competitive intermodal transportation system. To this end, barge transportation activities need to be accurately planned and synchronized with the other modes of transportation. On the other hand, barge transportation needs to propose attractive and adaptive offers of transport to be of interest for new customers and to use its resources more efficiently. This is where Revenue Management concepts and techniques come into play.

Intermodality is the process of transporting goods through two or more modes of transport, using dedicated Transportation Units (usually containers, accounted for as TEUs – Twenty-foot Equivalent Units). One important goal is to decrease the negative effect of GHG emissions by consolidating the transportation of goods for different customers, goods travelling between different origins and destinations, sharing the capacity of the same vehicle for some parts of their journeys.

The barge transportation problem is characterized by the carrier's need to meet the transport demands of its various customers while maximizing revenues by making the best use of its resources. Two main challenges of the barge transportation problem will be presented, the first being the organization of its limited and costly resources in a structured way and the second being optimally planning the use of these structured resources to satisfy customer demands.

As studied from the perspective of the Operational Research scientific field, these policies are classified as hierarchical decision-making levels including strategic (long-term), tactical (medium-term), and operational (short-term) planning. The conceptual diagram showing the link between strategic, tactical and operational planning is illustrated in Figure 6. As shown in this figure, the output of one planning level is the input of the one below.

[5] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split

[6] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Passenger_transport_statistics&oldid=499254#Modal_split_of_inland_passengers

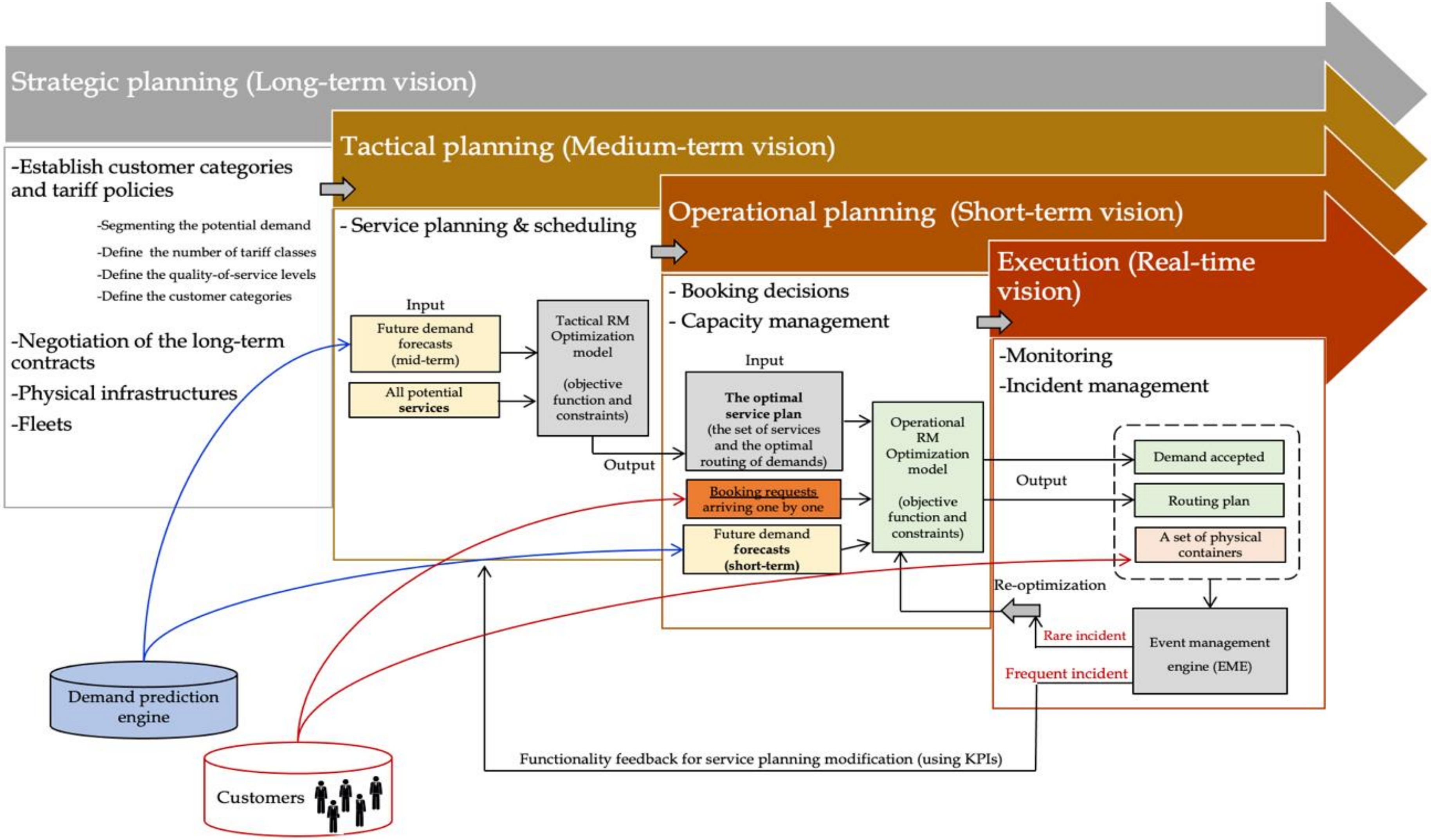

Figure 6: IWT planning levels

The RM based optimisation models have been developed under the assumption of hierarchical decision-making. In the scope of the present study, the strategic planning level was not considered, focusing in particular on the tactical and operational levels:

- the tactical level, where a scheduled service network is designed and where the resources are optimally allocated, based on aggregated demand forecasts,
- the operational level, namely the booking and capacity allocation decision, where the use of these scheduled services and their capacities are optimized to best meet the updated transport demand requirements.

This tactical versus operational planning framework is well-known in the literature (Harks et al., 2016; Fontaine et al., 2021). One strong argument in favour of this hierarchical approach is the necessity of differentiated decision levels in terms of scope and time horizon, the first type of decision being prospective while the second is dynamic. Demand stochasticity is also inherent at both levels, but the degree of aggregation of information is obviously different, higher at the tactical and lower at the operational level.

In the present study, the tactical planning of transportation activities is considered as a scheduled service network design problem (Bilegan et al., 2022; Taherkhani et al., 2022), and the operational planning as a dynamic capacity allocation problem (Wang et al., 2016). Detailed explanations regarding these two problem definitions are given in the following sections. Both problems take into consideration revenue management concepts and techniques in order to serve the transportation requests, with a twofold purpose: increase net revenue on the carriers' side and diversify offers and increase quality-of-service for the shippers, while fulfilling all operational, technical and regulatory constraints.

3.2.2 The tactical RM model

In the following, the tactical planning is described, under the form of a scheduled service network design problem, by elaborating on elements like the input and the output of the problem, the customers and their demand characteristics, the vessel characteristics and the physical networks on which they operate, transportation services characteristics, associated costs (fixed and variable). The required elements needed for the abstract representation and the mathematical modelling formulation (including decision variables, the objective function and constraints) are also presented.

3.2.2.1 Problem description at the tactical planning level

The planning process is summarized by taking the point of view of the carrier. Typically, the carrier aims to meet demand and the associated shipper requirements in the most resource and cost-efficient way (cost-efficient services and schedules, given the forecast demand). To do so, the carrier should plan services and operations in advance, with the purpose to best serve demand and thus maximize expected net profit. This fact implies that the carrier has some estimates about the periodic demands that should occur over the tactical planning horizon. To be more precise, in the proposed problem for tactical planning the carrier seeks to find, based on some aggregated information about potential future demand (demand forecasts), the best set of transportation scheduled services; once these services are defined, they are going to be operated and proposed by the carrier to the shipper companies for a predefined time period, *e.g.,* the next season (several months). A regular schedule for these services is built based on a schedule length (*e.g.*, a week); the services will then be operated repeatedly, following the same regular schedule, for the duration of the whole period, *i.e.*, the tactical planning horizon (the season).

The goals of the tactical RM optimisation problem can be stated as follows:

1. Select the best set of services, out of a set of potential feasible ones, and the schedules to operate, satisfying the estimated potential demands in the most efficient and profitable way.
2. Determine the circular routes of mobile resources (vehicles), namely the service cycles, and the utilization of other assets (infrastructure, equipment, terminals, …) that are supporting the selected services.
3. Identify the itineraries (routing) of forecast demands throughout the selected service network.

The combination of these three elements yields a set of loads on vessels during their movements from one stop to the next one on the corresponding service, *i.e.*, the traffic flows, and the set of activities related to the amount of work to be performed (loading/unloading/storing/…) on vessels and containers at each port of call in the network.

3.2.2.2 The integration of revenue management (RM) concepts at the tactical level

RM is expected to provide freight carriers with techniques to better manage revenues and enhance services by, in particular, tailoring the quality-of-service levels and tariffs to particular classes of customers and demands. The integration of revenue management considerations into **tactical** planning is performed through several major modifications performed on the traditional problem setting and modeling approach.

First, *several types of demand* requirements are explicitly considered, namely *express delivery* and *standard delivery*, and consequently different fare classes, *high contribution* and *low contribution*, respectively. Second, *several categories of customers* are explicitly considered: on the one hand, *regular* customers, those who have established long-term contracts with the carriers; on the other hand, *spot* customers, those who do not have long-term contracts with the carrier but who might have some *ad-hoc* demands; information about the spot demand is assumed to exist, and some aggregated forecasts of those demands are assumed to be available. The main difference with the regular customers' demand is that, since there are no contractual commitments on the long-term, the carrier is free to accept or reject (some of) the spot orders; this will depend on their opportunity cost*, i.e.*, their estimated profitability in regard to the transportation capacity the transporter is able or willing to deploy. Third, the total net revenue is accounted for; it is computed as the difference between the estimated revenue of servicing all regular and accepted spot potential customers and the cost of performing the selected services. These costs account both for setting up the services, for operating vessels, and transporting, storing and handling containers. It is thus summing up the fixed cost of operating the vehicles, the variable cost of transportation and the one of using the infrastructure. The revenue is calculated based on the type of delivery and the corresponding fare classes offered. The goal is thus the net revenue maximization, *i.e.,* the difference between total revenues and total costs.

The resulting tactical optimisation model may therefore be used both to plan scheduled transportation services for the next season and to provide a tool to evaluate RM policies, through implementation, extensive testing and validation on diversified scenarios and parameter settings.

3.2.2.3 Inputs and Outputs of the tactical RM optimisation model

- Inputs: the set of forecast demands and the set of all potential feasible services according to the available physical network, and the given schedule length.
- Output: the best set of scheduled services to open during the schedule length: the set of services that maximizes the net revenue and optimally serves the selected forecast demands.

3.2.2.4 Model assumptions

The practical problem the model is applied on concerns a physical network of rivers and canals. A number of physical characteristics often limit navigation on this network, such as the maximum number of vessels that can navigate on the same stretch at the same time. Several ports are located on the river network, with container terminals for loading and unloading goods. Each terminal, and therefore each port, has facilities and operating policies that define its capabilities in terms of the number and types of vessels that can be berthed and loaded at the same time, the number of containers that can be stored in the terminal, the costs of each operation, the opening hours, etc.

In Table 11, the various characteristics of a **demand** and of a **service** are defined. A description of the characteristics of a vessel, the costs including the fixed cost of the tactical plan (associated with design decisions) and the variable costs (depending on flows) and additional elements of the mathematical model such as decision variables, the objective function and constraints can be found in Annex II of this document.

Table 11: The characteristics of the demands and services

Demand characteristics	Service characteristics

➢ Category of customer
  ○ **Regular:** long-term contracts; demands must always be satisfied.
  ○ **P-spot**: no long-term contracts; demands may be partially satisfied
  ○ **F-spot**: no long-term contracts; demands may be either entirely accepted and serviced or not accepted at all.
➢ Origin and destination terminals
➢ Volume or quantity (in TEUs)
➢ Availability time: the time when the cargo becomes available for transportation, at its origin terminal
➢ Due date: the latest delivery time at destination terminal, required by the customer
➢ Fare classes: price category associated with *standard* or *express* delivery
➢ Value of fare for each fare class: high fare value for express delivery, low fare value for standard delivery
➢ Container type
	➢ Physical origin and destination terminals (ports)
	➢ Ordered set of consecutive stops of the service
	➢ The set of legs (non-stop movement between two terminals) describing the service itinerary
	➢ The path of each leg of the service in the physical network
	➢ Time related attributes of a service
	  ○ Travel time of each leg of the service
	  ○ Departure time from a terminal
	  ○ Arrival time at a terminal
	  ○ Waiting time at each terminal
	  ○ Initial loading time: availability time of the service to start loading at its origin terminal
	  ○ Final unloading time: time at destination when the vessel is completely unloaded and ready for the next service
	  ○ Total duration of the service
	➢ Vessel type required by the service
	➢ Capacity of the service, corresponding to the nominal capacity of the type of vessel required (in TEUs)

3.2.3 The operational RM model

At the operational level, a RM model is proposed to address the dynamic network capacity allocation problem of an intermodal barge transportation system. Demand consolidation and predictive routing are the key concepts developed here.

3.2.3.1 Problem description at the operational planning level

Given the scheduled services settled at the tactical level, the carrier has to decide, at the time of receiving demands, which are the ones to be satisfied and how. To make this type of decision, the carrier needs to have the newest update of the relevant information about the demand: origin, destination, quantity, pickup and delivery periods, etc. This decision-making process takes place sequentially, on a rolling horizon. Each time a transport request is received, the carrier should be able to evaluate its feasibility and profitability in order to decide whether or not to accept and transport it. If the request is accepted, the carrier decides about the itinerary of the demand by optimally assigning it to one or more services potentially available for that demand. This process may be viewed as a booking process. The schematical representation of the decision-making problem considered at the operational level is displayed in Figure 7.

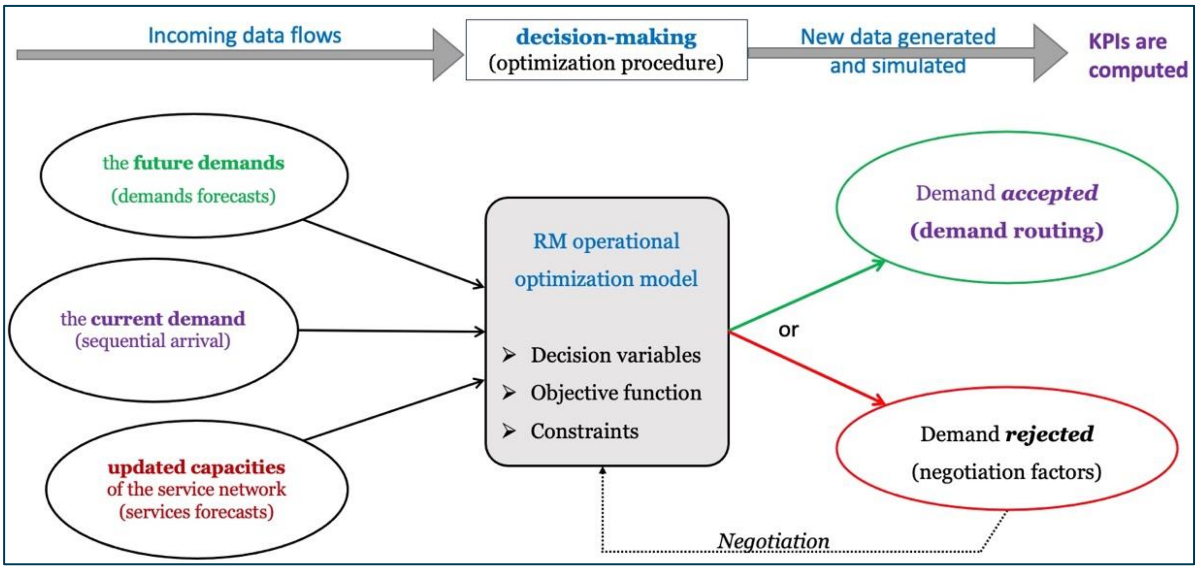

Figure 7: The inputs and outputs of the operational RM model

Based on the set of inputs (current demand, available capacity and demand forecasts), an optimal decision is computed, using a probabilistic mixed-integer optimisation model maximizing the expected revenue of the carrier. The feasibility and profitability of demands are evaluated, and the decision support system is able to suggest if a demand should be accepted or rejected. Indeed, as soon as a transport request arrives to the carrier, a mathematical model allows to compute simultaneously the best routing based on the residual capacities of the services in place, and the profitability of its acceptance based on the forecast of future transport requests. To deal with the case when a transport request is rejected, some negotiation mechanisms have been defined to find the best trade-off between the carrier and the customer regarding the acceptance and routing of that demand. The negotiation methods include the possibilities of postponing the due date and/or using alternative modes of transport such as trucks. The carrier is, in that case, supporting the extra-cost of using these alternatives. A mathematical model is then used to re-optimize and compute the best solution satisfying both parties (the carrier and the customer).

