IW-NET

Innovation-driven Collaborative European
Inland Waterways Transport Network

D3.1 Categorization of Innovative IWT green vessels and reference models for simulation-based impact assessment for specific corridors

Version: Final

Lead Beneficiary: KU Leuven

Delivery Date: 19/07/2022

Dissemination Level: Public

Type: Report

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 861377.

Document Information

Title:	D3.1 – Innovations review, categorisation, and analysis of Inland Waterway vessels
Acronym:	IW-NET
Call:	H2020-MG-2019-TwoStages
Type of Action:	RIA
Grant Number:	861377
Start date:	01 May 2020
Duration:	36 Months
URL	www.iw-net.eu

Deliverable

Title	D3.1 –Innovative IWT Green Vessels: Categorization of Innovative IWT green vessels and simulation-based impact assessment of key vessel innovations for specific corridors
Work Package	WP3
Dissemination Level	Public
Delivery Date	18/07/2022
Lead Beneficiary	KU Leuven
Lead Author	KU Leuven

Document History

Version	Date	Modifications	Contributors
0.1	30/01/2022	Categorization of vessel	KUL
0.2	30/02/2022	Figures added	KUL
0.3	14/03/2022	Apply to living labs	KUL
0.4	01/04/2022	Situational awareness added	KUL
0.5	21/04/2022	First draft	KUL
0.6	03/06/2022	Extending document	KUL
0.7	23/06/2022	Simulation section added	ITA
0.8	29/06/2022	Draft for final submission	KUL
0.9	10/07/2022	Final deliverable inspection and integration	ISL, ILS
1.0	13/07/2022	Final improvements, formatting, tables of contents, Exec Summary.	ISL, ILS
1.1	15/07/2022	Final improvements	ITA
Final	19/07/2022	Final formatting	ISL

Executive Summary

This report provides a technological basis in the form of (i) a categorisation and analysis of Inland Waterway (IW) vessels, focussing on a “single vessel”, (ii) an innovations review on vessel interoperability, including situational awareness and shared operational data, and (iii) the exploitation of (i) and (ii) as first-order adoptions in the IW-NET use cases.

A comprehensive study was performed so that related IW vessel and fleet components were analysed, creating a taxonomy of vessel types and components, aiming to provide a basis for extending simulation-based impact assessment on key vessel innovations for specific corridors. Specific aspects considered were the Vessel Geometry, hull types, deck types for bulk, tankers, or custom decks, the Actuation systems including different propulsion types and different energy options aiming to environmentally friendly solutions. Further, particular attention was given to the on-board sensor systems, for improved autonomy and manoeuvrability, while aspects of Vessel Interoperability and Situational Awareness were studied with regard to applicable standards and current state of art solutions.

The “single vessel" technologies described in this report, are being explored in the Living Lab of the IW-NET project also carried over, incorporated in the development of barges to be used for urban scenarios.

At the heart of the research performed in T3.1 is the attempt to answer the question; "which innovations are productive to not only allow for increased single vessel automation, but also to enable a smart, sustainable IWT supply chain?” Thereby, a quite important part of the study performed in this task concerns the vessel automation. This has been implemented by means of carefully weighing the added values of each separate technological innovation, resulting to an incremental approach towards sustainable interoperability between multiple vessels.

Further, the work concerning the simulation tools and libraries being developed within IW-NET resulted to simulation models in the form of a “digital twin” that would let simulate automated navigation of vessels within the canals, sensing the environment, approaching vehicles, obstacles etc., and simulation models that are to study and to optimise decisions at both the strategy and the tactical / operations level. These have been developed in connection with WP1 tasks, which have integrated the taxonomy of vessels, technologies, and components. This output is being applied to the IW-NET Applications Scenario AS3 (Introduction and testing innovative IW fleet including autonomous vessels for urban distribution), where interactions between several systems(-of-systems) are crucial for smart, safe, and efficient vessel operations.

Disclaimer

The authors of this document have taken any available measure to present the results as accurate, consistent and lawful as possible. However, use of any knowledge, information or data contained in this document shall be at the user's sole risk. Neither the IW-NET consortium nor any of its members, their officers, employees or agents shall be liable or responsible, in negligence or otherwise, for any loss, damage or expense whatever sustained by any person as a result of the use, in any manner or form, of any knowledge, information or data contained in this document, or due to any inaccuracy, omission or error therein contained.

The views represented in this document only reflect the views of the authors and not the views of INEA and the European Commission. INEA and the European Commission are not liable for any use that may be made of the information contained in this document.

List of Abbreviations

Abbreviation	Description
ABM	Agent-Based Modelling
AIS	Automatic Identification System
AS	Application Scenario
CAN	Controller Area Network (bus)
CCNR	Central Commission for the Navigation of the Rhine
CEMT	European Conference of Ministers of Transport
COLREG	International Regulations for Preventing Collisions at Sea
DES	Discrete Event Simulation
ECDIS	Electronic Chart Display and Information Systems
ECU	Electronic Control Unit
GHG	Greenhouse Gases
GNSS	Global Navigation Satellite System
IENC	Inland Electronic Navigational Chart
IHO	International Hydrographic Organization
IMU	Inertial Measurement Unit
ISV	Inland Surface Vessel
IW	Inland waterways
IWT	Inland Waterway Transport
LIDAR	Laser Imaging Detection and Ranging
LL	Living Lab
LPG	Liquefied Petroleum Gas
NFAS	Norwegian Forum for Autonomous Ships
PID	Proportional Integral Derivative controller
PLC	Programmable Logic Computer
RADAR	Radio Detection and Ranging
RCC	Remote Control Centres
RIS	River Information System
WLAN	Wireless LAN – Local Area Network

Table of Contents

1 Introduction ... 1
  1.1 Mapping IW-NET Outputs ... 2
2 Single vessel ... 3
  2.1 Vessel Geometry ... 3
    2.1.1 Hull type ... 4
    2.1.2 Vessel dimensions ... 6
    2.1.3 Deck type ... 8
  2.2 Actuation system ... 9
    2.2.1 Propulsion type(s) ... 9
    2.2.2 Propulsion configuration ... 11
    2.2.3 Energy source(s) ... 12
  2.3 Sensor system ... 13
    2.3.1 Proprioceptive sensors ... 13
    2.3.2 Exteroceptive sensors ... 15
  2.4 Control system ... 17
    2.4.1 Low-level controller ... 17
    2.4.2 High-level controller ... 17
  2.5 Communication system ... 19
    2.5.1 Internal (intra-vessel) ... 19
    2.5.2 External (inter-vessel, vessel-shore, vessel-to other systems) ... 20
  2.6 Example ... 20
3 Vessel Interoperability and situational awareness ... 21
  3.1 Context and motivation ... 21
  3.2 State of the art and corresponding limitations ... 22
    3.2.1 Electronic Navigational Charts and ECDIS ... 22
    3.2.2 Open standards and protocols ... 22
    3.2.3 Shared situational awareness ... 23
  3.3 First experiments with shared, dynamic maps and formal world models ... 24
4 IW-NET vessel ... 26
  4.1 IWT fleet ... 27
    4.1.1 Platooning vessel (software coupling) ... 27
    4.1.2 Coupled vessel (hardware coupling) ... 28
  4.2 Shoreside System ... 28
  4.3 Crew ... 29
    4.3.1 Onboard ... 29
    4.3.2 Onshore ... 29
  4.4 Shoreside infrastructure ... 29
  4.5 Autonomy level ... 30
5 Modelling and Simulation ... 32
  5.1 Modelling and simulation capabilities ... 32
  5.2 Example for Danube Application Scenario ... 36
6 Conclusions ... 39
7 References ... 40

List of Tables

Table 1: Adherence to IW-NET's GA Deliverables & Task Descriptions 2

Table 2: Classification of European inland waterway vessels, defined by the European Conference of Ministers of Transport (CEMT). Adapted from [3] 7

Table 3: Overview of a vessel's state 14

Table 4: Share in estimated tonne-kilometre performance and average fuel consumption of the main fleet families 33

Table 5: Inland waterways transport emission intensity factors 36

Table 6: Examples of KPI 36

Table 7: Summary key indicators for scenarios comparison 38

List of Figures

Figure 1: Flowchart for the classification of the current fleet of inland vessels.............................. 3

Figure 2: Flowchart showing the influence of the vessel geometry characteristics......................... 4

Figure 3: Picture of Watertruck^{+} vessel during operation 5

Figure 4: Picture of Cogge during operation.. 5

Figure 5: Picture of Zulu vessel during operation 6

Figure 6: Picture of Maverick during operation.. 6

Figure 7: Small inland vessels active in Utrecht (left) and Amsterdam (right), the Netherlands 7

Figure 8: Picture of inland container vessel 'Meyati' (captured by Kick van den Dool) 8

Figure 9: Flowchart showing the influence of the actuation system characteristics 9

Figure 10: Picture of a typical propeller-rudder configuration consisting of 2 propellers, each with their corresponding rudder. Picture adapted from [6] 10

Figure 11: Overview of different rotatable propellers: (a) Z-drive unit: the driving motor is located inside of the vessel and connected to the propeller using a 'z-drive' transmission. (b) Podded azimuth propeller: the motor is connected directly to the propeller 10

Figure 12: Embedded propulsion systems Cogge. (a) and (b) provide an overview of the location of the thrusters, (c) is a four-channel thruster integrated into the stern, and (d) is a steering-grid thruster integrated into the bow.. 11

Figure 13: Longitudinal position of the thrusters installed on Cogge... 12

Figure 14: Picture of Ampere, the world's first electric Ferry 12

Figure 15: Flowchart showing how the sensor system is related to other sub-systems of an inland cargo vessel.. 13

Figure 16: Earth-fixed/inertial (O_i) and body-fixed (O_b) reference frames....................................... 14

Figure 17: Working principle of an extended Kalman filter, using an IMU and GNSS [1, 2]............. 15

Figure 18: Shoreline extraction from lidar data. (a) lidar data set, (b) shoreline extraction, and (c) extracted shoreline and inland navigation chart shoreline comparison 16
Figure 19: Mobile plug-and-play sensor box 16
Figure 20: Flowchart showing how the control system is related to other sub-systems of an inland cargo vessel 17
Figure 21: Communication system architecture for Inland Cargo Vessels 19
Figure 22: Overview of communication between different sub-systems installed on Cogge 20
Figure 23: Overview of current awareness and navigation systems, and upgraded situational awareness system for inland waterway transport, explored and developed within IW-NET 24
Figure 24: Overview of communication between different vessels 25
Figure 25: W-NET Vessel conceptual model and concepts taxonomy 26
Figure 26: Screenshot from Novimar concept animation 27
Figure 27: Watertruck$^+$ vessel pushing two unpropelled barges 28
Figure 28: Shore control centre to control Cogge while looking at the available video streams and a real-time overview of useful (sensor) data 28
Figure 29: Additional shore-side control components for Cogge: (a) wearable remote controller with web-interface, (b) rugger computer (R-PC) running MOOS-IvP, and (c) an additional laptop monitoring the PLC web-interface 29
Figure 30: Levels of inland waterway transport automation defined by CCNR 30
Figure 31: Levels of autonomy of vessels defined by NFAS 31
Figure 32: Control hierarchy overview from [1,2] 31
Figure 33: Overview of communication between different sub-systems installed on Cogge and its surroundings 32
Figure 34: Correlation between vessel fuel consumption and water depth 34
Figure 35: Data collection framework for estimating GHG emissions for IWT (Source: STC-NESTRA) 35
Figure 36: Simulation runtime screen 37
Figure 37: Example of simulation indicators 38
Figure 38: Example of simulation exported indicators 38

1 Introduction

In the context of innovative technologies and applications related to smart IW (cargo) vessels, as part of IW-NET developments, this report aims to provide a technological basis in the form of (i) a categorisation and analysis of Inland Waterway vessels, focussing on a “single vessel”, (ii) an innovations review on vessel interoperability, and (iii) the exploitation of (i) and (ii) as first-order adoptions in the IW-NET use cases. The latter correlates with IW-NET applications scenario AS3 (Introduction and testing innovative IW fleet including autonomous vessels for urban distribution), where interactions between several systems(-of-systems) are crucial for smart, safe, and efficient vessel operations.