3.2.3.2 The integration of revenue management (RM) concepts at the operational level

As stated previously, two categories of customers are assumed, the regular ones having long-term contracts allowing them to have transport guarantees offered by the carrier. Often, these contracts commit, in advance, the customer and the carrier to a certain quantity of demand to be transported. The carrier must therefore give priority to these customers to fulfil the contract. Any other customer is considered as a spot customer, and its transport requests will not constrain the carrier, who could accept them if they are profitable. Subsets of these categories may be defined as well (*e.g.*, F-spot and P-spot customers) as already mentioned in the tactical model subsection (3.2.2). Indeed, this is useful since it allows the mathematical formulation to take into account different types of customer behaviour with different possible consequences on the decision process at the operational level as well.

A transport booking request is made to transport a stated quantity of demand (in TEUs) between two terminals in the network. The customer specifies the time the load will be available at the origin terminal, and the latest time it is to be delivered at destination, the so-called due time. Additional information can be provided if the transport requires special transportation conditions. The price of a shipment depends on several factors, such as the existence of long-term contracts, the time between the booking request and the availability of the cargo (booking anticipation: *early* or *late*) at the origin terminal, the time between the availability and the due date (delivery type: *standard* or *express*), the distance, the number of containers, etc.

Some examples of different types of demands are displayed in Table 12.

Table 12: The data set required to characterize a set of demands

Customer Type	Order ID	Origin	Destination	Number of Containers	Booking Time	Availability at Origin	Due Time at Destination	Booking Type	Delivery Type
Regular	0	3	1	4	0	4	168	Late	Standard
Regular	1	1	3	5	1	4	68	**Late**	**Express**
Full-spot	2	2	3	4	2	21	79	*Early*	*Standard*
Partial-spot	3	2	3	4	3	6	47	Late	Standard
Regular	4	3	1	1	4	16	89	**Early**	**Express**
Regular	5	1	2	1	5	11	46	**Early**	**Express**
Partial-spot	6	3	0	5	6	18	183	*Early*	*Standard*
Partial-spot	7	0	1	4	7	11	33	Late	Standard
Full-spot	8	3	2	2	8	13	44	**Late**	**Express**
Regular	9	0	3	3	9	11	93	**Late**	**Express**

In this table, the time dependent characteristics of the demand data (e.g., booking time, availability at origin, due time) have been converted into numbers of elapsed time periods (time units – TU), relative to a time zero reference (used as the reference of the simulation time axis), instead of a classic time format representation. Indeed, as a data pre-processing step, time is discretized into time periods corresponding, for instance, to half-a-day (12 hours), a quarter-of-day (6 hours), or less, depending on the degree of time discretization required by the application. This is done for the specific needs of the mathematical formulation of the optimisation models and allows a homogeneous representation of transportation activities, on a discrete time-space network.

Further assumptions and data requirements for the operational RM optimisation model have already been presented in a different deliverable of the IW-NET project (D1.7). Nevertheless, for the convenience of the reader, they have been added in Annex II of the current document.

4 Data Sources for IWT analysis

This chapter includes references to different data sources used to populate the inputs of the different simulation models. This information is used to characterise the river transport movements and also for estimating the value of the main indicators.

A data information system is one of the key elements of the simulation framework. Some of the main features that an information system needs for the development of reliable simulation models are outlined below.

- Identification: Each container and transport vehicle must have a unique global identifier in networks.
- Traceability and tracking: management systems must be able to locate each container and provide traceability information (e.g., status, arrival and departure dates in facilities, environmental conditions when necessary) to key stakeholders.
- Monitoring status: coordinators must be able to monitor the condition and integrity of the data of the cargo. For example, it implies obtaining information on legal agreements, respecting the cold chain for perishable products or opening of containers to prevent theft.
- Compatibility and interoperability of data: For the sake of coordinating actors and containers, coordinators must be able to communicate with the various information systems used by the users of the container.

4.1 Input data

The simulation model receives input data from the IT architecture and it needs a specific set of standard components such as: list of Container Id's, list of Nodes, available transports etc. and the corresponding master tables (or services) where the information of each element is consulted (i.e., masterContainers, masterNodes, masterNodes).

The simulation model needs a different type of information. Some of this information must be standardized in the "language" of IW-NET, as described by the simulation elements in Chapter 2.

Digital simulation models can use both real process information and synthetic information, created from statistical data that come from generic distribution processes. Application Scenario based simulation models usually use real information and generic simulation models usually use synthetic information.

sheet: 06_orders	demo value	demo value	demo value
Customer Type	R	P	F
Order ID	0	1	2
Origin	2	0	0
Origin Name	Belgrade	Regensburg	Regensburg
Destination	3	3	3
Destination Name	Silistra	Silistra	Silistra
Containers	4	1	3
Booking Time	0	1	2
Availability at Origin	1	15	6
Due Time in Destination	24	91	57

Figure 8: Example of configuration tables for the order simulation element

As an example, Figure 8 shows a configuration table for the order simulation element. In Annex I, the full list of the main input data from the simulation model it is shown.

4.1.1 Transport network data

The nodes table contains the description from each point in the network, the basis information, like latitude and longitude and also some attributes from the behaviour of every element, like the role in the supply chain (warehouse, port, shop…). The subsequent figure contains the link table. The link represents the connection between the nodes.

id	latitude	longitude	type	locationInfo	riverKm
1706	53,2485459	8,4742179	NODE		
1705	53,2268469	8,465003	NODE		
1239	53,1636143	8,6934419	NODE		
1789	53,1618253	8,6757414	NODE		
1181	52,9563895	9,1786363	NODE		
1112	52,9465384	9,1830832	NODE		
2632	52,9096699	9,1667768	NODE		
2662	52,8724186	9,211475	NODE		
1000	52,849459	9,2194106	NODE		

Figure 9: Example Node data for the IW-NET waterway network

id	source_id	target_id	geojson	category_id	category_name	name
1341	1408	1409	{"type":"LineString","coordinates":[[8.9325812,52.3031691],[8.9348201,5	305		Mittellandkanal
1342	1410	1408	{"type":"LineString","coordinates":[[8.9271494,52.3026331],[8.9325812,5	305		Mittellandkanal
1051	998	999	{"type":"LineString","coordinates":[[9.1680665,52.6311754],[9.1683802,5	304		Weser
1052	1000	1001	{"type":"LineString","coordinates":[[9.2194106,52.849459],[9.2182199,52.	304		
1110	1083	1084	{"type":"LineString","coordinates":[[9.1857039,52.6945212],[9.1862488,5	304		
1111	1085	1086	{"type":"LineString","coordinates":[[9.0259381,52.4795477],[9.0294008,5	304		Schleusenkanal Schlüsselburg
1112	1087	1088	{"type":"LineString","coordinates":[[8.932196,52.3035788],[8.9269439,52.	305		Mittellandkanal
1129	1111	1112	{"type":"LineString","coordinates":[[9.2212522,52.9275803],[9.2197256,5	303		Aller
1180	1181	1182	{"type":"LineString","coordinates":[[9.1786363,52.9563895],[9.1782145,5	304		Schleusenkanal Langwedel
1215	1238	1239	{"type":"LineString","coordinates":[[8.7426274,53.1718621],[8.742572,53.	303		Lesum
1225	1254	1255	{"type":"LineString","coordinates":[[8.9401976,52.3031021],[8.9414551,5	320		Oberschleuse
1226	1256	1257	{"type":"LineString","coordinates":[[8.9357882,52.2988071],[8.937039,52.	320		Unterschleuse Minden
1239	1274	1275	{"type":"LineString","coordinates":[[9.5320245,52.4023137],[9.5272842,5	305		Mittellandkanal

Figure 10: Example Link data for the IW-NET waterway network

A transport network component consists of a graph-based model of the waterways or fairways. The network data can be prepared easily as tabular data (e.g., an Excel file) and imported into the simulation model.

The data provision takes advantage of free map data from OpenStreetMap (OSM) (OpenStreetMap.org, n.d.). A transport network is usually based on infrastructure links (e.g., roads, railways and inland waterways) and transshipment points (e.g., terminals) whose corresponding elements of the geographic map data are nodes and edges. In order to assign traffic flows to feasible routes, the simulation environment includes a routable network representation that is aligned with its visualization function, such that a valid and consistent presentation and animation is possible.

Figure 11 shows the graphical representation of the fairway sections and different terminals or berths along the river Weser in northern Germany. Some designated sections can be highlighted, e.g., depending on the optional attributes of the edge input data, like type (locks are green) or regulation. The traffic regulation sections are shown as red and locks as green lines.

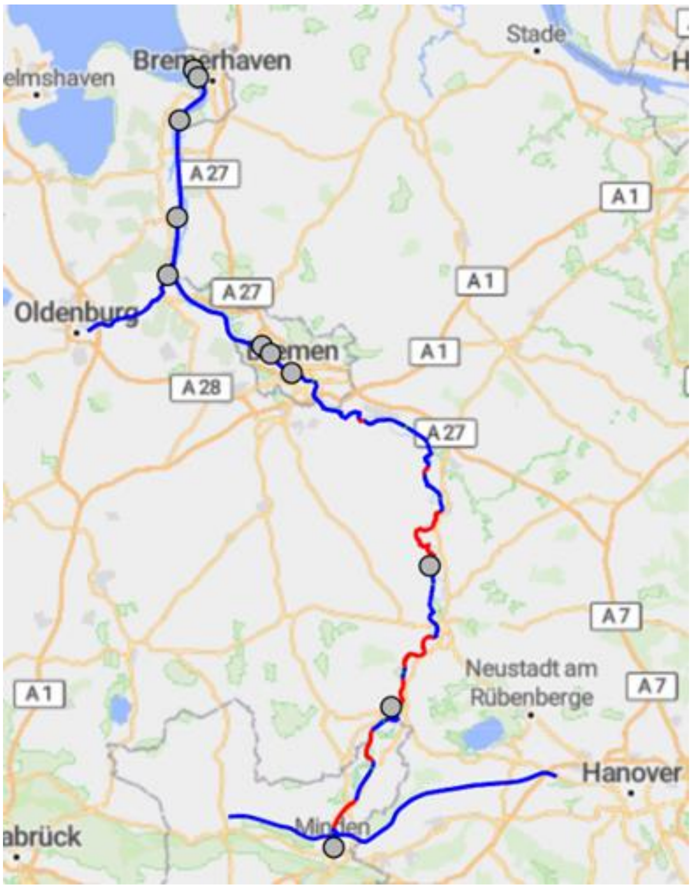

Figure 11: GIS-based IWT network

4.1.2 Transport cost data

This section includes some cost references related to the energy consumption of the different types of vessels and the different operations related to inland waterway transport. Following are some of the references that have been identified by the project partners.

4.1.2.1 Fuel consumption

Fuel consumption conditions are highly variable depending on the draught, direction of travel and the driving style of the vessel driver. Nevertheless, some reference data are included for use in the different simulation models to compare different strategies in different scenarios. The following table contains fuel consumption reference values for different types of engines.

Table 13: Fuel consumption within operating hours[7]

Engine Type	**Engine Power**	**Average fuel consumption (min.) [kg/h]**	**Average fuel consumption (max.) [kg/h]**
Motor c.v. 105m	engine 900 kWh	73	78
Motor c.v. 130m	engine 1600 kWh	131	138
Pusher (2b)	engine 1160 kWh	95	107
Pusher (4-6b)	engine 1700 kWh	139	148
Pusher (+6b)	engine 2400 kWh	196	212

[7] TTS, Austria

It is also recommended to use a fuel consumption factor when the vessel is not operational. As an average value it is recommended to use a value of 8 or 12% of the fuel consumption when operational[8]. Non-operating hours are by our definition only the hours when vessel is completely lying still in a port, parking position, etc.

4.1.2.2 Fuel price

The price of fuel has been fluctuating widely over the last few months and the following are some reference values:

Table 14: Cost of fuel based on an average rate of 20 top ports worldwide[9]

Date	USD/ tonne
15.09.2021	647,50
15.10.2021	749,00
15.11.2021	745,90
15.12.2021	697,50
15.01.2022	785,20
15.02.2022	884,50
15.03.2022	1.169,40

4.1.2.3 Staffing

Personnel costs are an important part of the total costs of any transport operation. Below is some data on personnel costs for inland waterway freight transport. The number of personnel required on board a vessel for navigation depends mainly on 2 factors.

1. The size of vessel / convoy.
2. The sailing regime (16-, 18- or 24-hours sailing regime).

Below is an example table for the crew cost required for a 24-hour navigation regime. Crew cost of smaller motor cargo vessel (105 meters) could be typically reduced by 15%.

Table 15: Crew cost for a 24-hour navigation regime[10]

Pusher type	Barges number	Staff cost
Pusher for 2 barges	2 barges possible	€ 610,00 / day
Pusher for 4 barges	4 barges possible	€ 670,00 / day
Pusher for 6+ barges	6+ barges possible	€ 800,00 / day

8 TTS, Austria
9 https://shipandbunker.com/prices/emea/medabs/tr-ist-istanbul#MGO
10 Market evaluation by TTS, Austria (November 2021)

4.1.2.4 Waterway transports cost in the Netherlands

Cost calculations for inland waterway transport are available for the Netherlands and distinguish three main markets:

- Rhine shipping (to/from Germany and beyond).
- Domestic shipping and transport to Belgium.
- North-south shipping (to/from France).

The cost calculation presented here is based on a volume-based weighted average for the three areas mentioned. The areas of operation in this analysis only concern differences in fuel costs, due to different currents for each area. For example, the Rhine has a strong upstream current, which leads to increased fuel use and thus fuel costs. The cost calculations have been solely based on Dutch vessels in use by companies based in the Netherlands. Still, the costs can be considered as representative for the cost of inland waterway transport in the entire Western-European market for three reasons:

1. The cost composition of inland waterway transport does not vary significantly in this region.
2. The Dutch inland waterway fleet has a market share of 50-60%
3. A large part of the Dutch inland waterway fleet's transport activity (tonne km) takes place outside the Netherlands.

For inland waterway transport, several navigational operating modes are common, which are a determining element to calculate transport costs per hour. The operating modes determine the average operational hours per year of a vessel related to manning requirements. Vessel owners need to register their operating mode in order to ensure a level playing field. The operating modes in inland shipping are:

- "Solo-navigation": 2.496 hr/yr.
- Day travel (A1 – 14 hours of operation per day): 3.360 hr/yr.
- Semi-continuous navigation (A2 – 18 hours of operation per day): 4.752 hr/ yr.
- (Fully) continuous navigation (B – 24 hours of operation per day): 8.064 hr/y.

The typical operating modes per cargo segment have been considered for the estimation of average calculation of inland waterway transport costs[11]. Altogether, cost figures in euros (€) are per type of cargo for small ships and push barges and, within cargo category, an average for transport of various commodities (e.g., coal, agribulk, ores, salt, metals, oil, chemicals, minerals, metals, containers). The average cost figures (base year 2018) are considered to have sufficient detail and variation between cargo types for the purpose of IWT modelling and simulation within IW-NET as default. Furthermore, it is possible for the users of the simulation tool to change the default transport cost figures based on own experiences or preference.

[11] Cost Figures for Freight Transport, Panteia

Cargo type	Costs per vessel size / type in [€ / tkm]			
	Small	medium	large	push barge
Dry Bulk	0.033	0.020	0.017	0.009
Break bulk	0.040	0.024	0.020	
Container	0.013	0.033	0.023	
Liquid bulk		0.037	0.027	

Figure 12: Average transport costs 2018 per vessel and cargo type in € / tkm [12]

Cargo type	Costs per truck type / size in [€ / tkm]			
	trucks	truck + trailers	tractor + trailer	LHVs
Dry Bulk	0,366	0,228		
Break bulk	0,348	0,189	0,145	0,113
Container			0,115	0,092
Liquid bulk			0,127	0,095

Figure 13: Average transport costs 2018 per truck and cargo type in € / tkm [13]

4.2 Inland Waterway emission data

This chapter contains the information required to assess the different types of environmental emissions associated with inland waterway transport.

A valuable input to consider for the GHG calculation and associated data reporting metrics comes from the GLEC Framework (based on results from various EU supported projects and sector analysis). Furthermore, an emission monitoring project has recently started called ‘IWT Footprinting’ to measure emission on representative IWT vessels in the Netherlands[14]. The emission monitoring will collect calibrated information on fuel consumption (and thus CO_2/GHG-emissions) and NOx in correlation with various parameters (e.g., Water depth, current, wind, engine load, etc.). Intermediate results will become available at the end of 2022.

For the consideration of NOx emission, the CLINSH project which is also EU-funded, could provide valuable input from practical measurements. CLINSH studied the improvement of air quality in urban areas (Antwerp, Rotterdam, Nijmegen, Duisburg) by accelerating emission reductions in Inland Waterway Transport. Various energy sources and greening measures were tested, for which emission-to-air data was recorded. Until the final report of the project the framework developed for estimating global GHG emissions for IWT is described. The framework has been broken down into multiple steps for collecting data by means of desk research, surveys and data analysis. The report provides GHG emission factors estimates that could be useful for the project.

[12] Cost Figures for Freight Transport, Panteia
[13] Cost Figures for Freight Transport, Panteia
[14] https://topsectorlogistiek.nl/2022/02/11/kick-off-monitoringprogramma-meten-op-schepen/ (in Dutch)

4.2.1 Inland Waterway Transport GHG emission data

GHG emissions are directly related to the consumption of fuel. Table 16 presents the division of the active European fleet of inland vessels based on fuel consumption and estimated tonne-kilometre performance. The comparison reveals that larger vessels have a high share in the transport performance and both the transport performance, as well as the annual fuel consumption, of smaller vessels (<80m) is relatively low.

Table 16: Share in estimated tonne-kilometre performance and average fuel consumption of the main fleet families [15]

Fleet families identified in PROMINENT	Share in estimated tonne-kilometres transported in EU (in %)	Average fuel consumption per year (in m3)
Push boats <500 kW (total engine power)	1%	32
Push boats 500-2000 kW (total engine power)	18%	158
Push boats ≥2000 kW (total engine power)	9%	2,070
Motor vessels dry cargo ≥110m length	19%	339
Motor vessels liquid cargo ≥110m length	14%	343
Motor vessels dry cargo 80-109m length	17%	162
Motor vessels liquid cargo 80-109m length	5%	237
Motor vessels <80 m. length	10%	49
Coupled convoys	7%	558

In order to collect more detailed data on the emission intensity of inland vessels, a framework for estimating global GHG emissions for IWT was developed for the framework of the Global Logistics Emission Council (GLEC). This framework, as illustrated in Figure 14, has been the basis for collecting data on vessel types, operational characteristics, and fuel consumption.

[15] Based on detailed information from Western-European countries. Source: PROMINENT D1.1

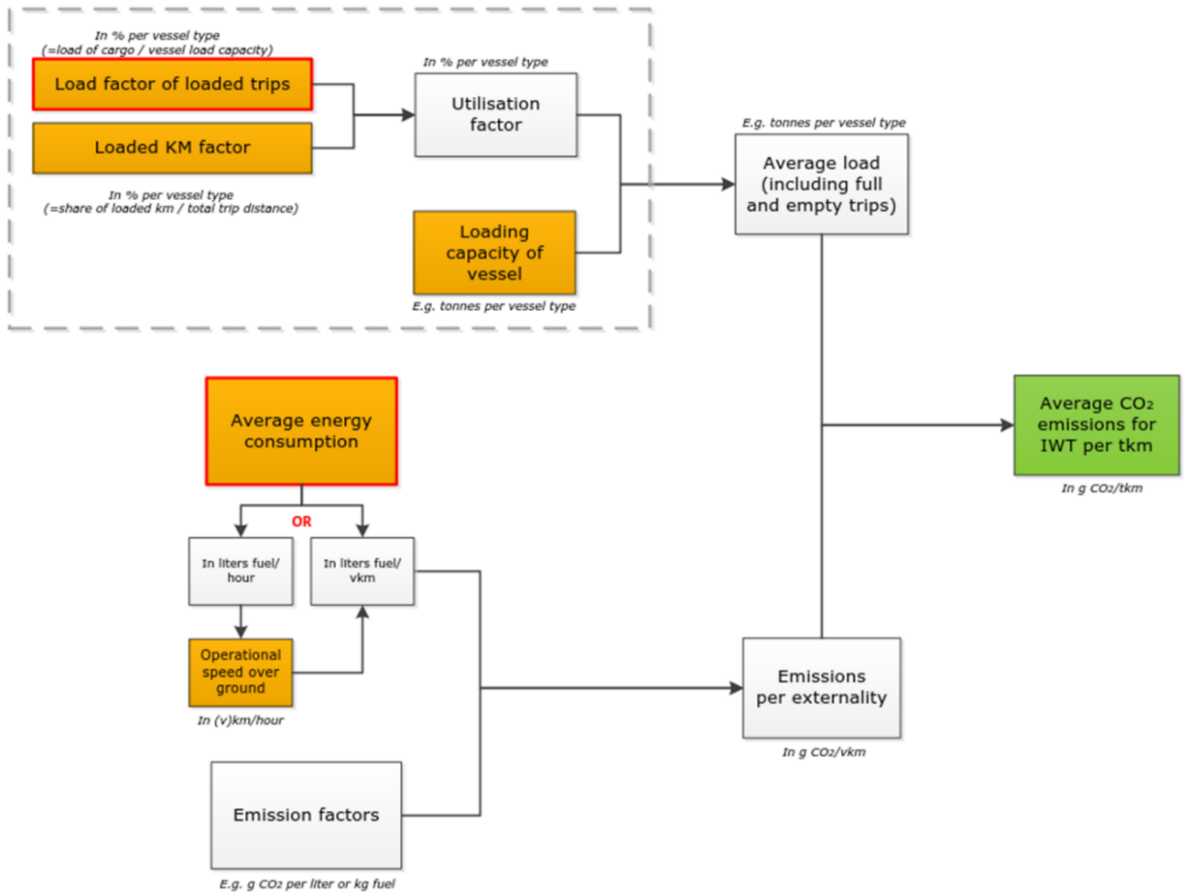

Figure 14: Data collection framework for estimating GHG emissions for IWT (Source: STC-NESTRA)

On the basis of real-life data from barge operators for multiple trips or year-round navigation, based on H2020 – PROMINENT and P. Oom / Kon. BLN- Schuttevaer, GHG emission factors have been calculated for representative vessel classes in Europe[16].

In Table 17 an overview is given of the GHG emission factors per representative vessel classes (fleet families) in Europe. The emission factors are based on Well-to-Propeller CO_2eq-emission factor for gasoil of 3240 gram per litre (EN590 without blending of BioDiesel[17]). The GHG emission mentioned are applied for inland shipping in the GLEC framework as globally recognized methodology for harmonized calculation and reporting of the logistics GHG footprint across the multi-modal supply chain. Therefore, within the IW-NET project, the GLEC GHG emissions for inland shipping are considered, which is the sum of upstream (well-to-tank, WTT) and downstream emissions (tank-to-wake, TTW), and thus well-to-wake (WTW). The values in the table below can be used for simulation purposed to showcase impacts of IW-NET application scenarios.

[16] https://www.smartfreightcentre.org/pdf/GLEC-report-on-GHG-Emission-Factors-for-Inland-Waterways-Transport-SFC2018.pdf

[17] EN590 B7 (93% gasoline 7% FAME) is also used in the IWT sector (the Netherlands), which results in a lower emission intensity. However, at the time of this report there is insufficient data on the actual bunkering of this fuel blend. Also, the emission intensity data has been determined on the basis of relatively small number of inland vessels in Europe, therefore adjusting emission values for use of EN590 B7 will not necessarily provide an actual or better representation of IWT emission factors.

Table 17: Inland waterways transport emission intensity factors[18]

Vehicle characteristics and size	Loading Basis: Combined Load Factor & Empty Running	Fuel	Consumption factor (kg/t-km)	Consumption factor (l/t-km)	Emission intensity (g CO_2e/t-km)		
					WTT	TTW	WTW
Motor vessels <- 80 m (<- 1000 t)	55%	Diesel	0.0076	0.0091	5.2	24	30
Motor vessels 85–110 m (1000–2000 t)	52%	Diesel	0.0048	0.0058	3.3	15	19
Motor vessels 135 m (2000–3000 t)	50%	Diesel	0.0049	0.0059	3.4	16	19
Coupled convoys (163–185 m)	61%	Diesel	0.0044	0.0052	3.0	14	17
Pushed convoy – push boat + 2 barges	70%	Diesel	0.0044	0.0053	3.1	14	17
Pushed convoy – push boat + 4/5 barges	70%	Diesel	0.0025	0.0030	1.7	8.0	10
Pushed convoy – push boat + 6 barges	70%	Diesel	0.0019	0.0023	1.3	6.1	7.4
Tanker vessels	65%	Diesel	0.0055	0.0066	3.8	18	21
Container vessels 110 m	75%	Diesel	0.0065	0.0079	4.5	21	26
Container vessels 135 m	75%	Diesel	0.0051	0.0061	3.5	16	20
Container vessels – Coupled convoys	68%	Diesel	0.0051	0.0061	3.5	16	20

4.2.2 Inland Waterway Transport air pollutant emission data

For air pollutant emission a reliable source of information is STREAM (Study on Transport Emissions of All Modes), which was updated in 2020. It provides emission factors per tonne-kilometre for a wide range of vehicles and vessels.

As mentioned earlier, for the simulation model the life-cycle emissions for Nitrogen Oxides (NOx) and Particulate Matter (PM) are considered, which is the sum of upstream (well-to-tank) and downstream emission (tank-to-wake), and thus well-to-wake.

The Annex III of the document contains tables with value references introduced including WTW emissions for inland vessels loaded with bulk/packaged goods and with containers.

4.3 Output data – KPIs

The KPIs (Key Performance Indicator) are the mechanism used to measure the impact of IWT on the global distribution network. Within the IW-NET project, indicators will be measured in three categories:

- **Economic costs**: refers to the financial cost of operations in the IW network. It is related with the investment in products and auxiliary elements such as transport or handling and storage elements.
- **Operational costs:** are the expenses related to the operation of a business, or to the operation of a device, component, or facility. They are the cost of resources used by an organization just to maintain its existence. For a commercial enterprise, operating costs fall into two categories:
    - fixed costs, which remain the same whether the operation is closed or running at 100% capacity.

[18] GLEC Framework, Smart Freight Center (https://www.feport.eu/images/downloads/glec-framework-20.pdf)

    - variable costs, which may increase depending on whether more production is done, and how it is done.
- **Environmental costs**: costs connected with the actual or potential deterioration of natural assets due to economic activities.

The following table presents a list of the main indicators which can be calculated from the models developed.

Table 18: Examples of KPI

Economic KPI	**Definition or link**
Transport cost	Transport cost calculated from movement data such as fuel consumption, staff costs or other items. Description available in chapter Ch 4.1.
Handling cost	Cost of cargo handling in loading and unloading operations usually in a port.
Waiting cost	Costs associated with the waiting times of a vessel either in port or at a lock.
Spot demand cost	Costs associated with the management of **one-off** transport orders.
Regular demand cost	Costs associated with the management of **regular** (periodical) transport orders.
Total cost	Total cost that includes the concepts associated with transport, handling, and waiting times at route.
Total profit	Total profit obtained in the transport operation through the difference between income and costs.
Operational KPI	**Definition or link**
Total transit time	Total travelling time from origin to destination.
On Time Delivery	Number of orders/containers that arrives on time.
Shortest route distance	Shortest route distance for a transport vehicle (truck, vessel...).
Actual route distance	Final route followed by a vehicle due to possible restrictions with respect to the optimal.
Total average speed	Average vehicle speed between all travelled edges.
Cost of transportation (Activity Based Cost principles)	Cost of transportation assigning indirect costs to direct costs.
Total distance travelled empty and loaded	For transport vehicles, total distance travelled with and without containers on board.
Labour utilization	Total wages per unit of time divided by the flow rate per unit of time.
Resource utilization KPI	**Definition or link**
Number of vehicles in use	Number of vehicles in use

Number of operating services	Total number of operating services
Operating hours of services	How many hours the service has been operating
Operating hours for repositioning	Total number of hours dedicated to repositioning
Duration of holding vehicles at nodes	Time spending by the vehicles on hold at the nodes
Ratio of number of vehicles used – vs fleet size	Relationship between the number of vehicles used and the size of the fleet
Vessel capacity utilization	Percentage of use of the vessels compared to the maximum capacity
Berthing capacity utilization	Percentage of use of the berthing compared to the maximum capacity
Ratio of number of direct services – vs total number of services	Relationship between the number of direct services vs. total number of services
Ratio of transhipped containers – vs total number of containers	Relationship between the transhipped containers – vs total number of containers
Quality of service KPI	**Definition or link**
Number of contracts served	Number of contracts successfully completed.
Waiting time in intermodal terminals	Waiting time for vehicles or containers at intermodal terminals.
Waiting time at other terminals (no transhipment)	Waiting time for vehicles or containers at other terminals (no transhipment).
Average lead time	Average time from container availability at origin to container arrival at destination.
Time on intermodal services	Time a container spends using an intermodal service.
Handling in intermodal terminals	Total container handling time (loading, unloading, inspection...) in intermodal terminals.
Waiting time at borders	Waiting time for containers or vehicles at borders due to customs, inspections or queues.
Containers transported by barge vs total transported	Percentage of containers that are transported by barge with respect to the total (also defined as barge modal split).
Empty containers transported	Number of empty containers transported by a vehicle.
Environmental KPI	**Definition or link**
Reduced CO2 emissions per fleet	CO_2 emissions savings (total GHG emissions difference between two scenarios)
Reduced fuel, energy	Energy (fuel, etc.) savings
Use of returnable containers	Number of returnable containers employed in a shipment
Emission intensity	Intensity of greenhouse gases emissions (kg CO2/km...)

This chapter describes the different sources of information available to quantify the parameters used in the different simulation and optimisation models. It also identifies the ratios for evaluating the main economic and environmental operational indicators. The following chapter describes a methodology for applying the data and models to different inland waterway transport scenarios.

5 Library of Models and Methods

This chapter describes the main functionalities that can be achieved with the library of models developed for the analysis of river transport. The following are different instances of analysis that can be carried out using the developed model library.

5.1 Dynamic simulation model

The developed dynamic simulation model allows evaluation of the temporal behaviour of the different elements of the water transport system. It quantifies the numerical impact of certain decisions and innovations related to freight transport.

Some of the questions that can be answered using this library of models may include the following:

1. What is the CO_2 impact of transporting a specific number of containers from Romania to Austria?
2. What difference does it make if cargo is transported by road or by vessel?
3. How can the water level influence transport times and fuel consumption?
4. How can congestion at some points on the river affect the delay in the delivery of containers?
5. What is the best type of vessel a shipper can use to move a larger number of containers every month between river ports?

In order to evaluate all scenarios, the model presents an intuitive interface where the transport flow of both vessels and trucks is visualised on the left side and the main indicators and diagrams to evaluate the dynamic behaviour of the model are shown on the right side.

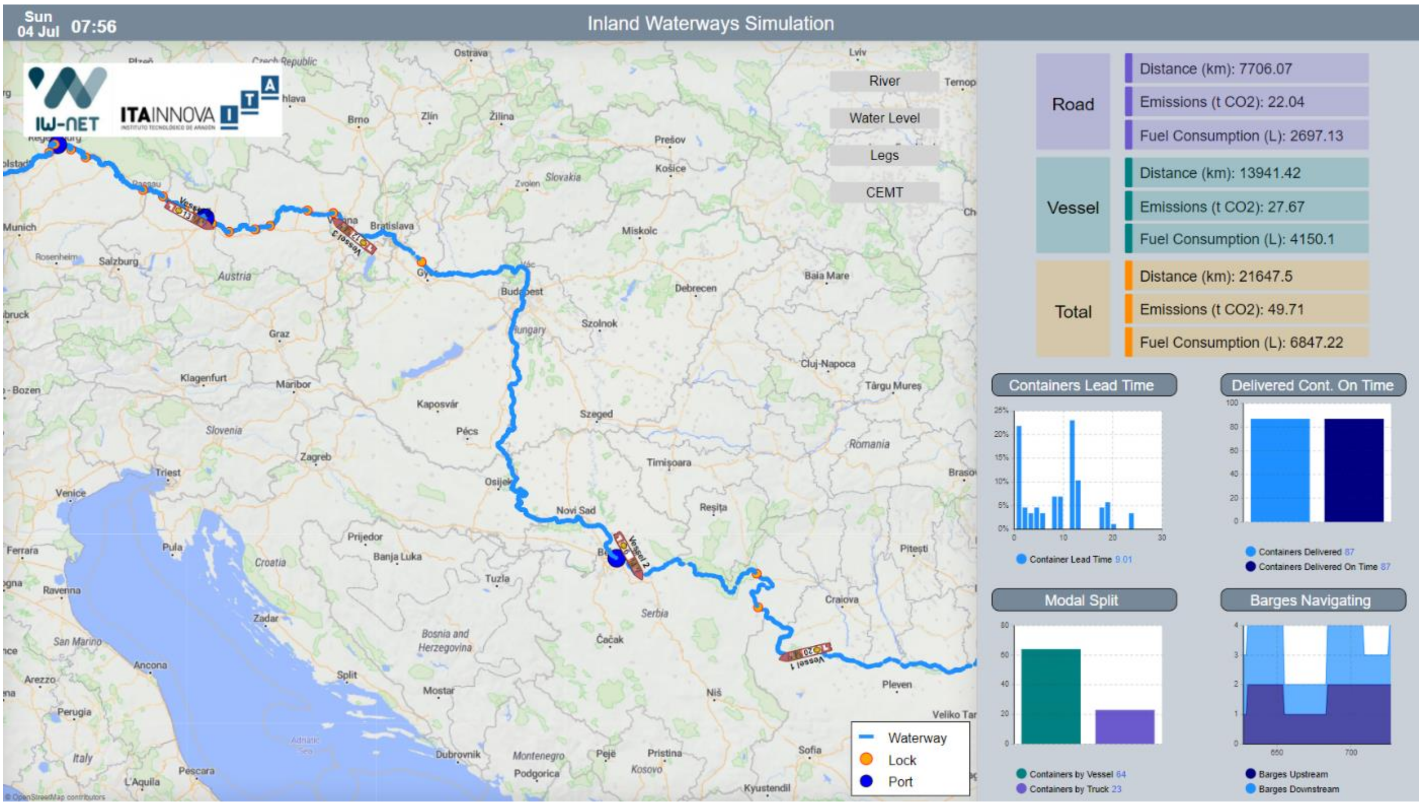

Figure 15: Dynamic simulation model image

The user can configure the use of simulation models through tables in Excel files. The following table shows the sequence of steps the user has to follow in order to correctly configure the simulation model. After the configuration of the model, numerical economic, operational and environmental results can be obtained for later comparison with other scenario configurations.