The vessel and fleet components discussed in this work aim to provide a basis for extending simulation-based impact assessment on key vessel innovations for specific corridors. The taxonomies, and corresponding technologies can provide a modelling basis for such simulation-based assessments in a specific corridor. Such extended simulations will allow for identifying "first order developments" in terms of increased automation and smart waterway systems, taking into account economic viability and cost-effective operations.

Various "single vessel" technologies are explored by several partners in the IW-NET project. By means of carefully weighing the added values of each separate technological innovation, this document moreover aims to construct an incremental approach towards sustainable interoperability between multiple vessels. As such, it tries to answer the question "which innovations are productive to not only allow for increased single vessel automation, but also to enable a smart, sustainable IWT supply chain?”

It should be noted that the simulations with respect to:

- Ship Management: Vessel lifecycle management, fleet management
- Navigation Management: Safety, greening
- Port operations: productivity improvements, SC-coordination
- Customers: Tracking Services/SC visibility improvements

are performed as part of WP1 (Open IWT Digitalization Infrastructure and Services for IWT Integration in Multimodal Transport and Urban Logistics).

These simulations can be extended with reference models in this document, for example, vessel actuation subsystem and corresponding manoeuvrability, level of autonomy, interface capabilities, among many other factors.

1.1 Mapping IW-NET Outputs

The purpose of this section is to map IW-NET's Grant 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 Deliverables & Task Descriptions

DELIVERABLE	
D3.1:	Categorization of Innovative IWT green vessels and simulation-based impact assessment of key vessel innovations for specific corridors
TASKS	
T3.1	Categorization of Innovative IWT green vessels and simulation-based impact assessment of key vessel innovations for specific corridors

IW-NET GA Component Title	**IW-NET GA Component Outline**	**Respective Document Chapter(s)**
ST3.1.1	Development of innovative and green IW vessel categorization scheme	Section 2, (Single vessel)
ST3.1.2	Development of reference model for smart connected ships	Section 3, (Vessel interoperability) Section 4, (IW-NET vessel)
ST3.1.3	Simulation based environmental impact assessment	Section 5, also see WP1, D1.1 by ITAINNOVA (Open IWT Digitalization Infrastructure and Services for IWT Integration in Multimodal Transport and Urban Logistics)

2 Single vessel

This section provides a categorisation scheme for the current fleet of Inland Surface Vessels (ISV's) based on design and available hardware. The purpose of this categorisation is twofold: (a) it provides an overview of all possible configurations, making sure they are all represented within the impact assessment, and (b) it allows for the targeted evaluation of the influence of a certain design choice with regards to ship management, navigation management, port operations and customers. Figure 1 gives an overview of the selected categorisation criteria, which are discussed one by one in this chapter.

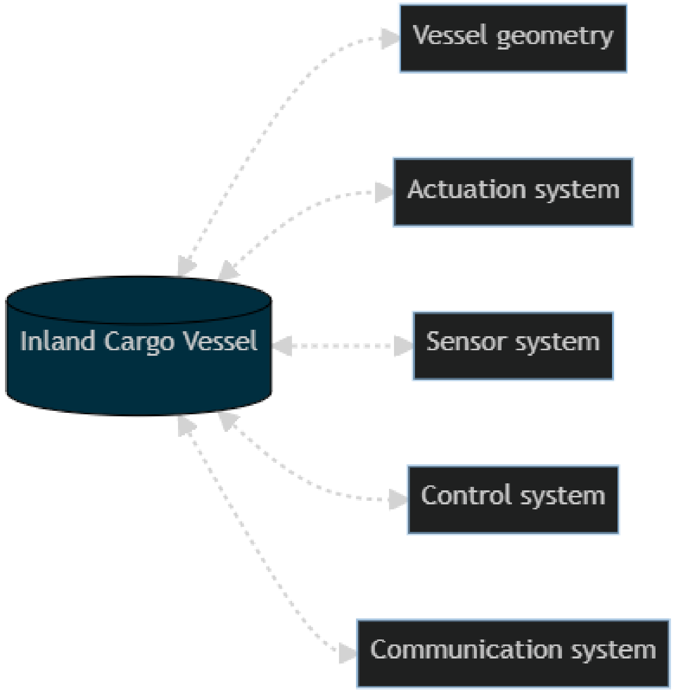


Figure 1: Flowchart for the classification of the current fleet of inland vessels

2.1 Vessel Geometry

The geometry of a vessel determines: (a) which waterways can be sailed, and therefore which ports can be reached, and (b) which type(s) of cargo can be transported, as well as how this cargo is (un)loaded. In this categorisation, the vessel's geometry is described by its hull type, deck type and vessel dimensions. Figure 1 shows how the aforementioned characteristics are interrelated.

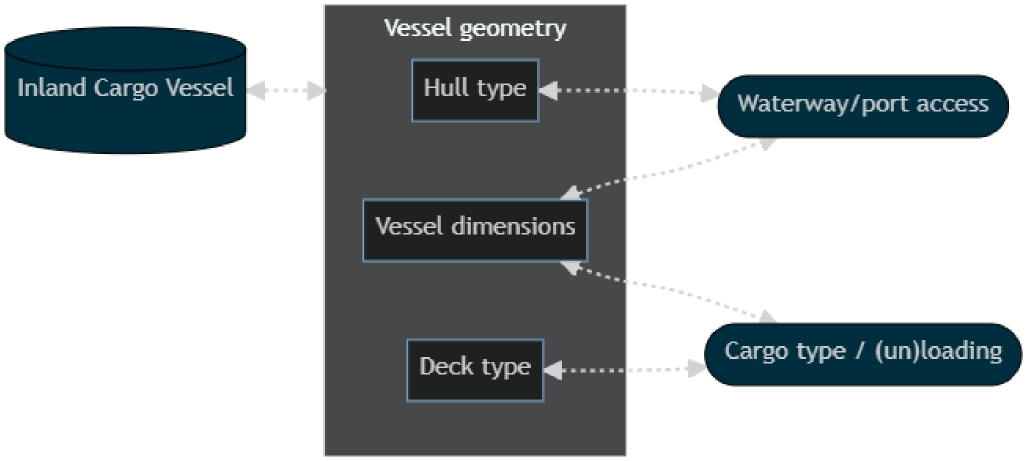


Figure 2: Flowchart showing the influence of the vessel geometry characteristics

2.1.1 Hull type

The hull is often referred to as the most important part of a vessel, as it is designed to keep the vessel and its cargo afloat in a stable manner. The shape of the hull influences the vessel's manoeuvrability and stability, as well as its draft (or draught). The latter is decisive for the accessibility of different waterways and ports. A first distinction is made based on the number of hulls.

2.1.1.1 Single hull

This is the typical configuration for inland barges. Single-hulled vessels can have different hull shapes, the most common of which are:

- A flat-bottomed hull: Most common for transporting cargo because of its good stability and high volume-to-draft ratio, granting a lot of cargo space while keeping the draft relatively small.
- A round-bottomed hull: Generally better manoeuvrability and more energy-efficient than flat-bottomed hulls in exchange for less stability.
- A V-shaped hull: Designed for high-speed applications, as the V-shape allows the ship to plane on top of the water at higher speeds.

In an IWT context, mostly flat-bottomed hulls are used because (a) they are most stable when (un)loading the vessel, and (b) they provide the most (loading) space for a specific draft.

Examples of single-hulled inland vessels:

- Watertruck$^+$ vessels[1] (see Figure 3).
- KU Leuven: Cogge [1, 2], a scale model research vessel (see Figure 4)

---

[1] Watertruck$^+$ project website: http://www.watertruckplus.eu/

Figure 3: Picture of Watertruck+ vessel during operation

2.1.1.2 *Multiple hulls*

Multi-hulled vessels have multiple, separate hulls, which are connected by the deck. Examples include catamarans (two hulls) and trimarans (three hulls). In general, these vessels are very stable but need quite some space for turning or berthing.

Examples of catamaran-type inland vessels:

- The Zulus from Blue Line Logistics[2] (see Figure 5).
- KU Leuven: Maverick [1], a pallet-carrier research vessel (see Figure 6).

Figure 4: Picture of Cogge during operation

---

[2] Blue Line Logistics website: http://www.bluelinelogistics.eu/

Figure 5: Picture of Zulu vessel during operation

Figure 6: Picture of Maverick during operation

2.1.2 Vessel dimensions

Firstly, the general size of a vessel determines the waterways on which it can sail. For European waterways, the European Conference of Ministers of Transport (official abbreviation from French: CEMT) defined a classification table for inland vessels and waterways [3] (shown in Table 2). The classes define the maximal outer dimensions a vessel may have, to be allowed to sail on a waterway of the according class. Note that classes IV through VII mostly (there are some exceptions in classes IV and V) refer to pushed convoys. The subclasses in classes V and VI are defined to make a distinction between different configurations for the pushed convoy (more details in [3]).

Secondly, the size of a vessel also influences the amount of cargo that can be transported. On the one hand, there is a direct link between the available space and the volume of cargo that can be transported. On the other hand, the mass of the cargo is limited by the CEMT classification (shown in Table 2).

Table 2: Classification of European inland waterway vessels, defined by the European Conference of Ministers of Transport (CEMT). Adapted from [3]

Class	Tonnage (t)	Length (m)	Breath (m)	Draught (m)	Air Draft (m)
I	250 – 400	38,5	5,05	1,80 – 2,20	3,70
II	400 – 650	50,0 – 55,0	6,60	2,50	3,70 – 4,70
III	650 – 1.000	67,0 – 80,0	8,20	2,50	4,70
IV	1.000 – 1.500	80,0 – 85,0	9,50	2,50	4,50; 6,70
Va	1.500 – 3.000	95,0 – 110,0	11,40	2,50 – 4,50	4,95; 6,70; 8,80
Vb	3.200 – 6.000	172,0 – 185,0	11,40	2,50 – 4,50	4,95; 6,70; 8,80
VIa	3.200 – 6.000	95,0 – 110,0	22,80	2,50 – 4,50	6,70; 8,80
VIb	6.400 – 12.000	185,0 – 195,0	22,80	2,50 – 4,50	6,70; 8,80
VIc	9.600 – 18.000	270 – 280	22,80	2,50 – 4,50	8,80
	9.600 – 18.000	195 – 200	33,00 – 34,20	2,50 – 4,50	8,80
VII	14.500 – 27.000	285	33,00 – 34,20	2,50 – 4,50	8,80

Not every inland vessel fits the CEMT categories. Two examples of a vessel smaller than class CEMT-I are shown in Figure 7 [1]. These smaller size vessels show potential for the distribution of parcels, small orders, or one/two pallets.

Figure 7: Small inland vessels active in Utrecht (left) and Amsterdam (right), the Netherlands

2.1.3 Deck type

The deck type determines the type(s) of cargo that can be transported, as well as how the cargo is (un)loaded.

2.1.3.1 Flat deck

This configuration is most commonly used for inland vessels. Flat-deck vessels often allow for wheeled cargo to be driven on and off the vessel, referred to as roll-on/roll-off (RoRo) vessels. Typical RoRo cargo includes pallets, containers, and wheeled vehicles.

Examples of flat-deck vessels:

- The Zulu's from Blue Line Logistics[2] (see Figure 5).
- Container vessel Meyati (see Figure 8)

Figure 8: Picture of inland container vessel 'Meyati' (captured by Kick van den Dool)

2.1.3.2 Bulk-carrier deck

Bulk carriers are vessels which are specially designed for transporting dry bulk cargo (e.g., coal, ore, grain). These vessels have big 'cargo boxes' to store the unpacked cargo, which are usually (un)loaded using cranes. The cranes can be installed on the vessel itself, making it a so-called 'geared vessel', but this is uncommon within an IWT context.