Different elements can be configured, such as the network of nodes that compose the river, the river ports, the locks, the types of vessels which can be used for the transport of freight, the orders that configure the demand and the containers that are associated with these orders. Once this has been configured, the user chooses between several transport options such as road or vessel transport. Finally, after launching the simulation, the user obtains the results through an Excel file.

Table 19: Simulation user steps

SIMULATION USER STEPS	
Step	**Description**
Step 1	Define the river network. Network is defined by a set of consecutives nodes characterised by their unique id, geolocation (lat, lon), type (water, lock, port), river km, country and CEMT class.
Step 2	Define the ports. Ports are characterised by their unique id, name, geolocation (lat, lon) and country.
Step 3	Define the locks. Locks are characterised by their unique id, name, geolocation (lat, lon), country, capacity and dimensions.
Step 4	Define the vessel services operating in the river network. Services are characterised by an array of consecutives visited port id's, an array of arrival times, an array of departure times and the id of the vessel that execute the service.
Step 5	Define the vessel fleet. Vessels are characterised by their unique id, name, capacity and speed.
Step 6	Define the demand (orders). Orders are characterised by their unique id, origin port id, destination port id, number of containers, booking time, availability time at origin and due time in destination.
Step 7	Define the demand (containers). Containers are characterised by their unique id and properties of the order it belongs to (origin port id, destination port id, booking time, availability time at origin, and due time in destination).
Step 8	Configure the simulation scenario (road transport, inland waterway transport).
Step 9	Run the simulation, visualize the movements, and download the results.
Step 10	Analyse results and compare simulation scenarios.

5.2 Revenue Management and dynamic simulation model

5.2.1 The case-study, physical and time-space networks

In order to define the mathematical formulation, a time-space network is considered that captures the time-dependency and repetitiveness of the demand and schedule (services and resource utilization). In the SSND-RM model, presented in Chapter 3, the network including the transportation plan and schedule is represented as nodes duplicated in time, over the **schedule length**. Movements in the time-space network are performed by services traveling on physical paths between two consecutive stops. Such service movements are called **legs** in this representation and they define the moving arcs in the time-space network (as displayed in Figure 17).

The **case-study** for the IW-NET project is Danube River as illustrated in Figure 16.

Figure 16: Danube River IW-NET project

5.2.2 Representation and assumptions

- The optimisation problem is formulated on a ***time-space network*** over a discretized time horizon; the nodes of the ***time-space network*** are obtained by duplicating the representation of the physical terminals at all time instants.
- A set of already selected (open) **services**, each with a given schedule, route and capacity, provides the transportation among the nodes.
- It is assumed that **services** have already been scheduled at the *tactical* planning level and are not to be rescheduled at the operational level.
- The capacities of scheduled services are fixed since vehicles are already assigned to services and no extra-vehicles are considered to be available upon request.
- Each *service leg* has a residual capacity associated to it, updated regularly by subtracting the already booked capacity (corresponding to the already accepted routed demands).

A **time-space network**, corresponding to the physical network and the schedule length on which planning takes place, can be represented as in Figure 17 (in this example, there are 4 ports and the schedule length is of 14 time periods):

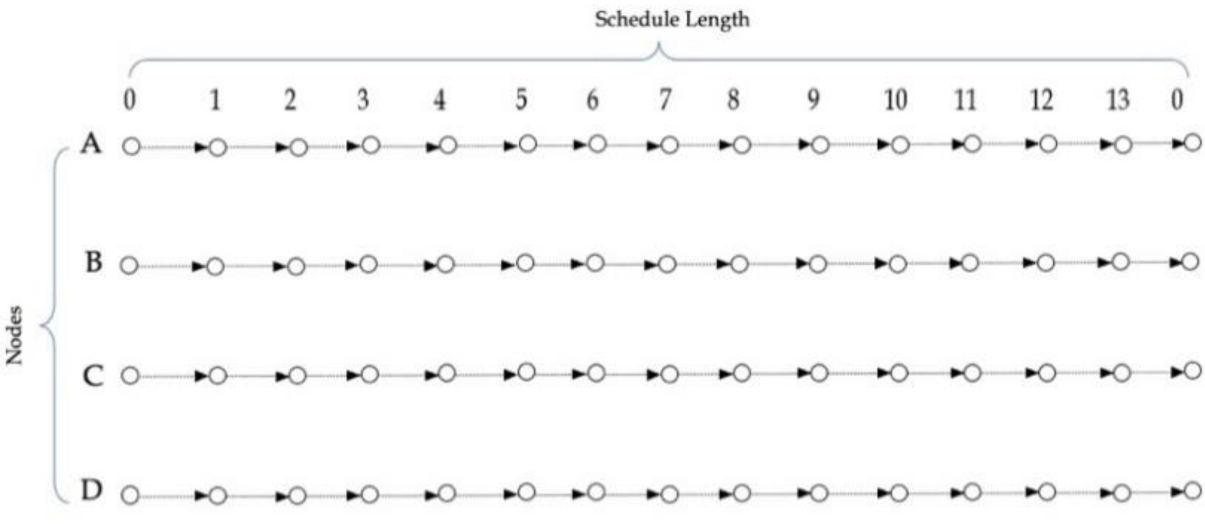

Figure 17: An example of time-space network

5.2.3 Example of the services on the time-space network

A set of potential **services** can be represented as shown in Figure 18.

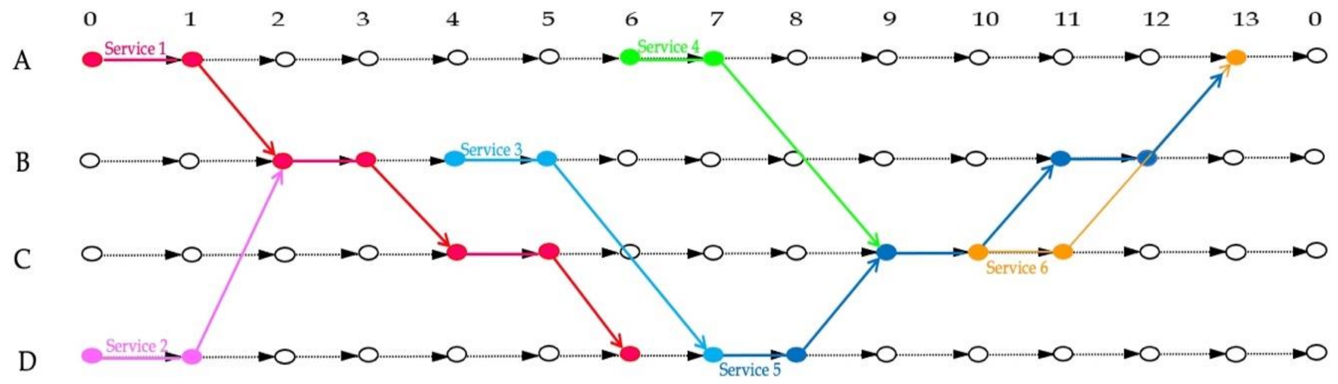

Figure 18: A set of potential services

The data set corresponding to these **services** is listed in Table 20.

Table 20: The data required to characterize multiple services on the time-space network

Service ID	Origin	Destination	Set of legs	Path of each leg	Travel time for each leg (in TUs)	Initial loading time at origin	Final unloading time at destination	Departure time from origin	Arrival time at destination	Stopping time at terminal i (Unloading)	Departure time from terminal i (Loading)	Capacity of the service (in TEUs)	Vessel type	Total duration of the service	Ordered set of consecutive stops
1	A	D	a1 a2 a3	a1 : A-B a2 : B-C a3 : C-D	a1 : 1 a2 : 1 a3 : 1	0	6	1	6	B, 2 C, 4	B, 3 C, 5	35	Large	6	[B, C]
2	D	B	a1	a1 : D-B	a1 : 1	0	2	1	2	-	-	25	Medium	2	-
3	B	D	a1	a1 : B-D	a1 : 2	4	7	5	7	-	-	10	Small	4	-
4	A	C	a1	a1 : A-C	a1 : 2	6	9	7	9	-	-	20	Medium	4	-
5	D	A	a1 a2 a3	a1 : D-C a2 : C-B a3 : B-A	a1 : 1 a2 : 1 a3 : 1	7	13	8	13	C, 9 B,11	C, 10 B,12	30	Large	6	C
6	C	A	a1	a1 : C-A	a1 : 2	10	13	11	13	-	-	15	Small	3	-

The dynamic simulation and the revenue management optimisation modules can work in coordination. A standard information data structure to connect both models with the same database has been defined (see Chapter 2). With the available information the optimisation system can create different instances with different complexity. The complexity is defined by the width of the time windows to be fulfilled in the product delivery. The simulation tool permits the comparison of different scenarios. In this case, two extreme scenarios are evaluated, all cargo by vessel and all cargo by truck. This is then compared with an optimised solution each to assess the relative benefits. A diagram of the connection between the models and the data structure is shown in Figure 19.

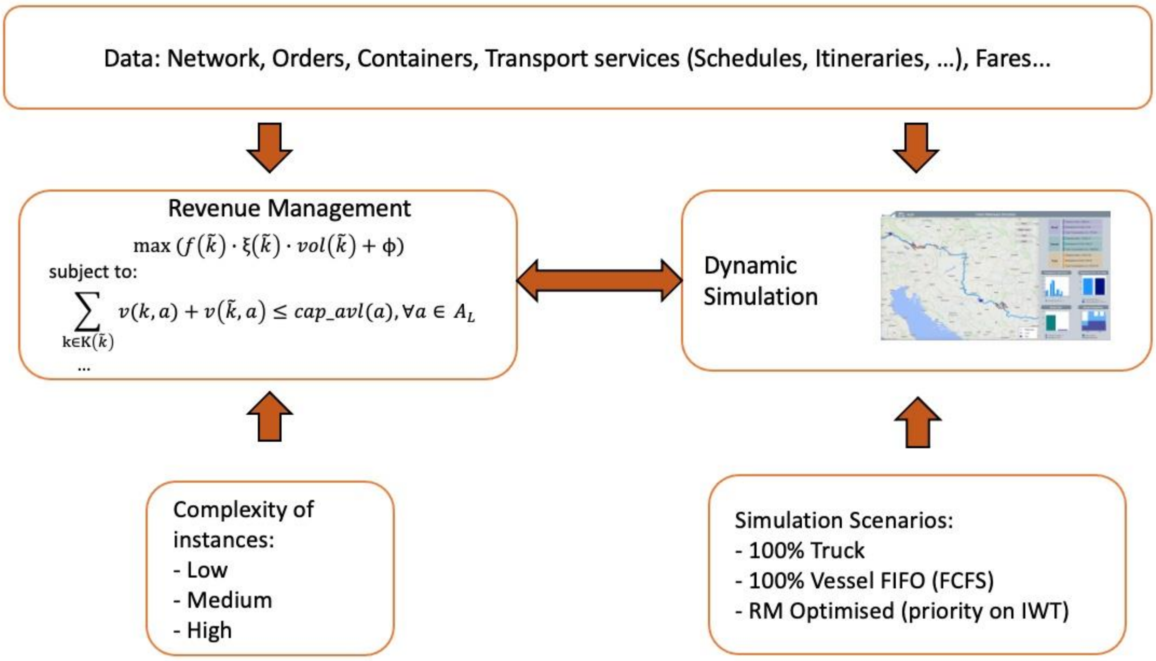

Figure 19: Connection between the models and the data structure

The analysis process begins with the data of the scenario being assessed. The data is processed by both the simulation model and the optimisation system. Initially the simulation model evaluates extreme scenarios, which are used as a reference to evaluate the impact of the optimisation system. In general, a scenario is evaluated with 100% of freight allocated to road transport and on the other hand 100% of freight allocated to inland waterway transport. The Revenue Management optimisation system will perform a better assignment than each of these extreme scenarios individually. The operational solution is then calculated by the RM optimisation system and registered in the information system. The simulation afterwards evaluates the optimal operational solution scenario and records the results in the system database. Finally, the main indicators are calculated to assess the impact of the optimal solution compared to the extreme scenarios. An example of this sequence is represented in the diagram in Figure 20. The full and extended version of the diagrams can be found in annex IV of this document.

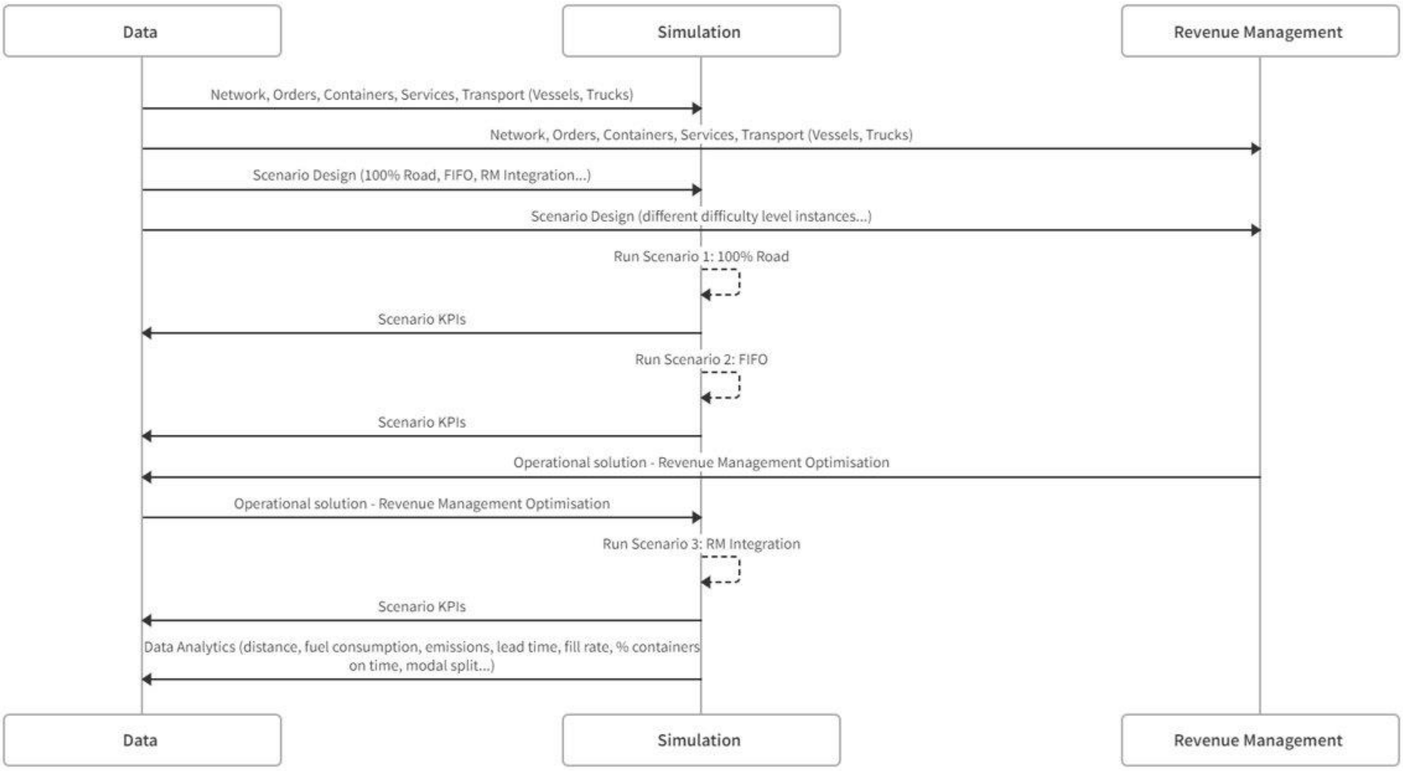

Figure 20: Message sequence diagram

In section 6.1 an example of the application of this methodology can be found for the analysis of inland waterway freight transport along the Danube River.

5.3 Dynamic simulation and traffic routing

The IW-NET traffic routing component supports vessel routing on complex networks. This component has been designed to consider various constraints and objectives in a flexible way. The routing includes CEMT classes of waterway sections and speed limitations. The routing algorithm can be used to find the shortest route between arbitrary nodes and the solution contains all available information from the underlying network.

The library can be easily included and used in the Anylogic simulation platform. Users of the routing library component, like in *IW-NET AS2 Collaborative IWT management*, must provide their waterway network data as described in section **Fehler! Verweisquelle konnte nicht gefunden werden.** and section 4.1.1 as an Excel file with the populated rows describing the waterway network.