2.1.3.3 Tanker deck

Tanker decks are, like bulk-carrier decks, specially designed for transporting liquids or (liquefied) gases in bulk. Common cargo includes oil, chemicals, compressed/liquefied natural gas and LPG. Tanker vessels are usually equipped with a piping system to (un)load the cargo using pumps. The deck should be divided into multiple tanks to keep the liquid cargo from flowing around freely in the hull, as it affects the stability of the ship (for more information about ship stability, see chapters 2-3 of [4]). Different types of cargo can lead to different designs, e.g., chemical tankers which are developed to handle dangerous chemicals.

2.1.3.4 Custom deck

Some vessels require a custom design to assist with or conduct certain tasks, usually referred to as 'service vessels'. Tasks can be related to exploration, development, and maintenance (e.g., dredging).

2.2 Actuation system

The actuation system of an inland vessel affects its travel range and manoeuvrability. In this categorisation, the actuation system is characterised by energy type, propulsion type and propulsion configuration. It is important to note that modelling this (sub)system can be of significant advantage for increased situational awareness, especially for close-encounter manoeuvring. See also Section 4. Figure 9 gives an overview of the influence of the different actuation system characteristics, which will be further discussed in the following sub-sections.

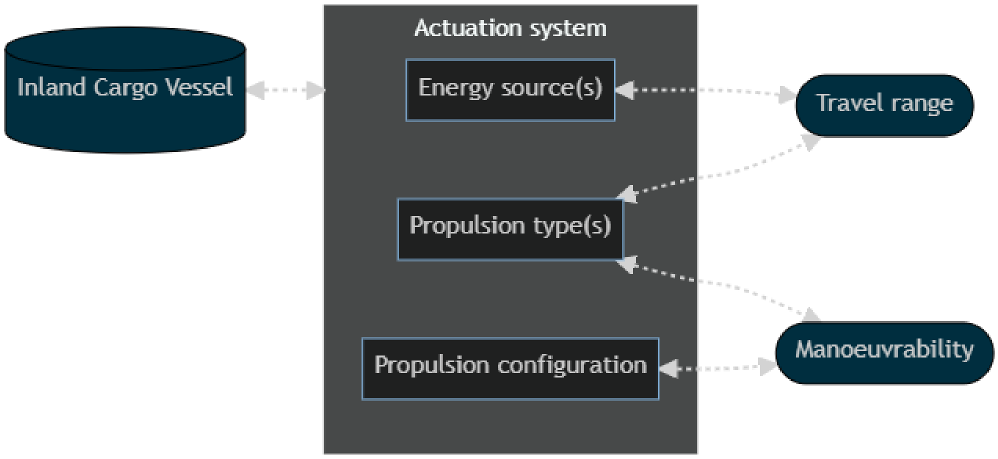


Figure 9: Flowchart showing the influence of the actuation system characteristics

2.2.1 Propulsion type(s)

This sub-section discusses different types of propulsion systems. The propulsion systems(s) of a vessel define the amount of force that can be generated as well as the achievable thrust angle, both of which influence the manoeuvrability of the vessel. The power consumption of the system(s), in combination with the energy source and capacity, defines the travel range of the vessel. The information given below is mainly based on [5], which can be consulted for additional information.

2.2.1.1 Static propeller

This is by far the most common propulsion type for both marine and inland vessels. The propeller typically has 3 to 5 blades and accelerates the surrounding fluid by rotating, creating a thrust force. Different propeller types have been developed, each with its specific (dis)advantages. Propeller types, other than the standard marine propeller, include controllable-pitch, ducted, contra-rotating and tandem propellers (more details can be found in [5]). The propeller can be used independently to generate thrust in a fixed direction (usually forward). It can also be used in combination with a rudder (as shown in Figure 10), which redirects the water flow and thereby induces a yawing (turning) moment on the vessel.

Figure 10: Picture of a typical propeller-rudder configuration consisting of 2 propellers, each with their corresponding rudder. Picture adapted from [6]

2.2.1.2 *Rotatable propeller*

Rotatable propellers include z-drive units and podded azimuth propellers. Both the aforementioned systems consist of a propeller, which is mounted on a rotatable shaft which can turn 360 degrees. The difference between the aforementioned systems is related to the location of the motor which drives the propeller, as shown in Figure 11. These systems are often used in pairs, one at the bow and one at the stern, and provide excellent manoeuvrability. A disadvantage of these systems is that the propeller needs to be located underneath the keel, which can significantly increase the draught of the vessel.

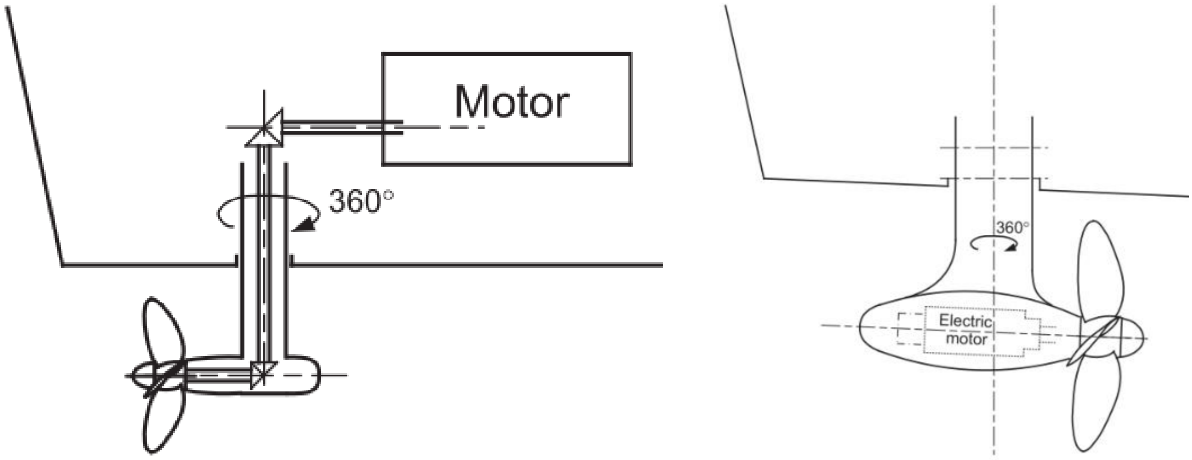


Figure 11: Overview of different rotatable propellers: (a) Z-drive unit: the driving motor is located inside of the vessel and connected to the propeller using a 'z-drive' transmission. (b) Podded azimuth propeller: the motor is connected directly to the propeller

2.2.1.3 *Waterjet propulsion*

Waterjet propulsion systems use a pump to draw water into the hull and subsequently discharge it through an outlet or nozzle. Various pumps can be used in this kind of system and the outlet can either be located above or below the water. A rotating nozzle or a reversing bucket can be used to provide a variable thrust direction or reverse thrust, respectively. The main advantage of waterjet systems is that they can be fully incorporated into the hull, introducing no underwater appendages. On top of that, similar to rotatable propellers, fully-rotatable waterjet thrusters can provide excellent manoeuvrability when used in pairs. A disadvantage is their relatively low power efficiency at low speeds. An example of waterjet-like systems is the propulsion setup of Cogge (based on the Watertruck^{+} project), which is shown in Figure 12.

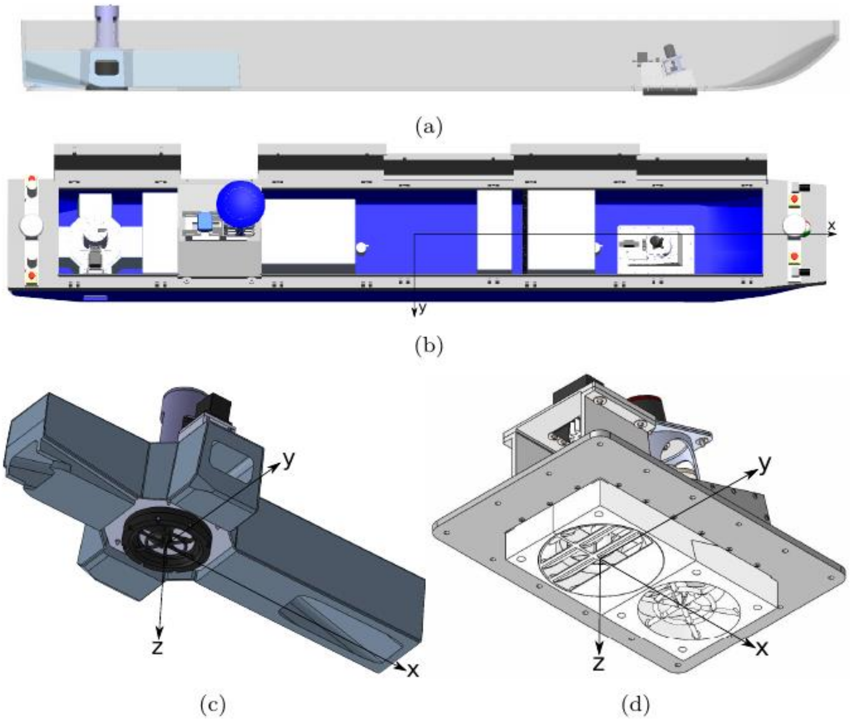


Figure 12: Embedded propulsion systems Cogge. (a) and (b) provide an overview of the location of the thrusters, (c) is a four-channel thruster integrated into the stern, and (d) is a steering-grid thruster integrated into the bow

2.2.1.4 Sails

Although uncommon in an inland navigation context, sails are also included for completeness. Sails act as an aerofoil, generating a propulsive force of which the direction depends on the wind angle and sail orientation. Within the IWT context, sails could be used as an auxiliary propulsion system, temporarily decreasing power consumption.

2.2.2 Propulsion configuration

The propulsion configuration refers to the physical placement of the different propulsion devices on the vessel (e.g., for Cogge [1, 2, 7] on Figure 13). The locations at which propulsive forces can be generated greatly influence the manoeuvrability of the ship. A commonly used configuration is to install two propeller-rudder systems at the back of the ship, as shown in Figure 10. Such a setup only slightly increases the manoeuvrability, as the vessel remains underactuated[3]. A setup as shown in Figure 13 offers great manoeuvrability, since it allows the vessel to move sideways and to make a turn while staying in the spot.

---

[3] Which means that, in theory, it cannot be commanded to follow any arbitrary trajectory on the waterway.

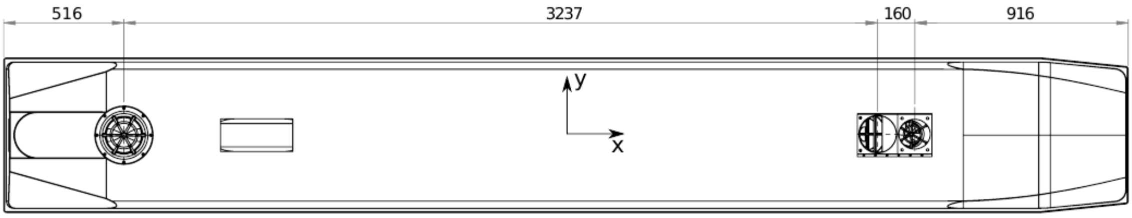


Figure 13: Longitudinal position of the thrusters installed on Cogge

2.2.3 Energy source(s)

The energy source(s), used to power the propulsion system, influence the travel range of the vessel. The available sources also depend on the propulsion setup, since some propulsion systems exclude certain options.

2.2.3.1 Fossil fuels

Diesel and gasoline-powered vessels currently dominate inland waterway transport. However, restrictions surrounding emissions of NOx, SOx and CO2 are pushing the industry towards the development of 'greener' ships.

2.2.3.2 (Hybrid-)electric

Recently, the use of batteries for power-demanding purposes (e.g. propulsion) of a vessel has been a major topic within the sector. The challenges that come along with these battery systems have been studied and reported by the EMSA [8]. Fully electric-powered vessels are already being developed, generating no local emissions and minimal noise. Ampere[4] (see Figure 14), for example, is the world's first electric ferry constructed by the Norwegian Shipyard Fjellstrand.

Figure 14: Picture of Ampere, the world's first electric Ferry

Hybrid-electric vessels are emerging worldwide, resulting in major fuel savings compared to their fuel-powered predecessors. Company 'Red and White' developed Enhydra[5], which is a 600-passenger, plug-

---

[4] Additional information on Ampere: https://www.fjellstrand.no/flyers/flyer_1696.pdf

[5] Webpage on Enhydra: https://redandwhite.com/enhydra/

in hybrid vessel, the company claims to provide between 20% and 30% fuel savings compared to conventional vessels of its size. These (hybrid-)electric vessels can be combined with renewable energy sources to increase the travel range. Both solar and wind (discussed in the next section) energy can be used to supplement the charge of the batteries. Large areas of solar panels are required to provide a significant contribution, which can be impractical for certain applications.

2.2.3.3 Wind

Wind can also be used as an alternative propulsion mode. Wind-assisted energy can be provided by wind turbines. These turbines can be connected directly to a propulsion system (e.g., a propeller) or to an electrical generator to supplement the battery charge. However, limitations on the freeboard height of inland vessels (due to bridges etc.) may oppose the installation of wind turbines on the deck. On top of that, the wind speeds on inland waterways are relatively low compared to the wind at sea. WASP (Wind Assisted Ship Propulsion[6]) is an example of an active project that focuses on the trial and validation of different wind propulsion solutions.

2.3 Sensor system

Inland vessels can also be categorised based on the installed on-board sensors. In general, a distinction is made between proprioceptive sensors, measuring the state of the vessel itself, and exteroceptive sensors, measuring the state of the vessel's environment. The available sensors greatly influence the possibilities when it comes to vessel control systems (further discussed in section 2.4) and environmental perception. Figure 15 gives an overview of how the sensor system relates to the other subsystem of an inland cargo vessel.

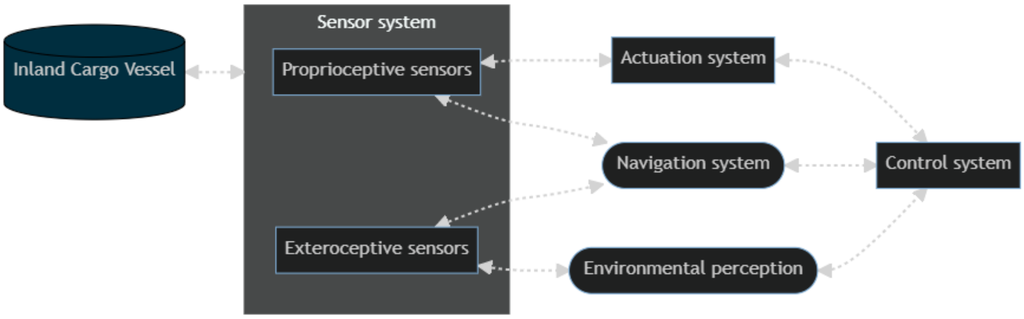


Figure 15: Flowchart showing how the sensor system is related to other sub-systems of an inland cargo vessel

2.3.1 Proprioceptive sensors

Proprioceptive sensors provide measurements of the state of the vessel itself. For a vessel, the state consists of its location, orientation, (angular) velocity, (angular) acceleration and actuator states (e.g., propeller speed and angle). Within an inland waterway context, the location, orientation, and dynamics are usually only considered within the horizontal frame. To define these states, two references frames are defined (shown in Figure 16): (i) An earth-fixed reference frame of which the axes point towards the North, East and the centre of the Earth (down). The exact location of this frame is defined

---

[6] WASP project website: https://northsearegion.eu/wasp

by the user (e.g., the starting point of a certain journey). This frame serves as the reference when computing the position/orientation of the vessel. (ii) A body-fixed reference frame, which is attached to the vessel itself in a user-defined location on the ship (e.g., the centre of gravity, at midship, location of a certain senor). The axes of this frame are usually aligned with the principal axes of inertia of the vessel. Table 3 gives an overview of the typical components contained within the vessel's state within the defined reference frames.

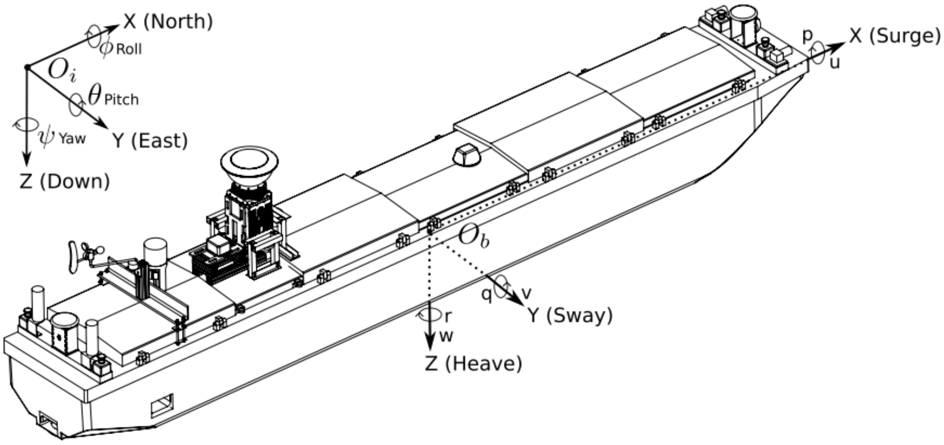


Figure 16: Earth-fixed/inertial (O_i) and body-fixed (O_b) reference frames

Table 3: Overview of a vessel's state

Subset of state	Symbolic	Definition of included variables
Position and orientation	$\boldsymbol{\eta} = \begin{bmatrix} \boldsymbol{N} \\ \boldsymbol{E} \\ \boldsymbol{\psi} \end{bmatrix}$	$\boldsymbol{N}$ and $\boldsymbol{E}$ are respectively the North and East position of the body-fixed frame relative to the earth-fixed frame in $\boldsymbol{m}$. $\boldsymbol{\psi}$ is the yaw angle, measured between the x-axes of the earth-fixed and body-fixed frames in $\boldsymbol{rad}$.
Velocity	$\boldsymbol{\nu} = \begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{v} \\ \boldsymbol{r} \end{bmatrix}$	$\boldsymbol{u}$ and $\boldsymbol{v}$ are the velocity in forward (surge) and lateral (sway) direction in $\boldsymbol{m/s}$. $\boldsymbol{r}$ is the angular velocity of the vessel around the vertical axis (yaw rate) in $\boldsymbol{rad/s}$.
Acceleration	$\dot{\boldsymbol{\nu}} = \begin{bmatrix} \dot{\boldsymbol{u}} \\ \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{r}} \end{bmatrix}$	$\dot{\boldsymbol{\nu}}$ is the derivative of $\boldsymbol{\nu}$, containing the linear accelerations in surge and sway direction as well as the angular yaw acceleration.
Actuator(s) state	$\boldsymbol{c} = \begin{bmatrix} \boldsymbol{n_1} \\ \boldsymbol{\alpha_1} \\ \cdots \\ \boldsymbol{n_k} \\ \boldsymbol{\alpha_k} \end{bmatrix}$	$\boldsymbol{c}$ contains the state of the thruster(s), where $\boldsymbol{k}$ represents the number of thrusters. For every thruster, $\boldsymbol{n}$ refers to the propeller speed and $\boldsymbol{\alpha}$ to the acuation angle.

To measure the vessel's η, ν and $\dot{\nu}$ (defined in Table 3), usually a Global Navigation Satellite System (GNSS) receiver is combined with an Inertial Measurement Unit (IMU). The GNSS receiver measures the vessel's location, whereas the IMU measures its linear accelerations ($\dot{u}$ and $\dot{v}$) and rotation rates (r) of the vessel using accelerometers and gyroscopes, respectively. The accuracy of the GNSS receiver depends on numerous factors: (i) the specifications of the receiver, (ii) the number of available satellites, (iii) the position of the available satellites (more dispersed is better), (iv) atmospheric interference, (v) signal obstruction (e.g., when passing a bridge), and (vi) possible GNSS corrections. The latter refers to a service (usually through a paid subscription) that provides corrections to the user's GNSS receiver based on data from a network of ground-based reference stations of which the true locations are known. By using a GNSS receiver with two antenna's, the orientation (ψ) of the vessel can also be measured by using trigonometry. The accuracy of the IMU mainly depends on the quality of the integrated accelerometers and gyroscopes. However, the acceleration measurements are influenced by active vibrations on the vessel, which can be caused by, e.g., the actuation system.

The GNSS and IMU typically work in combination, as shown in Figure 17. By fusing their data (e.g., with a Kalman filter), the entire η, ν and $\dot{\nu}$ of the vessel can be estimated by using sensor fusion. On top of that, by combining the data from multiple sensors, the accuracy of the states which are directly measured can be improved. Several sensor fusion algorithms exist, of which the (Extended) Kalman Filter is most widely applied.

The state of the actuators, which usually contains motor/propeller speeds and actuation angles, can be measured using tachometers/gyroscopes and encoders, respectively. In some cases, these sensors can be integrated within the actuator itself.

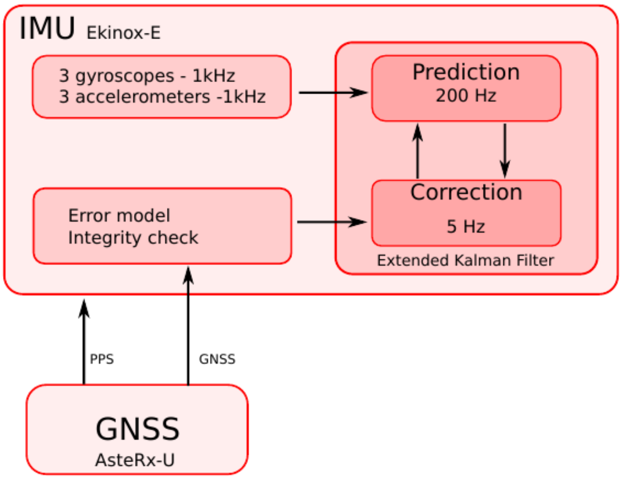


Figure 17: Working principle of an extended Kalman filter, using an IMU and GNSS [1, 2]

2.3.2 Exteroceptive sensors

Exteroceptive sensors measure the state of the inland vessel's environment, which comprises its physical surroundings as well as wind and local water current. To measure a vessel's physical surrounding, usually either one or a combination of the following sensors is used: (i) a Laser Imaging Detection And Ranging (LIDAR) sensor measures the distance to surrounding surfaces/objects by using a rotating laser. This sensor is most effective for measuring close-range (under $100m$) surroundings, has very high accuracy, but requires high computing power for data processing. (ii) a RAdio Detection And Ranging (RADAR) sensor measures the distance to surrounding surfaces/objects using radio waves. This sensor is most effective for measuring long-range surroundings. (iii) Cameras are mainly used as an auxiliary sensor for distinguishing shapes and colours. A disadvantage is that they are highly weather dependent. The data from the aforementioned sensors can be processed to create a map of the environment. As an example, a shoreline extraction based on a lidar scan is shown in Figure 18 [9].