Although Anylogic already supports the display and editing of GIS (Geographic Information Systems) maps within a model, manually capturing a larger GIS network is time consuming and tedious. The IW-NET traffic routing library therefore offers an easy-to-use alternative based on tabular data that can also be obtained from existing data sources, such as OpenStreetMap. The application of the library function is shown in the reference example for Weser Application Scenario in section 6.2.

6 Reference examples for Application Scenarios

This chapter describes some applications of these models for the evaluation of different project innovations in selected scenarios.

6.1 Reference example for Danube Application Scenario

The objective of the model in this application scenario is to analyse different container distribution strategies along the Danube River corridor, including navigable inland waterways and road-based alternatives. Road transport strategy, vessel transport FIFO[19] strategy and revenue management optimisation strategy are considered.

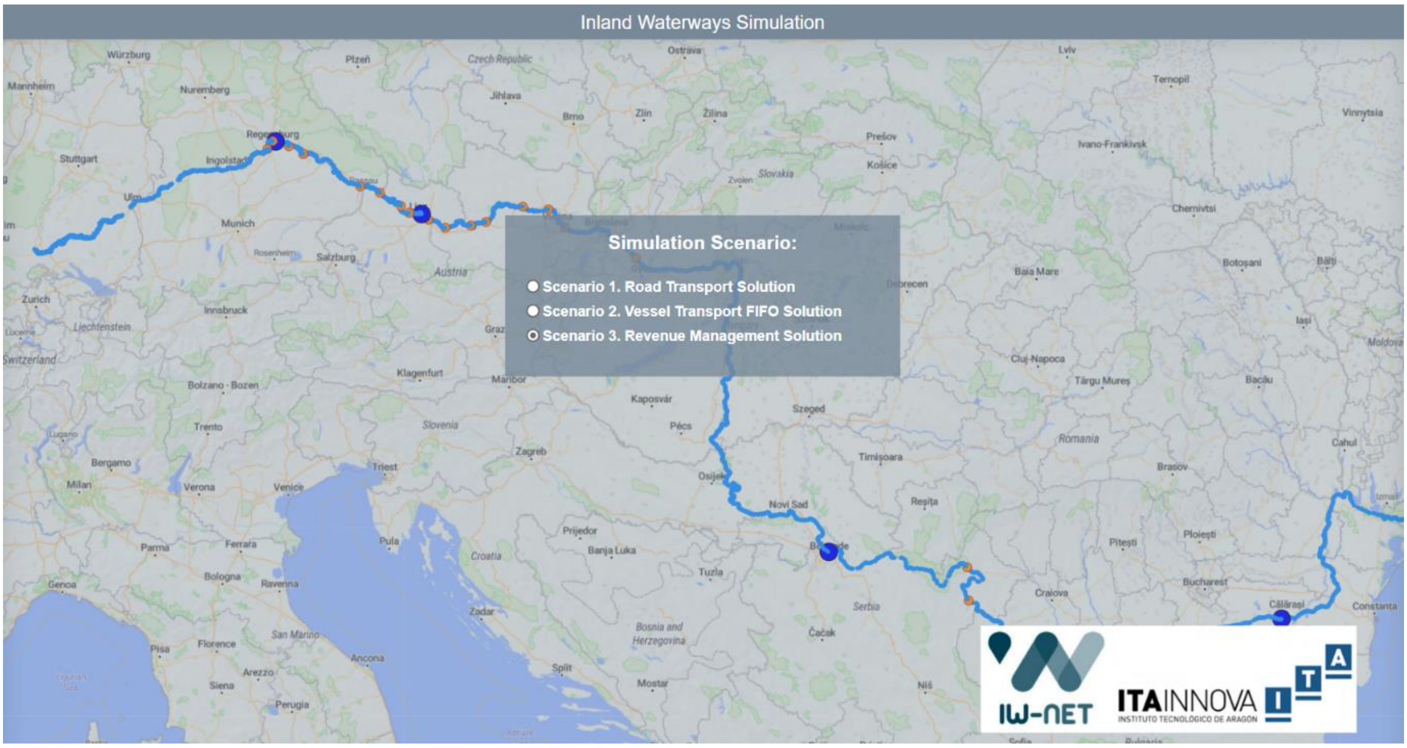

Figure 21: Simulation scenario selection screen

First, it is necessary to define the river network. In this case, 4 ports and 18 locks have been defined along the Danube. The distance between the considered ports (in km) is shown in Table 21.

Table 21: Distance matrix between Danube ports considered

Port Terminal	0. Regensburg (DE)	1. Linz (AT)	2. Belgrade (RS)	3. Silistra (BG)
0. Regensburg (DE)	0	242	1200	1992
1. Linz (AT)	242	0	959	1750
2. Belgrade (RS)	1200	959	0	791
3. Silistra (BG)	1992	1750	791	0

[19] FIFO (First In First Out) is a container handling strategy in which the first container that arrives at a queue (i.e., port terminal) is the first that is served and leaves the queue.

Secondly, a total demand of about 300 containers over 2 months has been considered. A matrix of origin and destination of these containers is shown in Table 22.

Table 22: Demand matrix between Danube ports considered

Port Terminal	0. Regensburg (DE)	1. Linz (AT)	2. Belgrade (RS)	3. Silistra (BG)
0. Regensburg (DE)	0	33	24	26
1. Linz (AT)	26	0	25	40
2. Belgrade (RS)	7	23	0	30
3. Silistra (BG)	27	17	23	0

With respect to transport services, 4 vessel services that visit all the ports considered have been defined (2 upstream services and 2 downstream services). Road transport services (trucks) are called on demand.

Once the network, demand, and transport services (vessels, trucks) are defined, the strategy chosen by the user is simulated. During the runtime, the user can visualize and validate the movements as well as different KPIs dynamically (delivered containers, lead time, distance, fuel consumption, emissions, etc.).

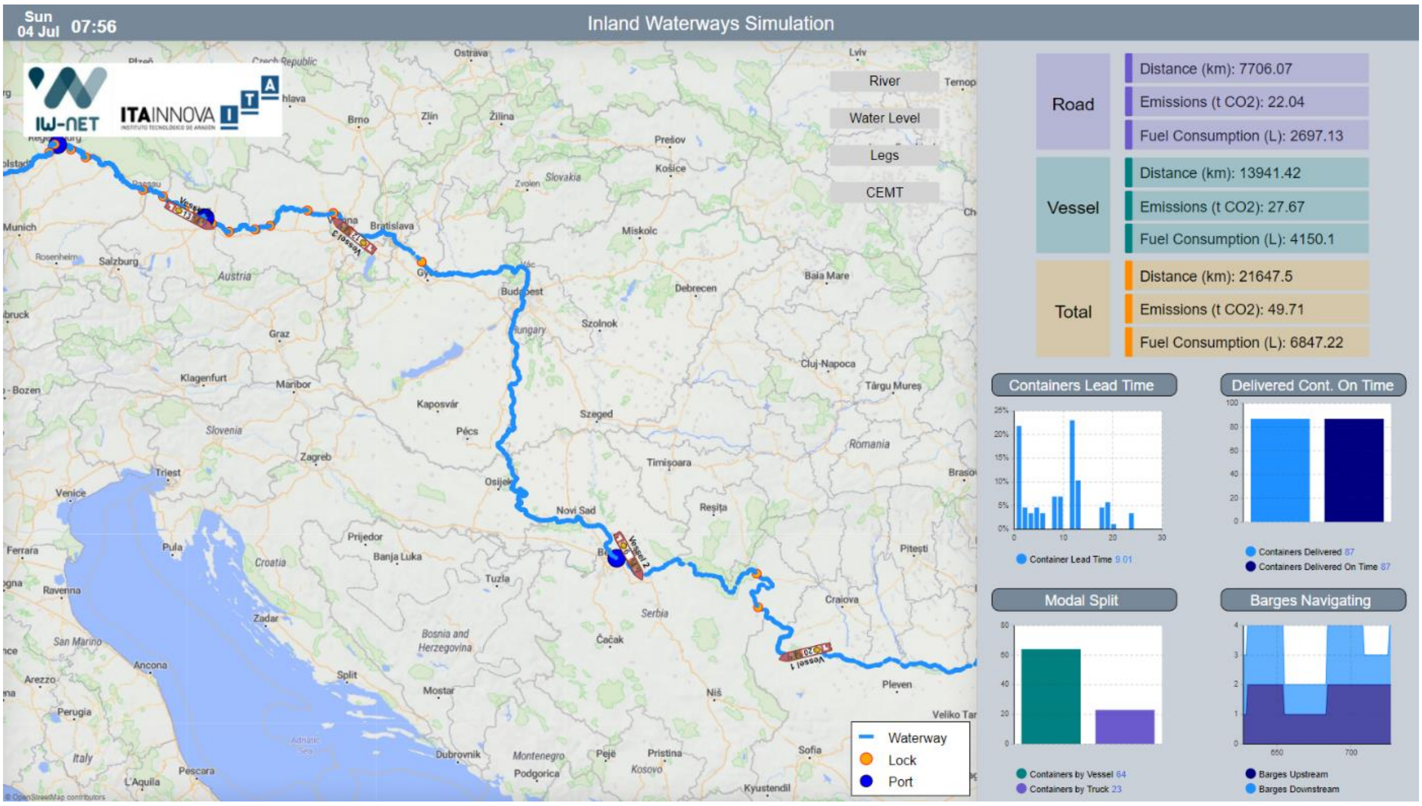

Figure 22: Simulation runtime screen

When the simulation is completed, the user can explore the scenario results within the tool or export them to a file for external analysis, as shown in Figure 23 and Figure 24 respectively.

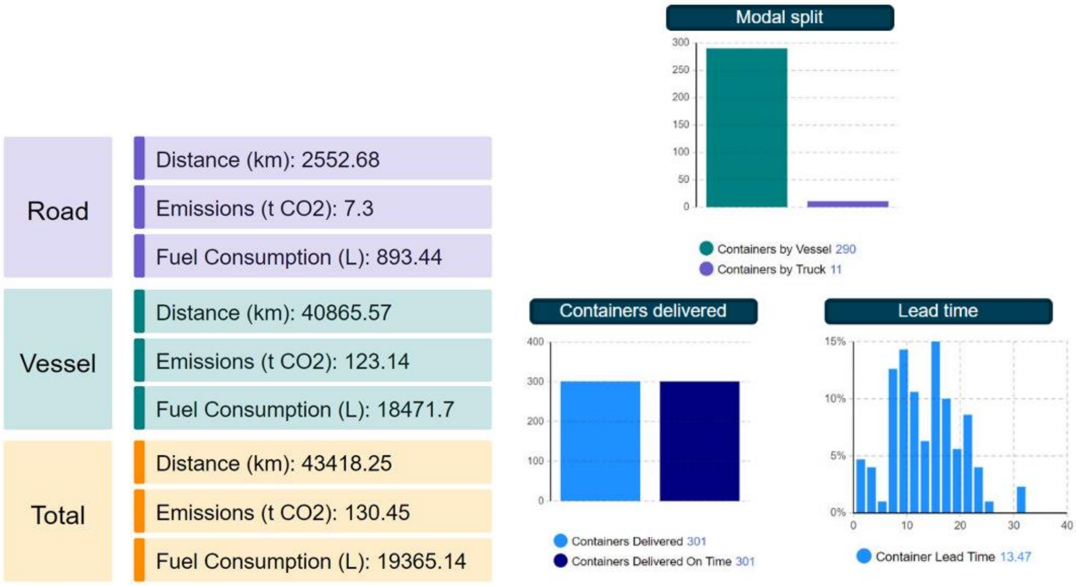

Figure 23: Example of simulation indicators

Scenario	Containers	%Containers On Time	Average Lead Time (days)	Modal Split (%Vessel)	Vessel Fill Rate (%)	Road Distance (km)	Vessel Distance (km)	Total Distance (km)	Road Fuel consumption (L)	Vessel Fuel Consumption (L)	Total Fuel Consumption (L)	Road CO2 Emissions (tCO2)	Vessel CO2 Emissions (tCO2)	Total CO2 Emissions (tCO2)
RM Solution	301	100	13.47	96.34	35.21	2552.68	40865.57	43418.25	893.44	18471.7	19365.14	7.3	123.14	130.45

Figure 24: Example of simulation exported indicators

Finally, after running different scenarios and storing the results, these can be compared to find which scenario is the best in terms of cost, emissions, % container delivered on time, etc., as shown in Table 23.

Table 23: Summary key indicators for scenarios comparison

Scenario	Distance (km x1000)	Fuel Consumption (L x1000)	Emissions (t CO2)	% Containers on time	Average Lead Time (days)	Modal Split (% barge)
S1. Road	292	102	833	100	2	0
S2. IW (FIFO)	37	19	124	96	11	100
S3. IW (RM Optim.)	44	20	131	100	13	96

One of the main conclusions obtained from this application scenario, through the use of simulation, is that it is advantageous to apply revenue management techniques to maximize the number of containers delivered on time and significantly reduce CO_2 emissions compared to road transport.

6.2 Reference example for Weser Application Scenario

The Weser River represents the IW hinterland link for the seaports of Bremen and Bremerhaven. Here the key challenge for logistics operators is that infrastructure conditions create bottlenecks that constrain profitable IWT services (especially for liner services). The reasons for such limitations are the very long total transit times combined with the strong competition with road transportation. Moreover, encounter restrictions on a large number of fairway sections, especially for large vessels and unpredictable lock transit times lead to a lack of predictability and reliability. The simulation aims at creating insights on the current traffic flow conditions and bottleneck impacts. The mapping of current traffic flow conditions on the Weser River in a simulation model allows to evaluate the effects of traffic management strategies on measurable and comparable KPIs, like transit times and waiting times. In addition, the results could be used for policy recommendations. For a complete description of AS2, please refer to IW-NET D4.3.

Based on the simulation modelling capabilities described in this deliverable, a traffic flow simulation model has been developed in task 2.3 of the IW-NET Project. As mentioned above, the main objective is to provide requirements and possible solutions for traffic flow management that can be adapted to different operational settings and be used to evaluate specific problems and solutions for traffic flow management on inland waterways. Infrastructure bottlenecks such as locks, bridges with limited clearance and narrow fairways lead to inefficient traffic flows that limit the competitiveness of IWT. In the scope of IW-NET, the application of simulation models and experiments will especially refer to the conditions analysed within AS2 but will be made adaptable to other comparable corridors. Since the development and analysis of the AS2 model is still ongoing and results will not be published until early 2023, the following section primarily provides initial insides into the model. This is done here merely from the user's perspective, as the details of implementation or programming are beyond the scope of this deliverable.

The simulation development process includes several phases from problem description to experimental stage as shown in Figure 25.

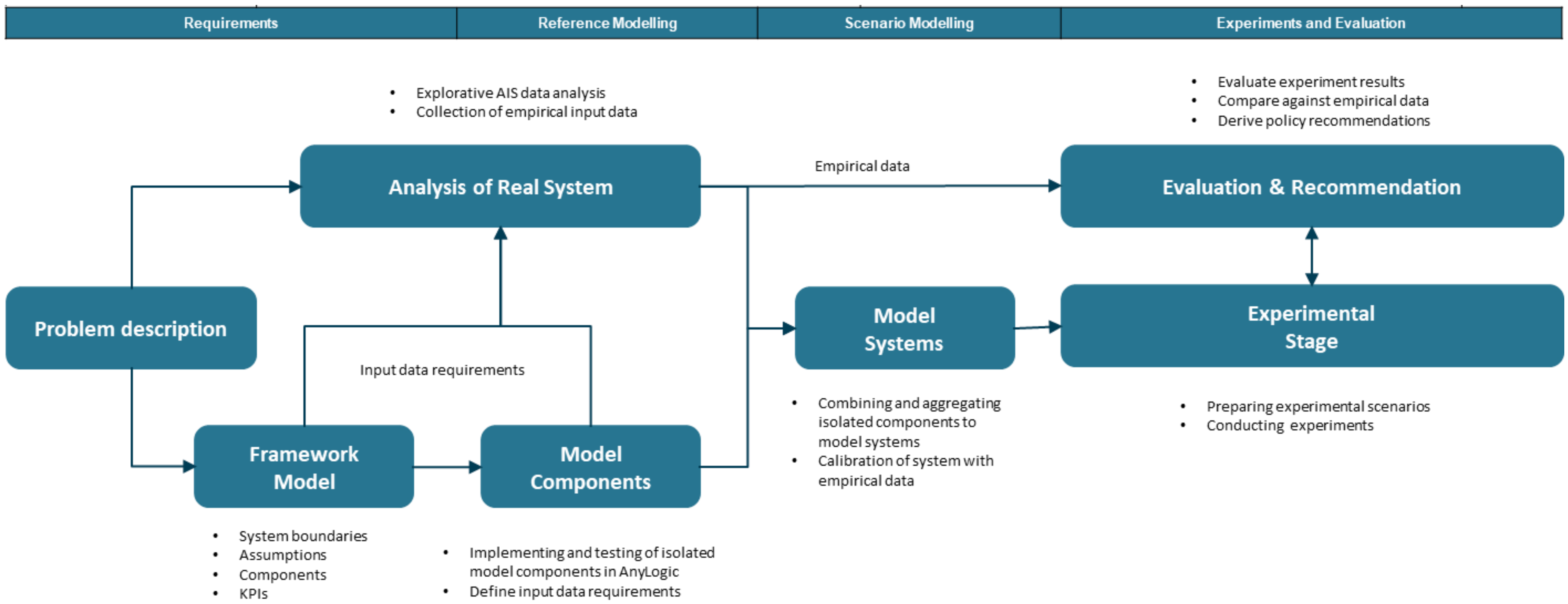

Figure 25: Simulation Development Process

The present deliverable focuses on the simulation framework and model components and this section shows the combination and aggregation of the simulation elements as the main objective of the system modelling phase. The calibration and initial setup with real/empirical data is an essential step toward the final simulation model. This step focuses on the conceptual and technical interoperability of the elements.