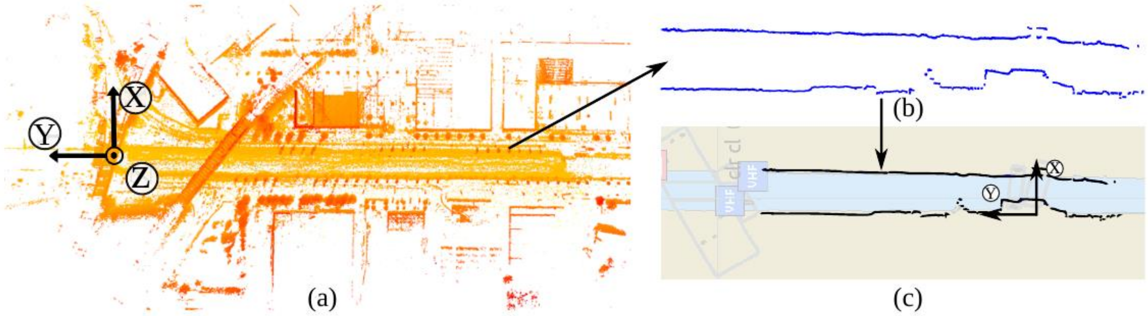


Figure 18: Shoreline extraction from lidar data. (a) lidar data set, (b) shoreline extraction, and (c) extracted shoreline and inland navigation chart shoreline comparison

Wind speed and water flow sensors can be used to estimate the external forces acting on the vessel due to wind and water current. This data can serve as useful information for advanced controllers (further discussed in section 2.4).

Figure 19 shows an interconnected mobile plug-and-play sensor box as above, installed at one barge.

Figure 19: Mobile plug-and-play sensor box

2.4 Control system

A control system can be defined as a system that regulates the behaviour of other devices or systems based on user-defined setpoints and/or the (estimated) state of the controlled device or system. In an inland navigation context, the outputs of such a control system are usually voltages, currents or electrical pulses that are used to drive the actuators. The control system can be split up into a 'low-level' and 'high-level' controller. The high-level controller will provide the low-level controller with the required motor speeds, rudder/thrust angles, etc. of the propulsion system to reach a user-defined objective. The low-level controller then converts these values into the proper format (voltage, current, electrical pulses, etc.) that is required to drive the actuators. Figure 20 shows the connection between the control system and the previously discussed sub-systems. The following sections will further discuss both the low and high-level controllers.

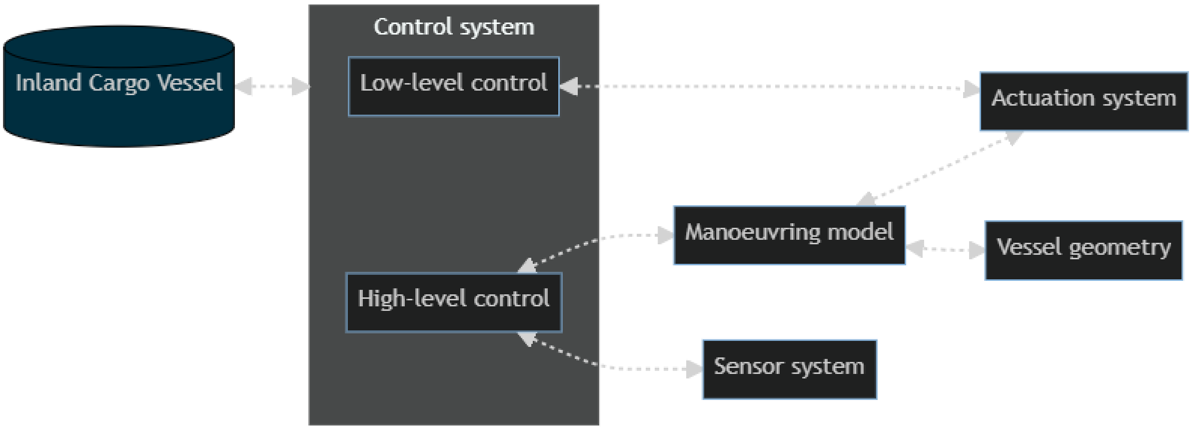


Figure 20: Flowchart showing how the control system is related to other sub-systems of an inland cargo vessel

2.4.1 Low-level controller

This controller provides the lowest level of control computations. Usually, some type of programmable logic computer (PLC) or equivalent machine is used for these computations, because of their high reliability and robustness.

2.4.2 High-level controller

This controller provides some level of automation, which can range from keeping the vessel at a constant heading up to fully autonomous operation, which would require little to no human interference. Usually, some type of (onboard) industrial computer is used to process these more advanced computations. The degree to which this controller can operate autonomously depends on: (a) the available real-time information on the vessel's state (position, orientation, velocity, etc.) and surroundings, which are provided by the sensor system, and (b) the available models that can describe the vessel's hydrodynamic behaviour (see section 2.4.2.1).

Currently, most ISV's have a relatively simple autopilot installed, allowing them to keep a desired heading and propeller speed. Most of these autopilots use a PID controller for this, controlling the angle of the ISV's rudder to keep the desired heading. Recently, more advanced controllers are being released, which can make the vessel follow a pre-defined path, e.g., the Tresco TrackPilot[7]. These controllers

---

[7] For more information, please visit: https://www.tresco.eu/trackpilot/

produce heading and propeller speed commands and can therefore be connected directly to the existing autopilots. However, these systems are far from fully autonomous since the pre-defined path does not consider it's environment in any way.

2.4.2.1 Manoeuvring models

A manoeuvring model is a mathematical model that approximates the dynamics of a certain vessel based on the active forces that are working on it. Within an inland navigation context, this model usually describes the dynamics in the horizontal plane, i.e., forward/surge motion, sideways/sway motion, and angular rotation within the horizontal frame (change of heading) or yaw motion. Such a model typically describes one or several of the following: (a) the vessel's hydrodynamic behaviour, which describes how the vessel moves through the waterway when subjected to a certain force vector, (b) the forces generated by the actuation system at different propeller speeds and/or vessel speeds, and (c) environmental forces, e.g. wind force, acting on the vessel as a function of a measurable variable(s), e.g. wind speed. [6] provides an overview of different types of manoeuvring models.

These models contain a series of parameters, which have varying values based on the hull geometry and propulsion system. This implies that, in order to be able to use the model, the values of these parameters need to be (experimentally) determined for every vessel. The process of selecting an appropriate model and estimating the model parameters for a certain ship is referred to as model identification. For inland vessels, hydrodynamic behaviour is heavily influenced by the clearance between the hull and the waterway. A change in keel clearance (between keel and bottom of waterway) therefore changes the value of certain parameters within the manoeuvring model. The university of Ghent is actively conducting research on the effects of a changing keel clearance [10, 11].

2.4.2.2 Vessel identification

The establishment of an appropriate model structure together with the estimation of the model parameters is referred to as vessel (model) identification. The most accurate results can be achieved using towing tanks, where the ship is connected to a towing carriage that forces the ship to sail a certain trajectory and simultaneously measures the required forces to do so[8]. These towing-tank tests are therefore optimal for defining accurate model structures that can be applied to real-size vessels. However, the values of the model parameters of a scale-model vessel cannot be directly converted to the corresponding parameters for a real-size vessel with the same geometry. Therefore, research is being conducted towards a model parameter estimation strategy/method using sensor data from free-sailing manoeuvres, e.g. in [12]. Such a strategy/method would enable the use of advanced manoeuvring models within a model-based high-level controller.

---

[8] Example of a towing tank: https://www.waterbouwkundiglaboratorium.be/en/facilities-and-tools/physical-modelling/towing-tank-confined-water-antwerp

2.5 Communication system

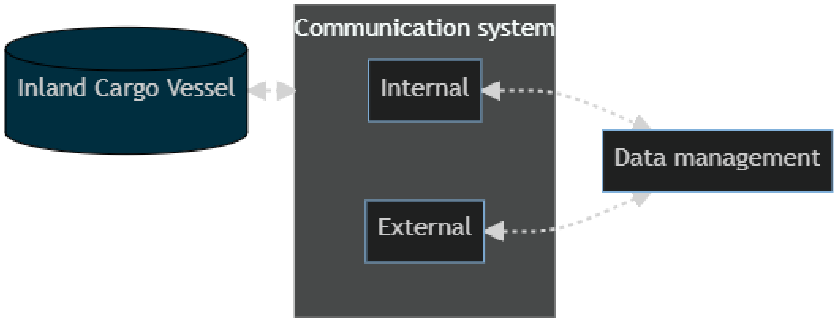


Figure 21: Communication system architecture for Inland Cargo Vessels

The vessel communication system includes both, internal and external communication subsystems (see Figure 21).

2.5.1 Internal (intra-vessel)

Internal communication between the computational, actuation, and sensor systems.

2.5.1.1 Hardware

- Routers/network switches
- Field buses
- Serial communication devices
- Antennas

2.5.1.2 Relevant examples and protocols

On board, several sensors and other subsystems communicate their data over a (W)LAN network (TCP/UDP) to a central server, or, receive data from the central computer over a network interface. Network communications. Protocols can be divided into two categories:

- **Transport protocols:** conventions for handling and converting data streams for exchange between computers over a physical network cable, a fiber optic cable, or a wireless network. These protocols correspond to the transport- oriented functions of the OSI model. Examples of transport protocols include TCP/IP, UDP, IPX/SPX, etc.

- **Communication protocols:** communication can be text-based, binary, or any form of encryption for certain tasks to be run on a (remote) computer.

A servers (or central computer) can support several transport and communication protocols in parallel. It is thus important to know which protocols exist with the corresponding communication mechanisms and for what purpose they are used. If required, you can install missing protocols later or remove superfluous protocols anytime to adapt to a changing network environment.

- **Serial communication** is a communication method that uses one or two transmission lines to send and receive data, and that data is continuously sent and received one bit at a time. Since it allows for connections with few signal wires, one of its merits is its ability to hold down on wiring material and relaying equipment costs. RS-232C, RS-422A, and RS-485 are EIA (Electronic Industries Association) communication standards. Of these communication standards, RS-232C has been widely adopted in a variety of applications, and it is even standard equipment on computers and is often used to connect modems and mice. S**ensors and**

actuators also contain these interfaces, many of which can be controlled via serial communication.

- **Field busses** (and their corresponding protocols) commonly integrated and used in vessels that are **built with automation and computer-driven** control in mind:
- **CAN** is a multi-master serial bus standard for connecting electronic control units (ECUs) also known as nodes (automotive electronics is a major application domain). Two or more nodes are required on the CAN network to communicate. The concept of CAN is that every device can be connected by a single set of wires, and every device that is connected can freely exchange data with any other device. An often-used extension of the CAN standard is the communication protocol **CANopen,** which has been standardized as European standard EN 50325-4.
- **MODBUS**: a serial bus to connect their programmable logic controllers (PLCs) called Modbus. The protocol itself is very simple with a master/slave protocol and the number of data types are limited to those understood by PLCs at the time. Nevertheless, Modbus is (with its Modbus-TCP/IP version) still one of the most used industrial networks, mainly in the building automation field.

2.5.2 External (inter-vessel, vessel-shore, vessel-to other systems)

External communication to the shore, other vessels, or similar. This is further discussed in Section 3, emphasising on the vessel interoperability and the situational awareness characteristics.

2.6 Example

A partially populated example of the schemes above is displayed in Figure 22 [1, 2]. This is the current communication architecture of the Cogge research vessel (KU Leuven).

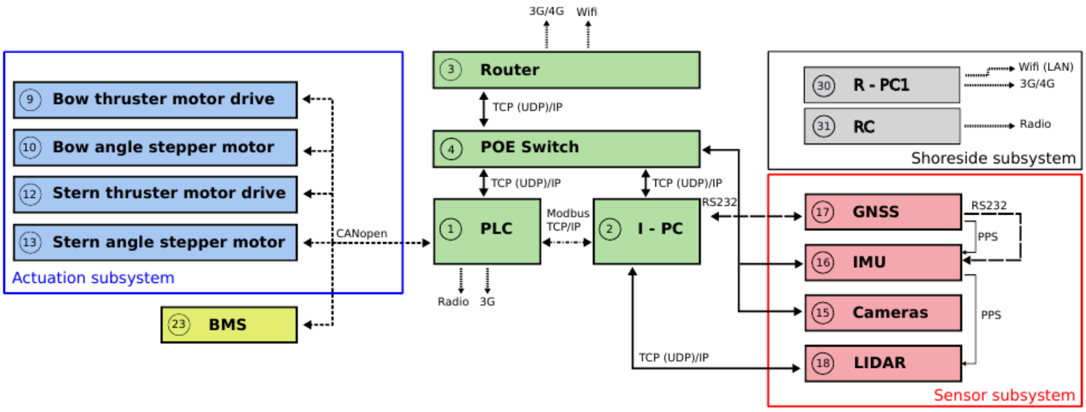


Figure 22: Overview of communication between different sub-systems installed on Cogge

3 Vessel Interoperability and situational awareness

Vessel-to-vessel and vessel-to-shoreside interactions will play a vital role in the Ghent living Lab, especially in Application Scenario 3. Customising every single "interaction", with corresponding *hard-coded* software pieces, is simply not sustainable, and will result in a lot of development overhead.

In general, ships and their associated infrastructure are becoming more and more connected. With the evolution towards remote controlled and autonomous vessels in mind, reliable data and communication is essential. However, interconnectivity and interoperability between systems in inland waterway environments is still a challenge, especially in terms of standardized protocols and interfaces.

In the "dynamic environments" of the IW-NET the Living Lab, automated vessels, and corresponding applications, as well as remote control and monitoring services, must integrate many tasks and motions at the same time [13]. Moreover, they need to account for physical disturbances, and dynamically allocate software resources available within a particular environment. To enable these higher levels of automation for inland cargo vessels and their associated shoreside infrastructure, new IWT developments will need to incorporate shared situational awareness, and define, or extend formal knowledge systems accordingly.

3.1 Context and motivation

In the roadmap for IWT [14], the presence of an adequate (ICT) infrastructure is identified as a critical enabler for increasing the capacity utilization of inland waterways, as well as for enhancing innovative technological developments. In a 2020 projection, the total cargo flow (271 million tonne*km) corresponding to small inland waterways is threatened to shift towards road transport when infrastructural and technological investments would only focus on road haulage rather than IWT, resulting in an additional external cost of over 6 million euros. At the EU level, the NAIADES II project[9] (2014–2020) aims to significantly increase the quality of IWT, with infrastructure and innovation stipulated as key areas of intervention. The NAIADES project acknowledges the importance of the River Information System (RIS) directive, providing various information services, such as (i) the introduction of new navigation tools and systems, e.g., to obtain a higher level of automation, and (ii) the electronic data exchange and corresponding international data standards.

Furthermore, it should be noted that initiatives such as Watertruck+ already contribute to unlocking the potential of small waterways. Within the RIS system, ECDIS[10] is a crucial navigational support component. With the use of ECDIS, it has become easier for a ship's navigating crew to pinpoint locations and attain safe navigational directions. The assistive navigational data is presented on top of the IENC as thematic overlays using ECDIS technology. In 2006, discrete realtime information, i.e. location, heading, depth display, weather, currents and tidal heights, among other data [14] has been integrated in ECDIS by the introduction of the AIS system. In the last decade, a continuous radar overlay is often added as well. This introduction of realtime data proved to be a significant first step towards increased

---

[9] For more information on the NAIADES II project, the interested reader can visit: https://transport.ec.europa.eu/transport-modes/inland-waterways/promotion-inland-waterway-transport/naiades-ii_en

[10] For more information on ECDIS, the interested reader visit: https://ecdis-info.com/question/

automation, i.e. automated decision aid; however, sensor data that is layered on top of the IENC charts is typically **not shared between assets or used to dynamically update features in the charts.**

3.2 State of the art and corresponding limitations

Inland navigational charts, infrastructure, and communication frameworks currently in place are inadequate to enable safe and reliable navigational assistance and automated operations on inland waterways, especially for close encounter manoeuvring of vessels.

3.2.1 Electronic Navigational Charts and ECDIS

Two types of limitation can be identified, one at sensor level and a second one at chart level:

(1) At sensor level the Inland ECDIS standard imposes the following minimal requirements under normal operation conditions for navigation:

- the average position estimation shall not deviate more than 5 meters from the true position and shall cover all systematic errors.
- the standard deviation σ shall be less than 5 meters and shall be based on random errors only.
- the system shall be capable to detect deviations of more than 3 σ within 30 seconds.

(2) At chart level there is no standard (or attribute) that defines the xy-accuracy of IENC objects presented on the screen. However, every chart cell is assigned a “usage”, ranging from 1 to 9. While this is not an absolute accuracy in terms of, for instance, distance between objects and/or vessels, it does assign a certain precision and detail to the charts and information shown on the screen. In fact, “usage” corresponds to a navigational purpose; for instance, “1” shows an overview used for route planning, while “9” has detailed data to aid berthing manoeuvring in inland navigation. This data alone, without for instance radar overlay, is not sufficient for navigational purposes. Whenever onboard sensor information such as RADAR, LiDAR, among other sensors, is available, it is not shared with other vessels operating in the same zone, nor is it integrated into the IENC charts. This means that ever-changing dynamic environments, e.g., other vessels, obstacles, among many others, are not updated or integrated into the charts.

Hence, these sensors mainly serve for onboard decision making, and do not contribute to a systems-of-systems control approach.

3.2.2 Open standards and protocols

Current IHO standards[11], such as S-57, S-63, S-52 aim to support safety on our waterways and provide uniformity in nautical charts and documents. Inland IENCs (IENC) conform to the IHO specifications contained in S-57, which is a transfer standard for vector data, used for the transfer of digital hydrographic data between national hydrographic offices and for its distribution to manufacturers, mari-

---

[11] For an overview and explanation of the current IHO standards, the interested reader can visit: https://www.admiralty.co.uk/news/blogs/s-57-and-the-latest-iho-standards

ners/skippers, and other data users. These standards are merely related to the production and distribution of IENCs, and their portrayal in ECDIS systems; they are not designed, not do they aim to be, to enhance higher levels of automation.

Moreover, these standards only cover the IENC-part. Companies that produce Inland ECDIS systems exploit other sensors and navigational data to develop a proprietary Inland ECDIS. Everything related to "increased onboard intelligence" is closed, which severely limits a shared autonomy approach in which systems and sub-systems from different assets can interactively "talk" and "act". Furthermore, mechatronic standardization is practically non-existent for inland waterways, while it could be a substantial enabler for higher levels of automation in a systems-of-systems philosophy.

3.2.3 Shared situational awareness

Advancements in interconnectivity and interoperability between different vessels and shoreside control- and monitoring centres are severely constrained by the limitations of existing communication frameworks and data exchange information. Due to the insecure nature of AIS, often integrated in an ECDIS, the current information sharing platform is vulnerable to spoofing. Data content of AIS is estimated to be correct in only 80% of the cases[12]. Standard deviation of the position is about 9.26m and the update rate (multiple seconds to minutes) is often too low to be valuable in autonomous systems, especially when many assets are active simultaneously within one zone.

In general, current solutions are restricted by the boundaries of available technology (e.g., 4G, Satcom and meshed WIFI to interconnect, control and harvest asset data). This has a large implication for shared situational awareness, where vessels exchange information with each other about their surroundings with the overarching goal of improved safety (e.g., for navigation), asset management, and enable higher levels of automation.

To this end, **the following challenges** need to be considered:

1. **Formal, semantic world models** and corresponding **relations** need to be constructed for different levels of interaction (e.g., onboard vessel components and their internal interfaces, interaction between vessels and shared maps, sharing sensor data, etc.).

2. Shared situational awareness requires extensive exchange of sensor data between vessels. From data intensive sensors, such as 3D point cloud generating **sensors**, the data must be reduced to **useful information** in such a way that there is a maximum value per byte transmitted.

3. Connectivity must be possible between assets at different levels (edge-fog-cloud) and from different manufacturers and owners, over various communication channels that can have fluctuating quality and that might only be temporarily available. To set up a distributed, shared environment model over such a **dynamic communication environment, flexible and secure multipath** communication **solutions are required**. At the same time, deeper insights in the communication behaviour are needed to optimize data distribution and adjust data reductions.

4. Data information communication should not only be point-to-point with customized protocols but kept and shared among multiple peers. (e.g., RADAR image sharing, collaborative collision avoidance, convoy sailing, etc.). The issue of which data to send to which vessel at which time, however, is currently not solved. **Data-sharing must be optimized intelligently**, as

---

[12] According to the reported data at: https://arundaleais.github.io/docs/ais/ais_reporting_rates.html

communication bandwidth is limited and not all data is needed by each actor in the environment.

5. Not all vessels are equipped with state-of-the-art positioning- and communication systems and **current infrastructure is not suited for an shared and cost-effective approach.** Vessels mainly rely on their onboard sensors. A significant challenge will be localizing these vessels, their route and anticipating their sailing behaviour.

An overview of the current navigation system for vessels (integrated ECDIS), which currently serves as the main system for situational awareness, and an upgraded, dynamic, situational awareness system with relevant components developed within (and outside) IW-NET, is illustrated in Figure 23.

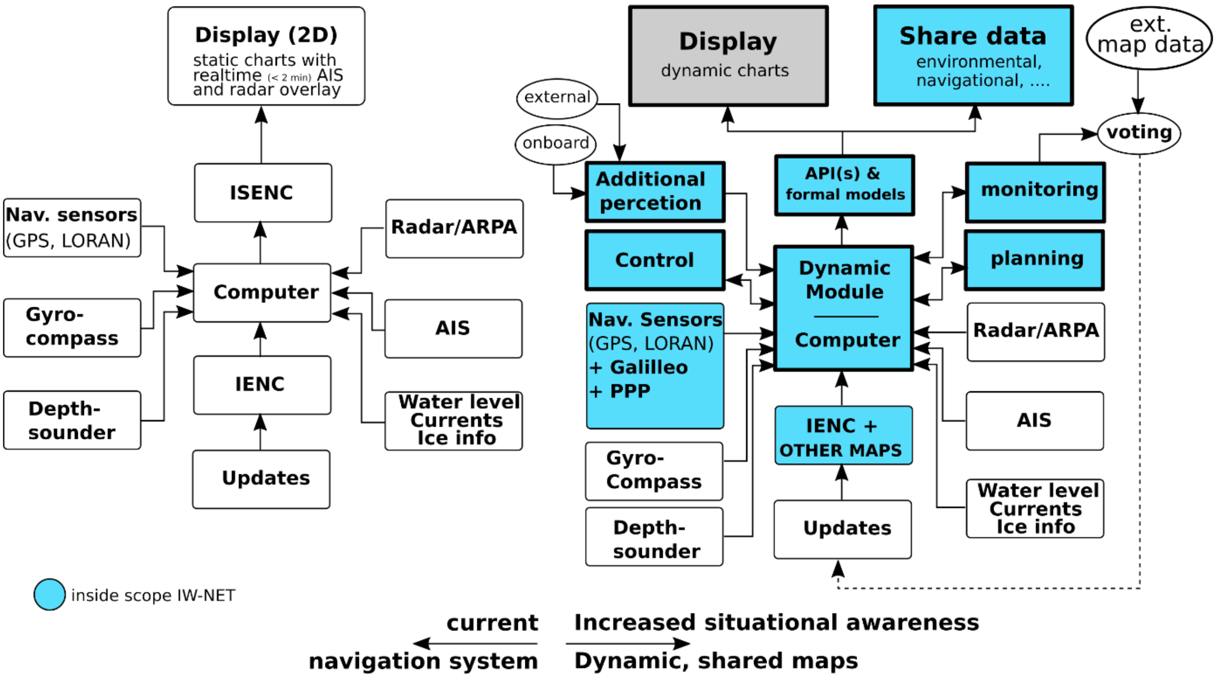


Figure 23: Overview of current awareness and navigation systems, and upgraded situational awareness system for inland waterway transport, explored and developed within IW-NET

3.3 First experiments with shared, dynamic maps and formal world models

In an effort to model such semantic information with respect to a single vessel, that is, mainly its vessel- and actuation components, as well as a set of models on *how* such vessels can ***interact,*** a research paper was published, by the KU Leuven research group in the beginning of 2022 [13]. In this IW-NET related work, experiments were performed in **simulation**. A key factor towards validation, identified as an import next step, is to perform similar experiments in real life. This is where the IW-NET test bed, i.e., the living labs, will prove to be extremely valuable.