For this reason, the following figures present some interesting views on the simulation model, especially how the various simulation elements are integrated in conjunction with a dynamic and interactive graphical user interface for simulation users, for experimenting and analysing different scenarios.

The main view in Figure 26 shows a GIS map with the Weser River and some of its tributaries. The waterway network data, the locks and restricted waterway sections were included via Excel sheets.

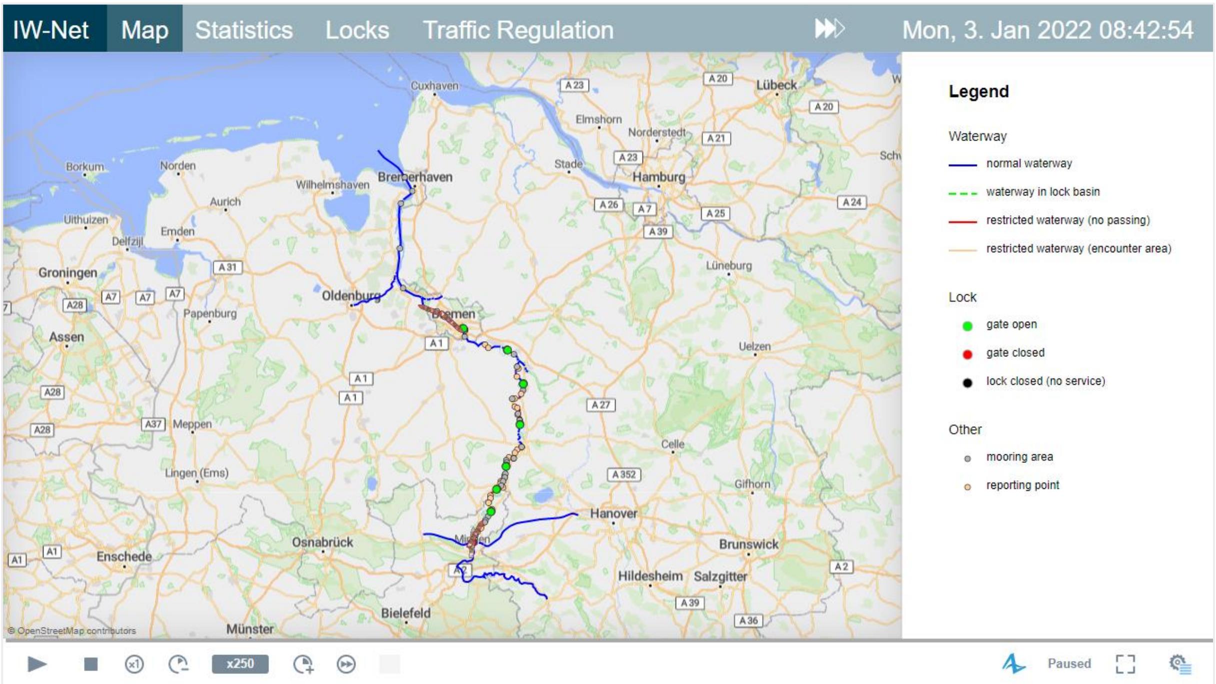

Figure 26: AS2 Simulation model main view

When zooming in, the operations at a lock can be observed in detail, including waiting and lockage through the respective lock chamber as shown in Figure 27.

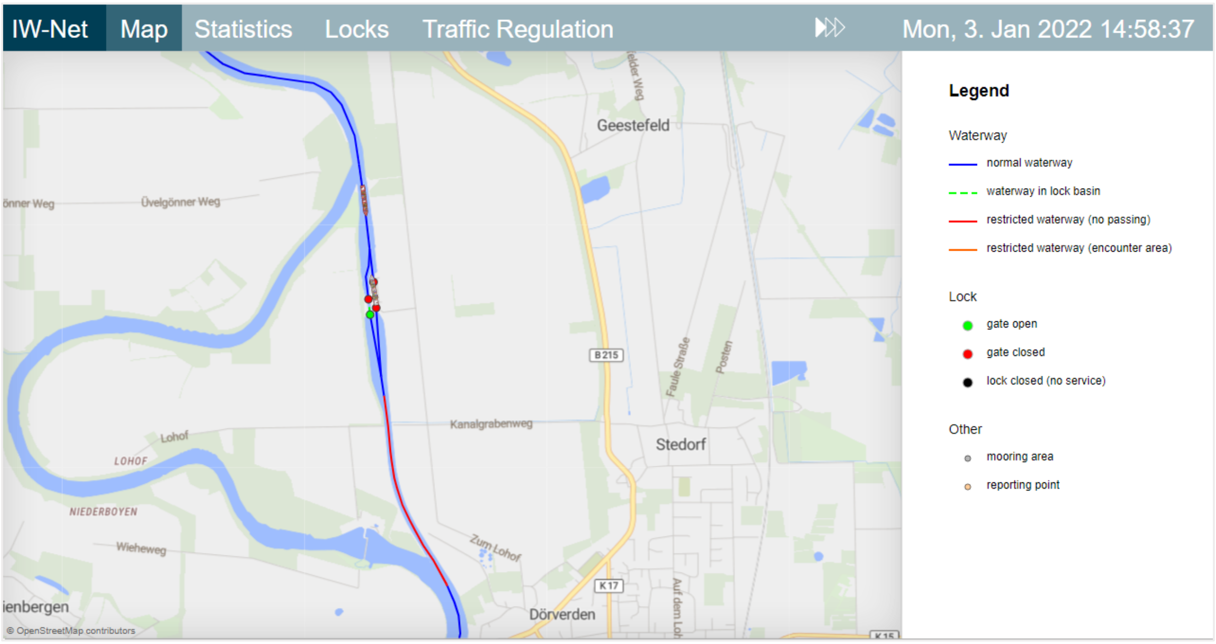

Figure 27: AS2 Simulation model GIS map with vessel during lockage operations

While the simulation is running, users can inspect and validate the vessel movements and check various KPIs after selecting the appropriate navigation element at the top. Figure 28 and Figure 29 show examples of fleet mixture, transit times and insight in lock operations with the related KPIs for a selected lock.

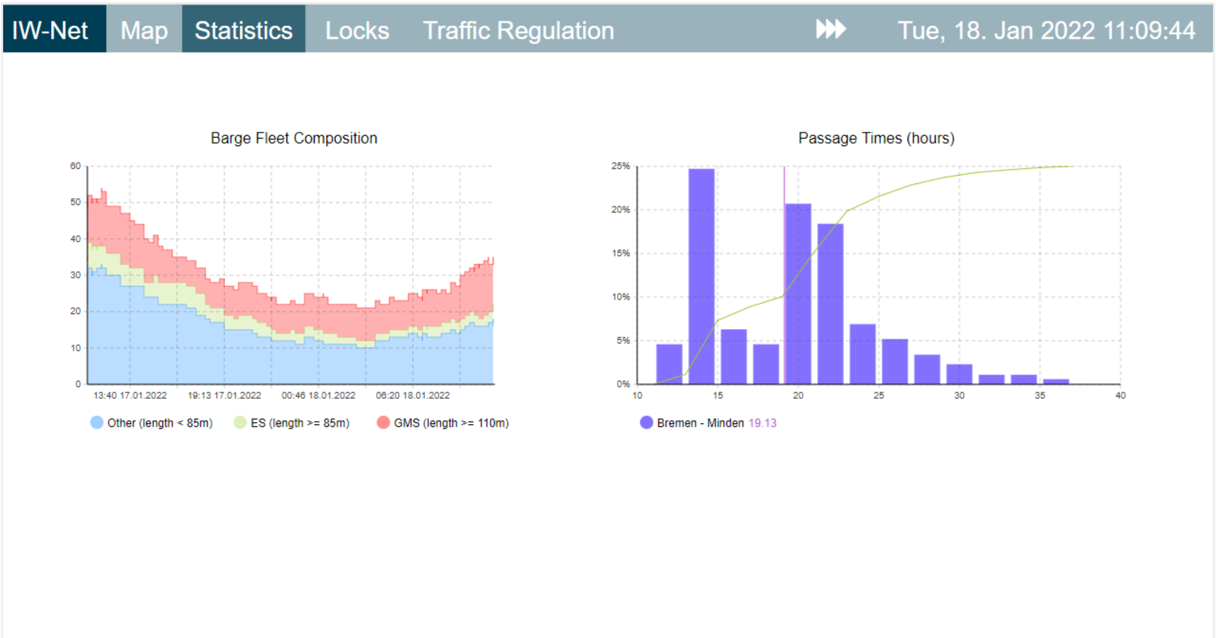

Figure 28: AS2 Simulation model statistics

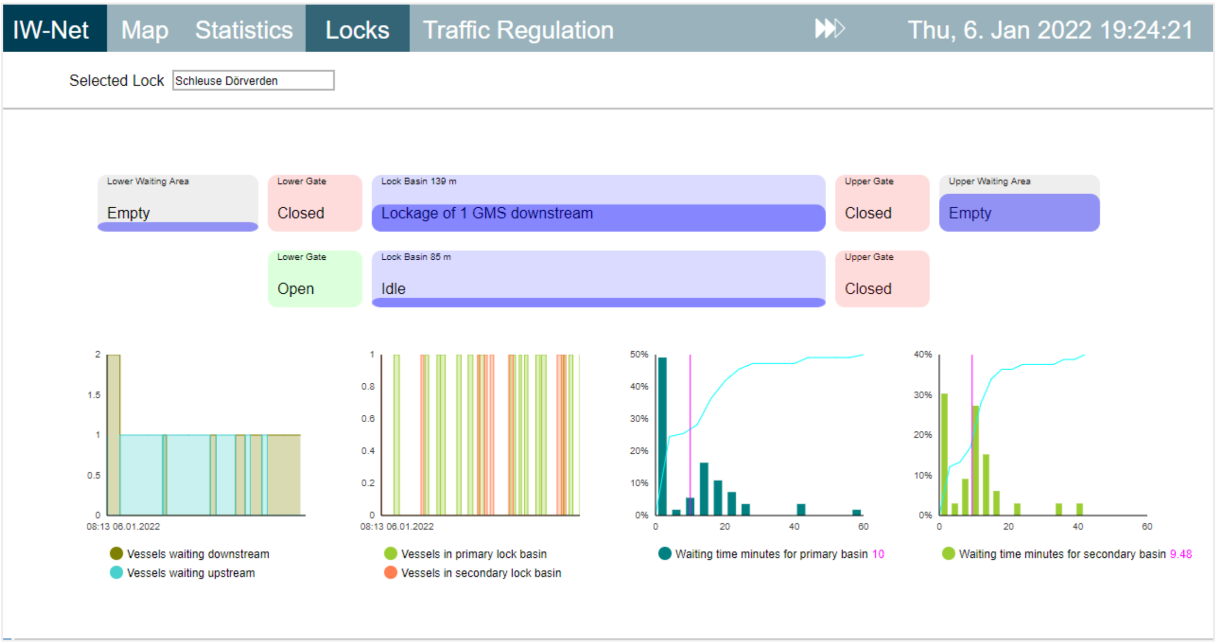

Figure 29: AS2 Simulation model lock statistics view

7 Conclusions

The movement of products and transport within the IWT in synchromodal conditions has a complex dynamic behaviour. Various simulation and optimisation techniques have been and continue to be engaged to represent these dynamic effects. The main advantages of these techniques are transparency, visualization, interaction and capability for creating deeper knowledge and understanding of the relevant processes.

In the document it is described how simulation and optimisation modelling technologies can help to create conceptual scenarios to evaluate the impact of some of the innovations developed in the IW-NET project to improve the management of the inland waterway transport process.

A group of elements to represent the behaviour of the agents that intervene in a waterway transport system has been defined. Both, the information necessary for their configuration and the behaviour that characterises them have been defined. These elements constitute a library of objects that enables the creation and evaluation of virtual waterway transport scenarios.

Revenue Management based optimisation methods are adapted, implemented and used in these scenarios in order to highlight potential advantages of these innovative techniques: high quality-of-service for shippers and profit maximization for carriers, via optimal resource utilization and intelligent planning of intermodal transport operations through the extensive and effective use of inland waterway networks. This approach provides flexible management of transport bookings and promotes the development of synchromodality. The mixed approach of combining optimisation and simulation models and methods enables the evaluation of the fine-tuned details of the optimisation solution and comparison with other transport alternatives.

To ensure that the models represent accurate and representative transport scenarios, it is necessary that they are supported by realistic business data. Different data sources have been identified to characterise the parameters of simulation and optimisation models with realistic values. In addition, methodologies for accurate costing and precise assessment of the environmental effects of river transport have been identified. In addition to operational and economic indicators, dynamic agent models are a useful instrument to benchmark the environmental impact of different strategies.

The methodology and models for scenario assessment have now been applied in cases of Danube River transport and Weser River traffic management. Additional scenarios are to be implemented in the near future.

8 Outlook

The research team will continue its investigations to validate and improve the models by evaluating them in different scenarios. The next steps will be to work together with the other partners in the project to apply the different simulation and optimisation models for the evaluation of different scenario applications.

The dynamic simulation models will be applied to urban river transport scenarios. They will be used to assess the performance of commercial transport flows on the Belgian inland waterway transport network.

Further development of the optimisation approach will focus on advanced testing and adaptation of RM policies. First, a joint validation of the tactical and operational RM optimisation models through simulation will be performed, based on new case studies (inspired from AS1a and AS1b). Second, new versions of these models to account for water level variations (based on AS1b) will be researched and analyzed.

For the analysis of the AS2 scenario, anonymised AIS data provided by the German Federal Waterway and Shipping Administration (WSV) has been used. A more detailed analysis of the traffic situation at the restricted waterway sections will be carried out next in order to calibrate the traffic regulation components of the simulation model. The final evaluation and testing of the simulation solution will be carried out within the scope of Application Scenario 2. The respective results will be presented in IW-NET D4.3, which is due in project month 32 (February 2023).

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Glossary

Concept	Description
Vessels	
Vessels ID	Vessel identifier.
Vessel name	Type/name of the vessel (e.g., Zulu, …).
Technical characteristics of the vessel	Size (small, medium, large), speed of the vessels (slow or fast), the dimensions of the vessel, type of engine/fuel...
TEU capacity	How many containers in equivalent TEUs unit can be loaded on the vessel (capacity of the vessel per type S, M, L) and dependence on the water level.
Fleet information	Additional fleet information.
Vessel information	Additional vessel information.
Schedule	Ports and departure/arrival times planned for a vessel.
Schedule length	The schedule is built for a given schedule length (e.g., a week); it is then operated repeatedly for the duration of the season.
Costs	
Unit transportation cost	Variable cost, additional transportation cost per TEU.
Penalty cost for not used vessels	Penalty cost for owning but not using the vessels in the service plan.
Fixed cost for operating the vessels	Fixed cost of operating the vessel (irrespective of the number of TEUs transported).
Physical network information	
Topology of the network	A corridor, a hub and spoke, a fully connected grid...
Zones per country	Name of the countries and the corresponding sections of the physical network.
River Name(s)	River name(s) in each section of the physical network.
Ports	
Port ID	Port identifier.
Port Name	Name of the port.
Latitude	Geographical position in terms of latitude.
Longitude	Geographical position in terms of longitude.
Country	Name of the country the port belongs to.
Berthing capacity at each port	Capacity for holding vessels.
Costs at ports	

Holding cost of a vessel at a port	Cost of holding a vessel in a port that depends on the port and the vessel type.
Holding cost of a container at a port	Storage cost per container at a port that depends on the port.
Handling cost of a container at a port	The cost for loading and unloading a container in a port that depends on the port.
Locks	
Lock ID	Lock identifier.
Lock Name	Name of the lock.
Country	Name of the country.
River km	Location of the lock along the river (km stamp).
Lock dimensions (Length x Width)	Dimensions of the lock in terms of the length and width (meters).
Lock capacity	Number of barges that the locks can take at the same time.
Latitude	Geographical position in terms of latitude.
Longitude	Geographical position in terms of longitude.
Rivers	
Way ID	inland waterway identifier
Node ID	Node identifier.
Latitude	Geographical position in terms of latitude.
Longitude	Geographical position in terms of longitude.
Type	e.g., node, terminal, berth, lock gate, reporting point...
River (km)	River km where the node is located.
Countries	Country name where the node is located.
CEMT	Indicates the maximum size of a vessel suitable for a particular waterway.
Tide window	Variation of the water level during a specific period.
Water Level	The level of the water on each link of the network.
Bridges	
Bridge ID	Bridge identifier.
Bridge Name	Name of the bridge.
Length	Length of the bridge (meters).
Altitude	Altitude of the highest point of the bridge.
Location	River km stamp (position of the bridge along the river).
River Name	Name of the river where the bridge is located.
Country	Name of the country where the bridge is located.

Service information	
Service ID	Service identifier.
Vessel type	Types of vessels in terms of size (small, medium, and large) required by the service.
Service capacity	How many TEUs can be transported by the service; corresponds to the vessel capacity.
Service fixed cost	Cost for operating the service.
Origin port	Origin port of the service.
Destination port	Destination port of the service.
Number of the intermediate stops (ports)	Number of the intermediate stops/ports between the origin and destination.
List of travel times between two stops (ports)	Travel time between two consecutive stops; the list of all the legs.
Initial loading time at origin port	Time of initial loading of the vessel the origin of the service.
Departure time from origin port	Departure time of the service from its origin; time when initial loading terminates.
Arrival time at destination port	Arrival time at final destination of the service; time when final unloading may take place.
Final unloading time at destination port	Final unloading time at final destination; time when final unloading terminates; time when the vessel is available to start a new service.
Container handling time at each intermediate port	The time to load/unload containers at intermediate stops/ports.
Demand information	
Customer type	R/P/F (depending on the contract type).
Customer ID	Customer identifier.
Origin port ID	Port ID of the origin port of the demand.
Origin name	Name of the physical origin port of the demand.
Destination port ID	Port ID of the destination port of the demand.
Destination name	Name of the physical destination port.
Quantity of demand to be transported (TEUs)	Volume of demand in number of TEUs.
Booking time	Time when the customer calls in to make a transport request (to place an order).
Availability time at origin	Time the demand is ready for pick-up at the origin port (available for transportation).
Due time at destination	Maximum delivery time (required by the shipper).
Booking type	Late/early: differentiation of demands in terms of anticipation.

Delivery type	Express/standard: differentiation of demands in terms of delivery type (urgent or non-urgent).
Container information	
Customer type	Customer category (R/P/F).
Container ID	Container identifier.
Container type	20 and 40-foot long (They may also differ in scope and requirements, e.g., insulated, refrigerated, bulk, tank, open top, high cube, …).
Origin	Origin port of the container; the same as the origin of the demand it belongs to.
Destination	Destination port of the container; the same as the destination of the demand it belongs to.
Reservation time	The same as the booking time of the demand the container belongs to.
Port sequence	Sequence of ports constituting its route (computed by the optimisation module).
Service sequence	Sequence of services used to its transportation (computed by the optimisation module).
Alternative Mode of transport	Transportation mode (computed by the optimisation module).
Optimizer status result	If the request is rejected by the optimisation module, the value is 0; if accepted, the value is 1; if accepted after negotiation, the value is 2; if rejected after negotiation, the value is 3.

ANNEX I: EXCEL TABLE DATA

Annex I of this document contains the tables that have been developed to configure the different scenarios.

1.Node	Node id: The node identifier Lat: The geographical position in terms of latitude Lon: The geographical position in terms of longitude Type: The type of node (e.g., port, lock...) River km: The kilometric point of the river Country: The name of the country where the node is located CEMT: The CEMT class indicates the maximum size of a vessel suitable for a particular waterway

sheet: 01_river	demo value	demo value	demo value
Node id	0	1	2
Lat	47,9510373	47,9512392	47,9514151
Lon	8,5205163	8,5210125	8,521696
Type	Water	Water	Water
River km	0	0,043412417	0,098185688
Country	DE	DE	DE
CEMT	VI	VI	VI

2. Ports	Id: The port identifier Name: The name of the port Lat: The geographical position in terms of latitude Lon: The geographical position in terms of longitude Country: The name of the country where the inland port is placed in.

sheet: 02_ports	demo value	demo value	demo value
Id	0	1	2
Name	Regensburg	Linz	Belgrade
Lat	49,0225514	48,3048787	44,8341777
Lon	12,1429915	14,3349612	20,4507708
Country	DE	AT	RS

3. Locks	Id: The lock identifier Lock: The name of the lock Country: The name of the country where the lock is located River-km: The river km where the lock is located Lock chambers L x W (m): The dimension of the lock in terms of the length and width (measured in meters) Capacity: The size of vessels or convoys that can pass through the lock Lat: The geographical position in terms of latitude Lon: The geographical position in terms of longitude

sheet: 03_locks	demo value	demo value	demo value
Id	0	1	2
Lock	Bad Abbach	Regensburg	Geisling
Country	DE	DE	DE
River-km	2397,17	2379,68	2354,29
Lock chambers L x W (m)	190 x 12	190 x 12	230 x 24
Capacity	1	1	1
Lat	49,0306294	49,0255014	48,9520745
Lon	12,057837	12,2318564	12,4717212

4. Services	Service Line Id: The service identifier Stop: The sequence of ports for this service Arrival Time: The scheduled arrival time (discretised in time intervals) Departure Time: The scheduled departure time (discretised in time intervals) Vessel Id: The vessel identifier

sheet: 04_services	demo value	demo value	demo value
Service Line Id	0	1	2
Stop	0,1,2,3	3,2,1,0	0,1,2,3
Arrival Time	0,5,17,26	0,9,21,26	14,19,31,40
Departure Time	1,6,18,26	1,10,22,26	15,20,32,40
Vessel ID	0	1	2

5. Vessels	Vessel Id: The vessel identifier Name: The name of the vessel Capacity: The vessel capacity (TEUs, pallets...)

sheet: 05_vessels	demo value	demo value	demo value
Vessel ID	0	1	2
Vessel Name	Vessel 0	Vessel 1	Vessel 2
Capacity	50	50	50

6.Orders	Costumer Type: The customer type, they can be regular or spot customers Order Id: The order identifier Origin: The origin port ID Origin name: The name of the origin port Destination: The destination port ID Destination name: The name of the destination port Containers: The number of containers composing the order Booking time: The time at which the client requests the order Availability at origin: The time at which the cargo is ready at the port of origin Due Time in destination: The contractual due time

sheet: 06_orders	demo value	demo value	demo value
Customer Type	R	P	F
Order ID	0	1	2
Origin	2	0	0
Origin Name	Belgrade	Regensburg	Regensburg
Destination	3	3	3
Destination Name	Silistra	Silistra	Silistra
Containers	4	1	3
Booking Time	0	1	2
Availability at Origin	1	15	6
Due Time in Destination	24	91	57

7.Containers	Costumer Type: The customer type they can be regular or spot customers Container Id: The container identifier Order Id: The identifier of the order the container belongs to Origin: The origin port ID Destination: The destination port ID Reservation time: The time at which the client requests the container Optimizer result: The result of the optimizer. If the request is rejected the value is 0. If the request is accepted the value is 1. For the rejected requests there is a negotiation phase. If after the negotiation the request is accepted, the value is 2 and if not, the value is 3 (RM) Port Sequence: The sequence of ports the container has to visit Service sequence: The sequence of services the container has to take [RM] Alternative modes: The alternatives transport modes: 1 if the cargo has to be delivered by truck, 0 otherwise

sheet: 07_containers	demo value	demo value	demo value
Customer Type	P	F	R
Container ID	4	5	2
Order ID	1	2	0
Origin	0	0	2
Destination	3	3	3
Reservation Time	1	2	0
Optimizer Result	1	1	2
Port Sequence	0, 1, 2, 3	0, 1, 2, 3	2, 3
Service Sequence	0, 0, 0	2, 2, 0	0
Alternative Modes	0	0	1

ANNEX II: RM TACTICAL AND OPERATIONAL MATHEMATICAL MODELS

Elements of the tactical RM mathematical model

Decision variables	➢ Binary decision variable for service selection (open / do not open) ➢ Continuous decision variable for the percentage of the acceptance of the partial P-spot demands (varies within [0, 1]) ➢ Binary decision variable for accepting or rejecting the F-spot demands ➢ The number of temporarily idle vessels of each type, at each terminal, at each time period ➢ The total number of vessels (of each type) used in the optimal service plan ➢ The volume of each demand transported by each leg of a service ➢ The volume of each demand to be loaded upon departure from a particular terminal, at a particular time (on a particular leg of a particular service) ➢ The volume of each demand to be unloaded upon arrival at a particular terminal, at a particular time (from a particular leg of a particular service) ➢ The volume of each demand on hold, in the yard of a particular terminal, during one time period (*i.e.*, (t, t+1))
The objective function	○ Revenue (unit price * volume of demand) obtained by servicing: • all demands of regular customers • the selected portion of P-spot demands • the complete volume of the accepted F-spot demands ○ Fixed Cost: • The fixed cost of setting up and operating a service ○ Variable Costs: • The penalty cost of having but not using vessels (available in the fleet but never assigned to a service during the entire schedule length) • The idling cost of vessels (waiting at a port for their next service departure) • The unit cost of transportation on a service (per container) • The unit cost of holding containers at a terminal (storage cost per container) • The cost of handling (loading/unloading) containers at terminals
The constraints	➢ Flow-conservation constraints: ○ Flow-conservation of the containers of each demand at its origin ○ Flow-conservation of the containers of each demand at its destination ○ Flow-conservation of the containers of each demand at its intermediate terminals ○ Flow-conservation of the containers of all demands on each service at its origin ○ Flow-conservation of the containers of all demands on each service at its destination ○ Flow-conservation of the containers of all demands on each service at its intermediate terminals ○ The design-balance constraints for vehicle-flow conservation at terminals

	➢ Constraint on the service capacity of each leg ➢ Constraint for computing the number of temporarily idle vessels (per type of vessel) at each terminal ➢ Constraint on the berthing capacity of each terminal

The characteristics of the vessels and costs used in the tactical model

Vessel and **Fleet** characteristics	Unit **costs**
➢ Capacity of a vessel of type $l \in L$ (in TEUs) ➢ Speed of vessel of type $l \in L$ in normal operations, yielding the normal travel time ($\delta_{ij}(l)$) of a vessel of type l over an arc belonging to the physical network ($(i, j) \in A_{ph}$) ➢ Capacity of the fleet: the number of available vessels of each type ($l \in L$)	○ cost of transportation of a container (of type γ (d)), by a vessel (of type $l(s)$), on a specific leg (the k^{th}) of a service (s) ○ holding cost of a container (of type γ (d)) at a specific terminal (i) for one period ○ loading/unloading cost of a container (of type γ (d)) at a specific terminal (i) ○ cost of holding a vessel (of type l) at a specific terminal (i) for one time period ○ penalty cost for a vessel (of type l) that is not used in the optimal service plan

Operational RM model assumptions and data requirements (as per D1.7)

To design and implement a dynamic capacity allocation problem with revenue management concepts, the following assumptions and data requirements are made:

- The offer of a carrier consists of its transportation services scheduled to operate on the IW network and the available capacities of each barge at each time period; the carrier's offer has to be known in advance.
- Several product fares and several categories of customers are considered by the carrier, the objective being to propose a diversified tariff offer and capture an increasing number of demands from many different customers.
- The carrier will manage its limited resources using computational techniques that integrate information about future potential demands.
- The optimal decision of accepting/rejecting booking demands is made according to their feasibility and profitability regarding the current status of resource capacities on the network.

The Customer assumptions

There are two types of customers:

- Regular customers: customers with long-term contracts with the carrier guaranteeing the transport of their goods. Their demands can't be rejected (unless for feasibility reasons, in which case penalties are to be supported by the carrier).
- Spot customers: customers with no contract with the carrier. Their requests are therefore sequentially accepted/rejected according to feasibility and profitability criteria (based on opportunity costs). Two different types of spot customers are defined:
    - full-spot (F-Spot) customers whose request have to be accepted as a whole.
    - partial-spot (P-Spot) customers whose request may be partially satisfied (a fraction of the total volume is transported).

The Booking framework assumptions

- For each demand, three time-instants are required from the booking system:
    - Reservation time: the moment when the customer calls in to make a request.
    - Availability time: the moment the demand arrives to the origin port and is available for transportation by the carrier.
    - Maximum delivery time: the due date (at the destination port).
- A decision must be made as to whether accept or reject a demand at the time of call (reservation time). If accepted, the demand must be routed on the network (optimal predictive routing - integrating future demand forecasts).
- The carrier charges different fares: based on the anticipation (time interval between the reservation time and the availability time) and the urgency (time interval between the availability time and the maximum delivery time) of the demand.

The forecast demand availability assumptions

The future demand is assumed known at different levels of aggregation depending on the decision level: tactical (high level of aggregation, in space and time), operational (low level of aggregation in space and time), execution (only relevant subsets of demand are considered, in space and time).

The demand and services data requirements

The data requirements regarding the demand and services characteristics are summarized in Table 24.

Table 24: Demand and Service characteristics at the Operational Level

Demand characteristics	Service characteristics

▪ Category of the customer (Regular, P-Spot or F-Spot)
▪ Origin IWT terminal of the demand
▪ Destination IWT terminal of the demand
▪ Volume of the demand (in TEUs)
▪ The *booking time*: the time period when the customer calls in to make a reservation
▪ The *availability time*: the time period when the demand becomes available for transportation
▪ *Due date* at destination: the latest time period the demand has to be delivered at destination
▪ Fare class associated with the demand
▪ Fare value (price) of the demand
▪ Container type of the demand
	▪ Physical origin and destination terminals
	▪ Ordered set of consecutive intermediate stops (a direct service has an empty set of stops)
	▪ The set of legs of the service
	▪ The path of each leg of the service in the physical network
	▪ Time related attributes per service:
	  o Availability time of the service to start loading at the origin terminal (e.g., initial loading time)
	  o Departure time of the service from a terminal
	  o Arrival time of the service at a terminal
	▪ Capacity of the service (in TEUs)

Input, outputs and optimal decision-making

The inputs and outputs, as defined by the DCA-RM operational optimisation model and used in the computational algorithm are:

- Inputs:
    - Service Plan: the set of operating services (with their itineraries and schedules) deployed on a rolling horizon.
    - Transport requests for each period of the rolling horizon.
    - Forecast of future demands, updated on a rolling horizon.
- Outputs:
    - The optimal decision regarding the booking request (accept/reject).
    - The predictive routing of an accepted demand.

- The optimal decision is made based on two criteria:
  - Feasibility: if one or multiple service(s) have available capacity, in space and time, to transport the volume of the demand with respect to its due date.

Profitability: if the current demand remains profitable when putting it in competition with the forecast future demands, under the same network available capacity.

ANNEX III: TABLES AIR POLLUTANT EMISSION DATA

For inland shipping several vessel sizes are distinguished operating on smaller and larger waterways, obviously in relation to their size (a CEMT V class vessel cannot operate on a CEMT I waterway). The tables below show inland vessels with an average/medium load, both considering Tank-To-Wake and Well-to-Wake emissions.