The main idea put forward in this paper is that every *actor* operating in a specific environment or corridor can share model-conform information with its peer, which can as such be visualised on a shared, dynamic map. This map is the same for all actors (including shoreside RCCs), albeit with transformed origins, and needs to be updated in real-time, for instance, with data from perception sensors.

With the models described in [13], a simulation was performed where two vessels cross each other in a COLREG-compliant manner, in a rather narrow (20m) channel. The shared information that is put into the map in real-time can be used as a high-level controller (constraints), or as a shoreside monitoring tool, to make sure the automated operation is performed in a safe and standard-compliant way. An example of such a manoeuvre is illustrated in Figure 24.

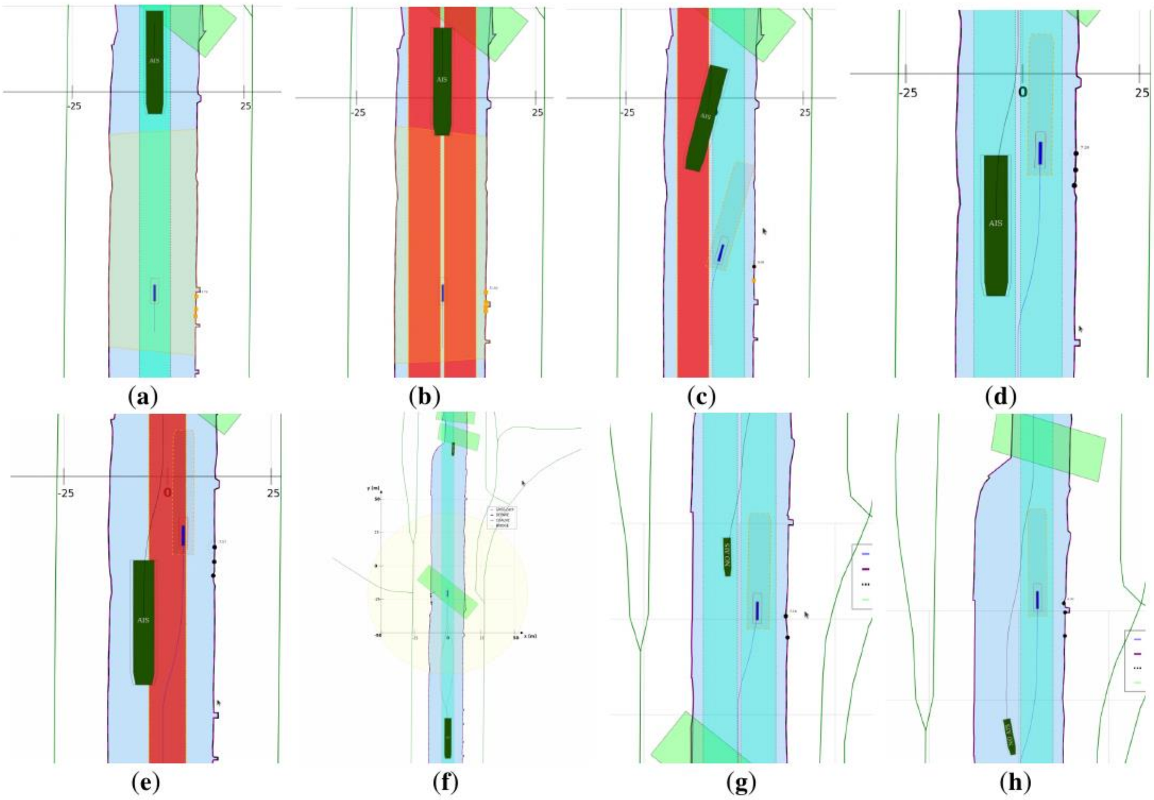


Figure 24: Overview of communication between different vessels

The most important concepts here are:

- A lane-shift primitive is added, as an additional (dynamic) geometry agreed upon by both parties. When the two vessels perceive each other (or one perceives the other), a COLREG-compliant lane protocol is initiated, with geometric dimensions based on the vessel models.
- The small “single vessels“ have at least one, and ideally 3 semantic vessel zones, with geometries that are dynamically updated based on speed and external disturbances.
- When the uncertainty zone (black, minimal requirement) of a single vessel lies *within* the lane geometry, i.e., within the navigational constraints agreed upon beforehand, the zone turns green, and the vessel can safely continue its operation.
  When one vessel is not able to navigate into a (virtual) lane *before* a predefined distance, it has to initiate a fallback scenario (typically remote-control takeover and give priority to the other vessel).

A **video** of this simulation experiment can be found here.

The models in [13] will be extended with a new set of world models relevant in the IW-NET context.

4 IW-NET vessel

Given that a Single Vessel may be part of an IWT fleet, may or may not have an onboard or onshore crew, and may have some kind of autonomy/automation software on board, this section serves to categorise these additional integrations. Figure 25 provides a high level view of all important vessel parameters, also captured as a model and modelled as library components of the IW-NET simulation library, described in section 5. These parameters are discussed in the following paragraphs.

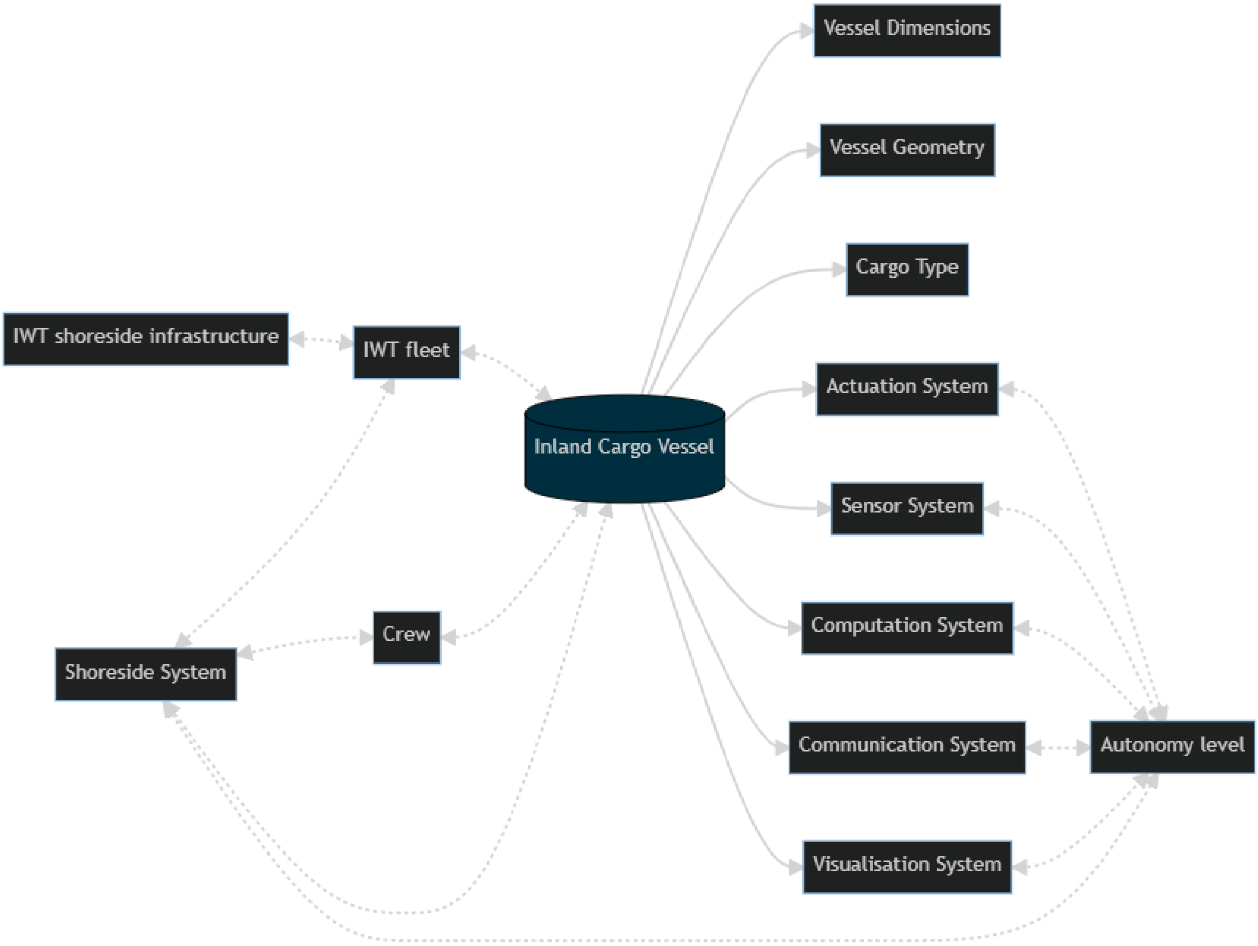


Figure 25: W-NET Vessel conceptual model and concepts taxonomy

4.1 IWT fleet

In this section, a range of innovations and technologies related to vessel fleets are discussed. Furthermore, technologies of Section 2 and 3 will be applied to the IW-NET fleet in the living labs.

4.1.1 Platooning vessel (software coupling)

Vessels that follow each other through a digital connection, e.g., Novimar[13] (Figure 26). For this, a critical enabler will be a formal data- and communication protocol, as discussed in Section 3. While a customised (software) interface for platooning with IW-NET vessels is certainly possible, it would significantly limit the adoption of such a technology for use in other situations, and with other systems.

Figure 26: Screenshot from Novimar concept animation

---

[13] Animation explaining the Novimar 'vesseltrain': https://novimar.eu/animation/

4.1.2 Coupled vessel (hardware coupling)

Vessels that are connected through a physical connection, e.g., Watertruck⁺ (Figure 27)

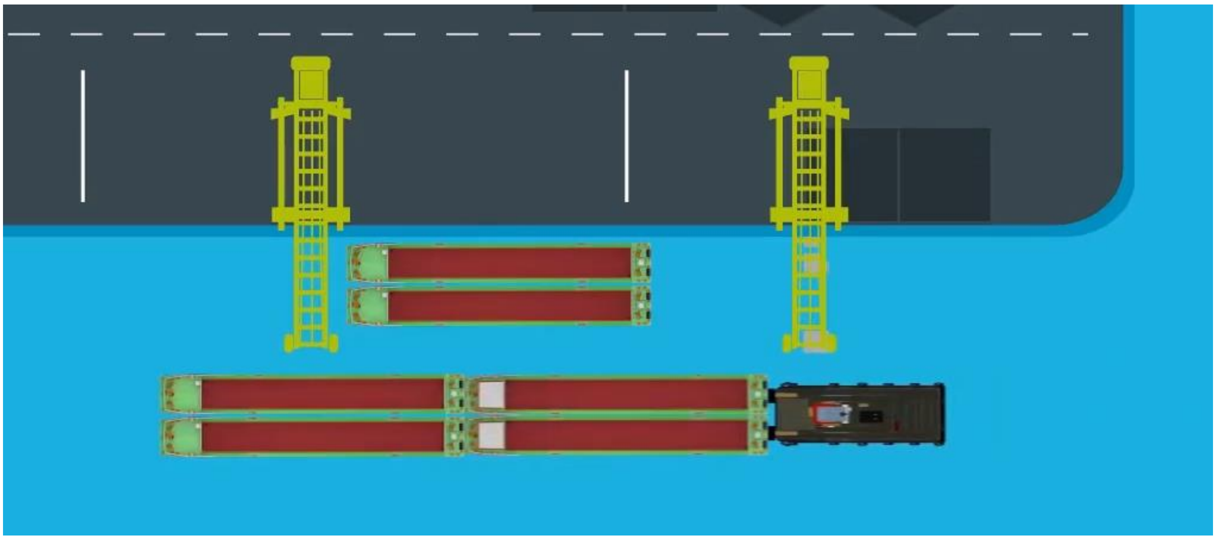


Figure 27: Watertruck⁺ vessel pushing two unpropelled barges

4.2 Shoreside System

These systems allow for remote (from the shore) monitoring and/or control of the vessel. Examples are provided below:

- Land-based, fixed, shore control centre, e.g., from [15] (Figure 28).