Table 25: Emission factors per tkm, TTW and WTW, inland shipping, medium load, bulk/packaged goods, 2018[20]

Vessel/ Waterway	Load cap.(t)	MJ/tkm	TTW emissions (g/tkm)					WTW emissions (g/tkm)				
			CO_2-eq.	SO_2	PM_c	NO_x	PM_w	CO_2-eq.	SO_2	PM_c	NO_x	PM_w
Spits												
CEMT I	365	0.26	18.19	0.00011	0.015	0.27	0	23.97	0.025	0.016	0.28	0
CEMT Va	365	0.32	22.27	0.00013	0.016	0.32	0	29.35	0.030	0.017	0.33	0
CEMT VIb	365	0.36	24.89	0.00015	0.017	0.36	0	32.81	0.034	0.019	0.37	0
Waal	365	0.43	29.84	0.00018	0.021	0.43	0	39.33	0.041	0.022	0.44	0
Campine vessel												
CEMT II	617	0.25	17.17	0.00010	0.012	0.26	0	22.63	0.023	0.013	0.27	0
CEMT Va	617	0.37	25.52	0.00015	0.016	0.37	0	33.63	0.035	0.017	0.38	0
CEMT VIb	617	0.45	31.07	0.00019	0.019	0.46	0	40.96	0.042	0.021	0.47	0
Waal	617	0.45	31.62	0.00019	0.020	0.47	0	41.67	0.043	0.021	0.48	0
Rhine-Herne canal vessel												
CEMT IV	1,537	0.26	18.13	0.00011	0.009	0.25	0	23.90	0.025	0.010	0.26	0
CEMT Va	1,537	0.28	19.36	0.00012	0.009	0.26	0	25.51	0.026	0.010	0.27	0
CEMT VIb	1,537	0.36	25.27	0.00015	0.012	0.35	0	33.31	0.034	0.013	0.36	0
Waal	1,537	0.42	28.95	0.00017	0.014	0.40	0	38.16	0.039	0.016	0.42	0
Large Rhine vessel												
CEMT Va	3,013	0.17	12.15	0.00007	0.008	0.18	0	16.02	0.017	0.008	0.18	0
CEMT VIb	3,013	0.25	17.17	0.00010	0.009	0.24	0	22.62	0.023	0.010	0.25	0
Waal	3,013	0.26	18.13	0.00011	0.010	0.26	0	23.89	0.025	0.011	0.27	0
Class Va + 1 Europa II barge, wide												
CEMT VIb	5,046	0.33	22.68	0.00014	0.009	0.30	0	29.89	0.031	0.010	0.31	0
Waal	5,046	0.28	19.46	0.00012	0.008	0.26	0	25.65	0.026	0.009	0.27	0
4-barge push convoy												
CEMT VIb	11,181	0.17	12.07	0.00007	0.004	0.15	0	15.95	0.016	0.005	0.15	0
Waal	11,181	0.22	15.33	0.00009	0.005	0.19	0	20.23	0.021	0.006	0.20	0
6-barge push convoy, wide												
CEMT VIb	16,481	0.23	16.09	0.00010	0.005	0.20	0	21.21	0.022	0.006	0.20	0
Waal	16,481	0.18	12.56	0.00008	0.004	0.16	0	16.56	0.017	0.005	0.16	0

[20] 2018 (Source: Stream 2020, CE Delft)

Table 26: Emission factors per tkm, TTW and WTW, inland shipping, medium load, containers, 2018 [21]

Vessel/ Waterw.	Load cap. (TEU)	MJ/tkm	TTW emissions (g/tkm)					WTW emissions (g/tkm)				
			CO_2-eq.	SO_2	PM_c	NO_x	PM_w	CO_2-eq.	SO_2	PM_c	NO_x	PM_w
Neo Kemp (32-48 TEU)												
CEMT III	40	0.24	17.04	0.00011	0.014	0.27	0	22.46	0.023	0.014	0.28	0
CEMT Va	40	0.43	29.77	0.00019	0.018	0.43	0	39.24	0.041	0.020	0.44	0
CEMT VIb	40	0.52	36.34	0.00023	0.023	0.53	0	47.90	0.050	0.025	0.55	0
Waal	40	0.58	40.68	0.00026	0.025	0.60	0	53.62	0.055	0.028	0.62	0
Rhine-Herne canal vessel (96 TEU)												
CEMT IV	96	0.32	22.29	0.00014	0.012	0.32	0	29.38	0.030	0.013	0.33	0
CEMT Va	96	0.35	24.27	0.00015	0.012	0.34	0	31.99	0.033	0.014	0.35	0
CEMT VIb	96	0.49	33.90	0.00021	0.016	0.47	0	44.67	0.046	0.018	0.48	0
Waal	96	0.56	39.29	0.00025	0.019	0.55	0	51.78	0.054	0.021	0.57	0
Europa IIa push convoy (160 TEU)												
CEMT Va	160	0.40	27.80	0.00017	0.010	0.35	0	36.65	0.038	0.011	0.36	0
CEMT VIb	160	0.56	38.93	0.00024	0.014	0.49	0	51.31	0.053	0.016	0.51	0
Waal	160	0.60	41.67	0.00026	0.015	0.53	0	54.92	0.057	0.017	0.55	0
Large Rhine vessel (208 TEU)												
CEMT Va	208	0.22	15.03	0.00009	0.010	0.22	0	19.81	0.020	0.010	0.23	0
CEMT VIb	208	0.32	22.43	0.00014	0.012	0.31	0	29.57	0.031	0.013	0.32	0
Waal	208	0.35	24.16	0.00015	0.013	0.34	0	31.85	0.033	0.015	0.35	0
Extended Large Rhine vessel (272 TEU)												
CEMT Va	272	0.25	17.46	0.00011	0.008	0.24	0	23.01	0.024	0.009	0.25	0
CEMT VIb	272	0.31	21.83	0.00014	0.009	0.29	0	28.78	0.030	0.010	0.30	0
Waal	272	0.30	20.83	0.00013	0.008	0.27	0	27.45	0.028	0.009	0.28	0
Coupled: Europa II-C3l (348 TEU)												
CEMT Vb	348	0.21	14.75	0.00009	0.007	0.20	0	19.44	0.020	0.007	0.21	0
CEMT VIb	348	0.31	21.34	0.00013	0.008	0.28	0	28.12	0.029	0.009	0.29	0
Waal	348	0.29	20.40	0.00013	0.008	0.27	0	26.89	0.028	0.009	0.28	0
Rhinemax vessel (398-470 TEU)												
CEMT VIb	434	0.29	20.48	0.00013	0.008	0.26	0	26.99	0.028	0.009	0.27	0
Waal	434	0.27	18.72	0.00012	0.007	0.24	0	24.67	0.026	0.008	0.25	0

[21] (Source: Stream 2020, CE Delft)

Road transport GHG emission data

Both the GLEC Framework and STREAM also provide WTW emission for road transport.

Table 27: Emission factors per tkm, TTW and WTW, road transport, medium load, bulk/packaged goods, 2018 [22]

Vehicle cat.	Load	MJ/	TTW emissions (g/tkm)					WTW emissions (g/tkm)				
/Road class	cap. (t)	tkm	CO_2-eq.	SO_2	PM_c	NO_x	PM_w	CO_2-eq.	SO_2	PM_c	NO_x	PM_w
Tractor-semitrailer, light												
Average	15.7	1.9	135.5	0.0008	0.002	0.522	0.011	178.3	0.183	0.009	0.59	0.011
Urban	15.7	3.1	220.0	0.0013	0.005	1.185	0.018	289.4	0.297	0.017	1.29	0.018
Rural	15.7	2.2	151.5	0.0009	0.003	0.686	0.009	199.3	0.204	0.011	0.76	0.009
Motorway	15.7	1.8	124.3	0.0007	0.002	0.424	0.010	163.4	0.168	0.008	0.48	0.010
Tractor-semitrailer heavy												
Average	29.2	1.0	67.2	0.0004	0.002	0.215	0.004	88.4	0.091	0.005	0.25	0.004
Urban	29.2	1.9	135.6	0.0008	0.005	0.447	0.007	178.4	0.183	0.012	0.51	0.007
Rural	29.2	1.2	85.1	0.0005	0.003	0.266	0.004	111.9	0.115	0.007	0.31	0.004
Motorway	29.2	0.8	57.1	0.0003	0.002	0.184	0.004	75.1	0.077	0.005	0.21	0.004
LHV												
Average	40.8	0.9	64.9	0.0004	0.002	0.196	0.005	85.4	0.088	0.005	0.23	0.005
Urban	40.8	1.9	131.0	0.0008	0.004	0.407	0.007	172.3	0.177	0.011	0.47	0.007
Rural	40.8	1.2	82.2	0.0005	0.002	0.242	0.004	108.1	0.111	0.006	0.28	0.004
Motorway	40.8	0.8	55.6	0.0003	0.001	0.168	0.005	73.1	0.075	0.004	0.19	0.005

For containers

Table 28: Emission factors per tkm, TTW and WTW, road transport, medium load, containers, 2018 [23]

Vehicle cat.	Load		TTW emissions (g/tkm)					WTW emissions (g/tkm)				
/Road class	cap. (t)	MJ/tkm	CO_2-eq.	SO_2	PM_c	NO_x	PM_w	CO_2-eq.	SO_2	PM_c	NO_x	PM_w
Truck, GVW >20 t, no trailer												
Average	1	2.3	161.1	0.0010	0.008	1.055	0.016	211.9	0.217	0.016	1.13	0.016
Urban	1	3.6	256.2	0.0015	0.014	1.890	0.025	337.0	0.346	0.027	2.01	0.025
Rural	1	2.4	170.7	0.0010	0.008	1.209	0.014	224.5	0.230	0.017	1.29	0.014
Motorway	1	2.0	140.8	0.0008	0.006	0.849	0.015	185.2	0.190	0.014	0.92	0.015
Truck, GVW >20 t, with trailer												
Average	2	1.3	92.5	0.0006	0.003	0.333	0.008	121.6	0.125	0.007	0.38	0.008
Urban	2	2.3	159.1	0.0009	0.005	0.658	0.013	209.2	0.215	0.013	0.73	0.013
Rural	2	1.4	96.1	0.0006	0.003	0.386	0.007	126.4	0.130	0.008	0.43	0.007
Motorway	2	1.1	78.8	0.0005	0.002	0.253	0.008	103.6	0.106	0.006	0.29	0.008
Tractor-semitrailer, heavy												
Average	2	1.3	91.9	0.0005	0.003	0.303	0.006	120.9	0.124	0.008	0.35	0.006
Urban	2	2.6	185.6	0.0011	0.007	0.630	0.010	244.1	0.250	0.016	0.72	0.010
Rural	2	1.7	116.5	0.0007	0.004	0.374	0.005	153.2	0.157	0.009	0.43	0.005
Motorway	2	1.1	78.1	0.0005	0.002	0.259	0.006	102.8	0.105	0.006	0.30	0.006
LHV												
Average	3	1.2	82.8	0.0005	0.002	0.259	0.006	108.9	0.112	0.006	0.30	0.006
Urban	3	2.4	167.0	0.0010	0.005	0.539	0.009	219.6	0.225	0.014	0.62	0.009
Rural	3	1.5	104.8	0.0006	0.003	0.320	0.005	137.9	0.141	0.008	0.37	0.005
Motorway	3	1.0	70.3	0.0004	0.002	0.221	0.006	92.5	0.095	0.005	0.25	0.006

[22] (Source: Stream 2020, CE Delft)
[23] (Source: Stream 2020, CE Delft)

ANNEX IV: DYNAMIC SIMULATION – REVENUE MANAGEMENT INTEGRATION SEQUENCE

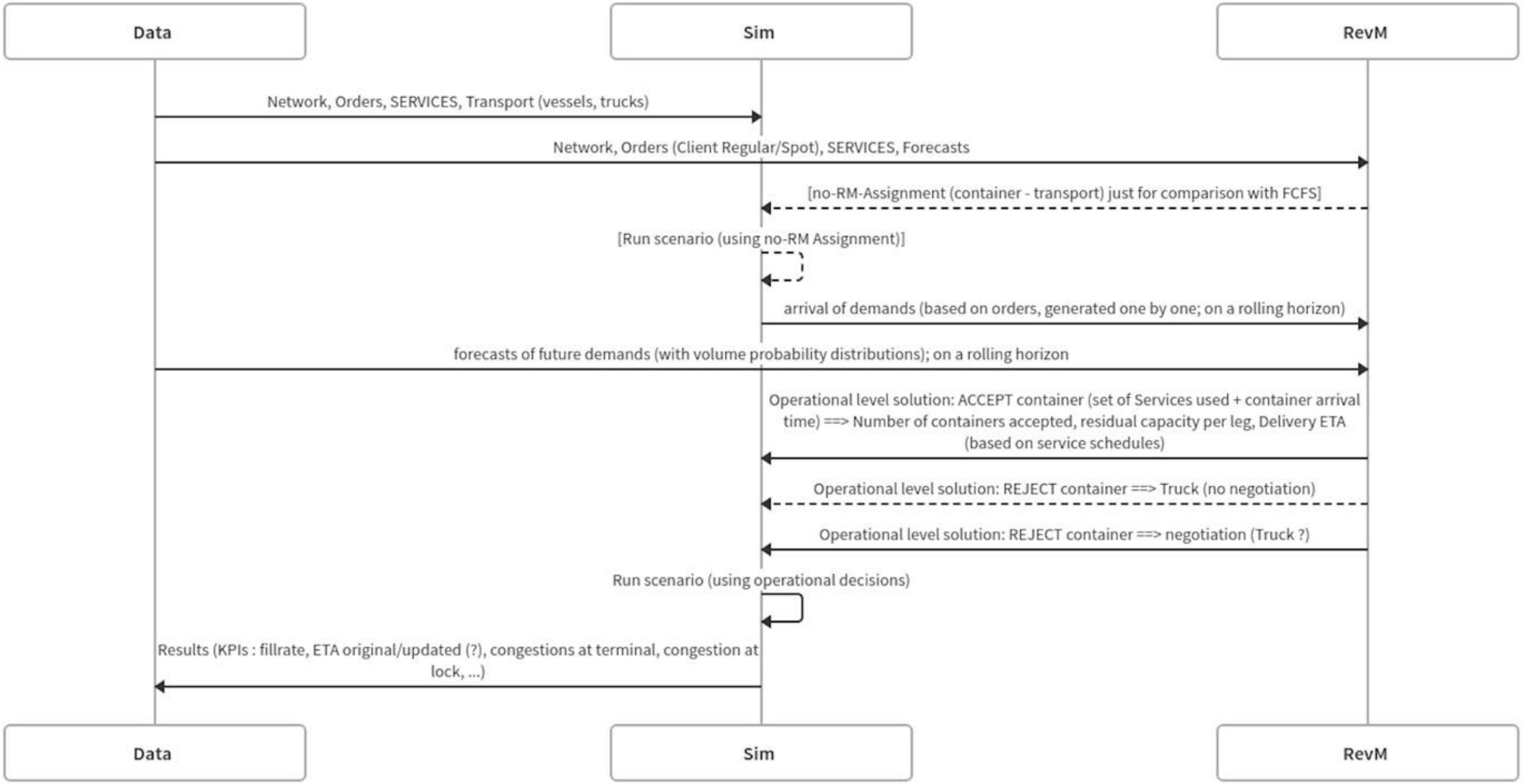

Figure 30: Integration first phase (RM optimisation model for the operational planning)

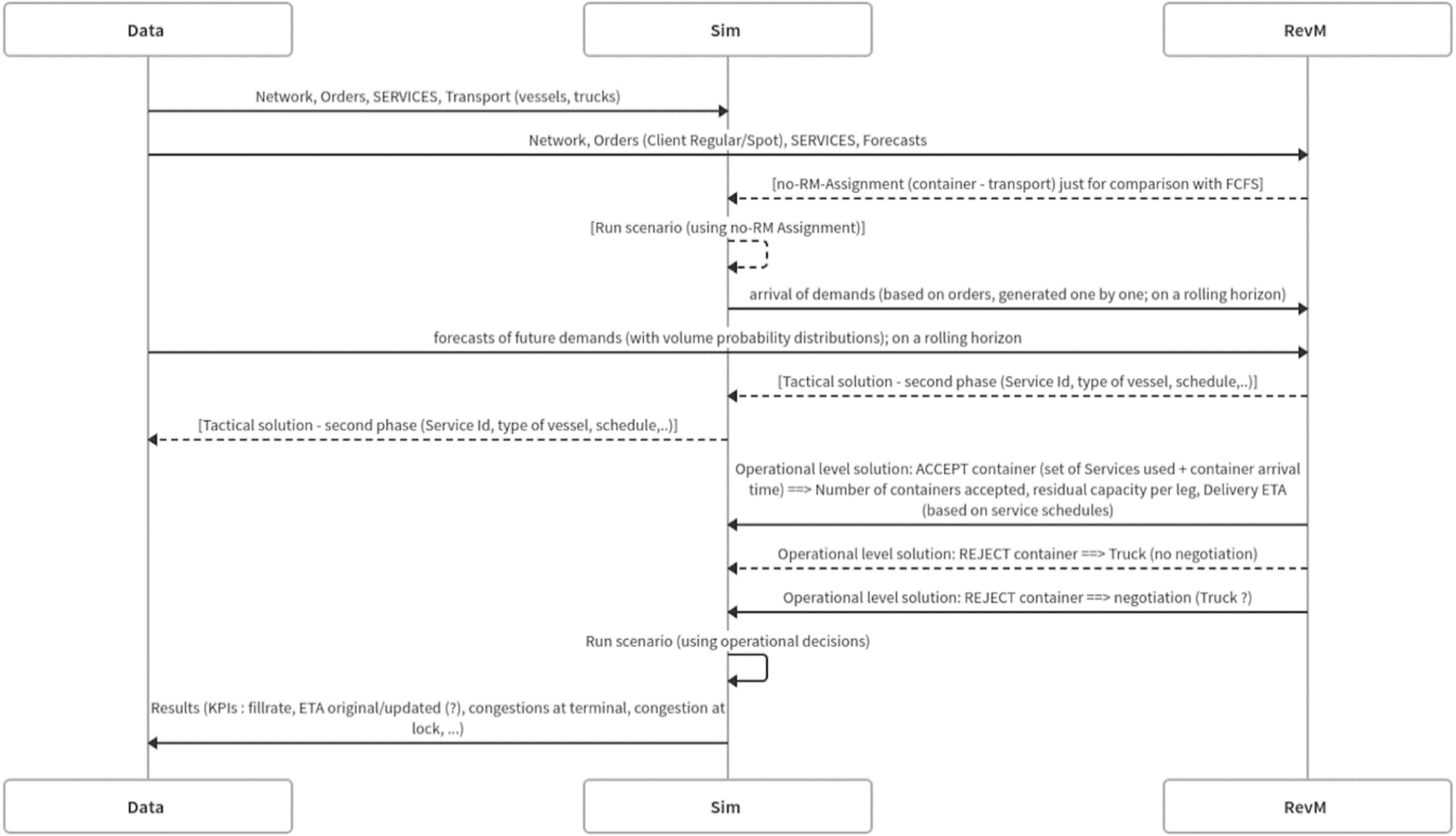

Figure 31: Integration second phase (RM optimisation model for tactical planning)