Figure 28: Shore control centre to control Cogge while looking at the available video streams and a real-time overview of useful (sensor) data

- Flexible, wearable, remotely-accessible (web-based) interfaces/devices, e.g., from [15] (see Figure 29)

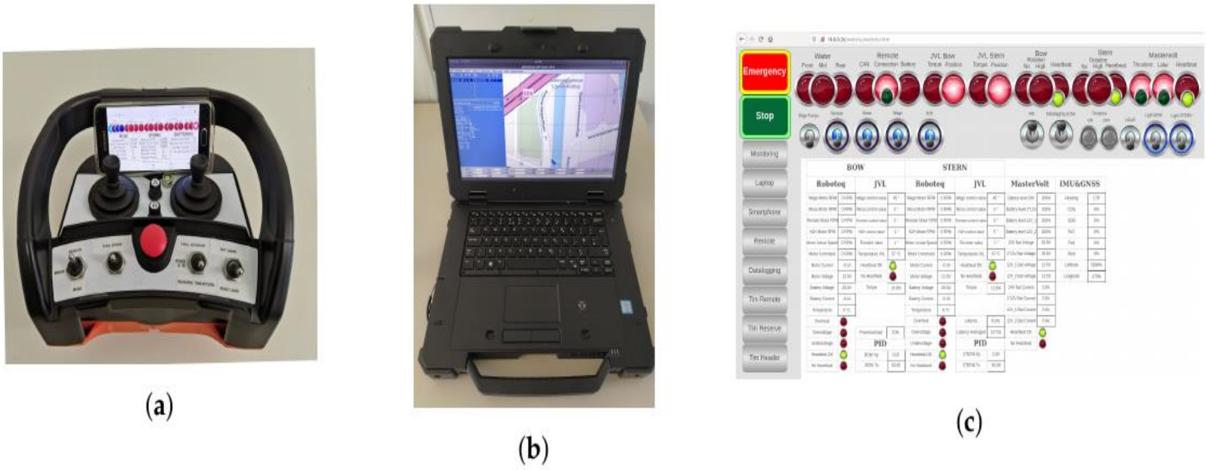


Figure 29: Additional shore-side control components for Cogge: (a) wearable remote controller with web-interface, (b) rugger computer (R-PC) running MOOS-IvP, and (c) an additional laptop monitoring the PLC web-interface

4.3 Crew

4.3.1 Onboard

Their tasks would include:

- Direct control
- Supervision
- Unmanned bridge

4.3.2 Onshore

Their tasks would include:

- Direct remote control
- Supervising vessel autonomy

4.4 Shoreside infrastructure

To allow for shared, cost-effective automation, shoreside infrastructure plays a vital role. Especially at critical regions (lots of traffic), such as quays, terminals, locks, etc., shoreside sensors that collect data and share it with the environment can reduced the investment cost for new “Smart” vessels if they can exploit this data in their operations.

It is within the scope of IW-NET to identify *which* sensors and shoreside systems can have a substantial impact on the situational awareness, safety, and level of autonomy on inland waterways.

4.5 Autonomy level

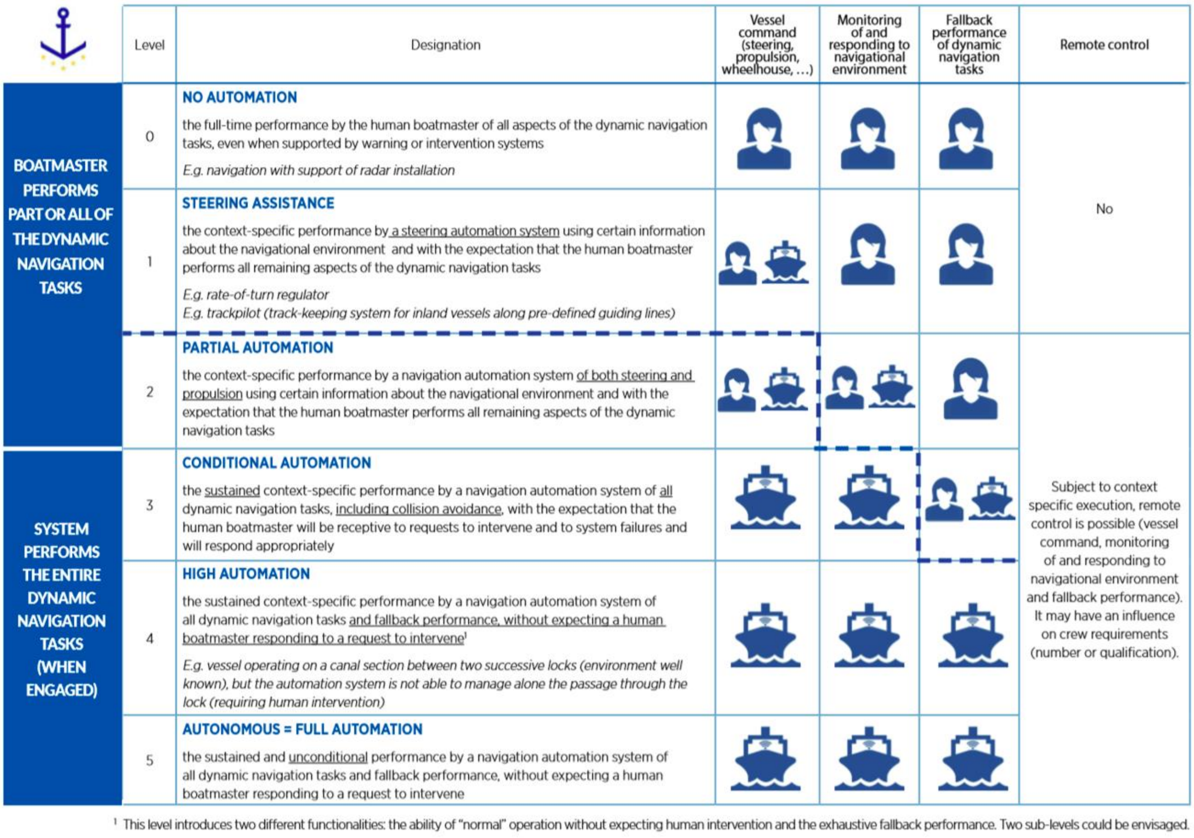
Full automation is at this point practically unfeasible unless the environment is adequately controlled. As such, the IW-NET living lab in Ghent aims for incremental innovation towards increased autonomy, alongside experiments in several different situations to identify risks and operational feasibility related to a certain level of autonomy.

Furthermore, the levels of autonomy, and the associated tasks vessels need to be able to perform, will be closely related to regulation. One could imagine different levels of certification for automated vessels, depending on their capabilities with respected to automated navigation, data communication, and interoperability.

Different statements exist to define the level of autonomy:

- Levels defined by Central Commission for the Navigation of the Rhine (CCNR): 'First international definition of levels of automation in inland navigation' (see Figure 30).
- Levels defined by Norwegian Forum for Autonomous Ships (NFAS) [16] (see Figure 31).

E.g., a specific level of vessel automation: waypoint following (GNSS and IMU-based) [1, 2] (see Figure 32)



	Level	Designation	Vessel command (steering, propulsion, wheelhouse, ...)	Monitoring of and responding to navigational environment	Fallback performance of dynamic navigation tasks	Remote control
BOATMASTER PERFORMS PART OR ALL OF THE DYNAMIC NAVIGATION TASKS	0	**NO AUTOMATION** the full-time performance by the human boatmaster of all aspects of the dynamic navigation tasks, even when supported by warning or intervention systems *E.g. navigation with support of radar installation*	👤	👤	👤	No
	1	**STEERING ASSISTANCE** the context-specific performance by a steering automation system using certain information about the navigational environment and with the expectation that the human boatmaster performs all remaining aspects of the dynamic navigation tasks *E.g. rate-of-turn regulator* *E.g. trackpilot (track-keeping system for inland vessels along pre-defined guiding lines)*	👤 🚢	👤	👤	
	2	**PARTIAL AUTOMATION** the context-specific performance by a navigation automation system of both steering and propulsion using certain information about the navigational environment and with the expectation that the human boatmaster performs all remaining aspects of the dynamic navigation tasks	👤 🚢	👤 🚢	👤	Subject to context specific execution, remote control is possible (vessel command, monitoring of and responding to navigational environment and fallback performance). It may have an influence on crew requirements (number or qualification).
SYSTEM PERFORMS THE ENTIRE DYNAMIC NAVIGATION TASKS (WHEN ENGAGED)	3	**CONDITIONAL AUTOMATION** the sustained context-specific performance by a navigation automation system of all dynamic navigation tasks, including collision avoidance, with the expectation that the human boatmaster will be receptive to requests to intervene and to system failures and will respond appropriately	🚢	🚢	👤 🚢	
	4	**HIGH AUTOMATION** the sustained context-specific performance by a navigation automation system of all dynamic navigation tasks and fallback performance, without expecting a human boatmaster responding to a request to intervene[1] *E.g. vessel operating on a canal section between two successive locks (environment well known), but the automation system is not able to manage alone the passage through the lock (requiring human intervention)*	🚢	🚢	🚢	
	5	**AUTONOMOUS = FULL AUTOMATION** the sustained and unconditional performance by a navigation automation system of all dynamic navigation tasks and fallback performance, without expecting a human boatmaster responding to a request to intervene	🚢	🚢	🚢	

[1] This level introduces two different functionalities: the ability of "normal" operation without expecting human intervention and the exhaustive fallback performance. Two sub-levels could be envisaged.

Figure 30: Levels of inland waterway transport automation defined by CCNR

Level	Description
Direct control	Direct control of ship from crew on bridge, no decision support.
Decision support	Decision support and advice to crew on bridge. Crew decides.
Automatic bridge	Automated operation, but under continuous supervision by crew.
Periodically unmanned	Continuously supervised by shore. Muster crew if necessary.
Remote control	Unmanned, continuously monitoring and direct control from shore.
Automatic	Unmanned under automatic control, monitored from shore.
Constrained autonomous	Unmanned, partly autonomous, continuously supervised from shore.
Fully autonomous	Unmanned and without supervision.

Figure 31: Levels of autonomy of vessels defined by NFAS

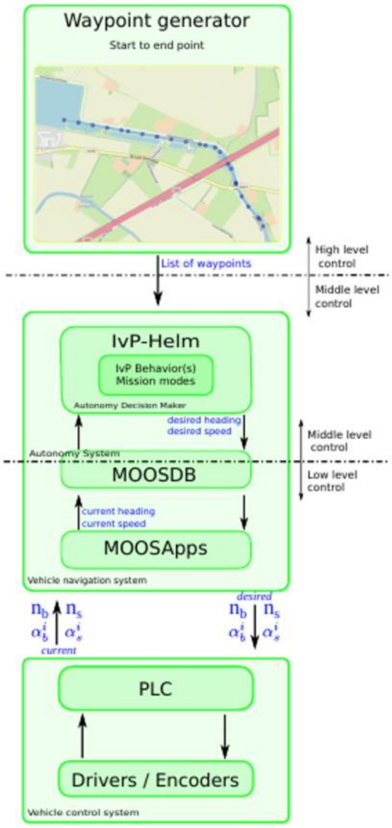


Figure 32: Control hierarchy overview from [1,2]

A partially populated example of the schemes above from [1, 2] (see Figure 33).

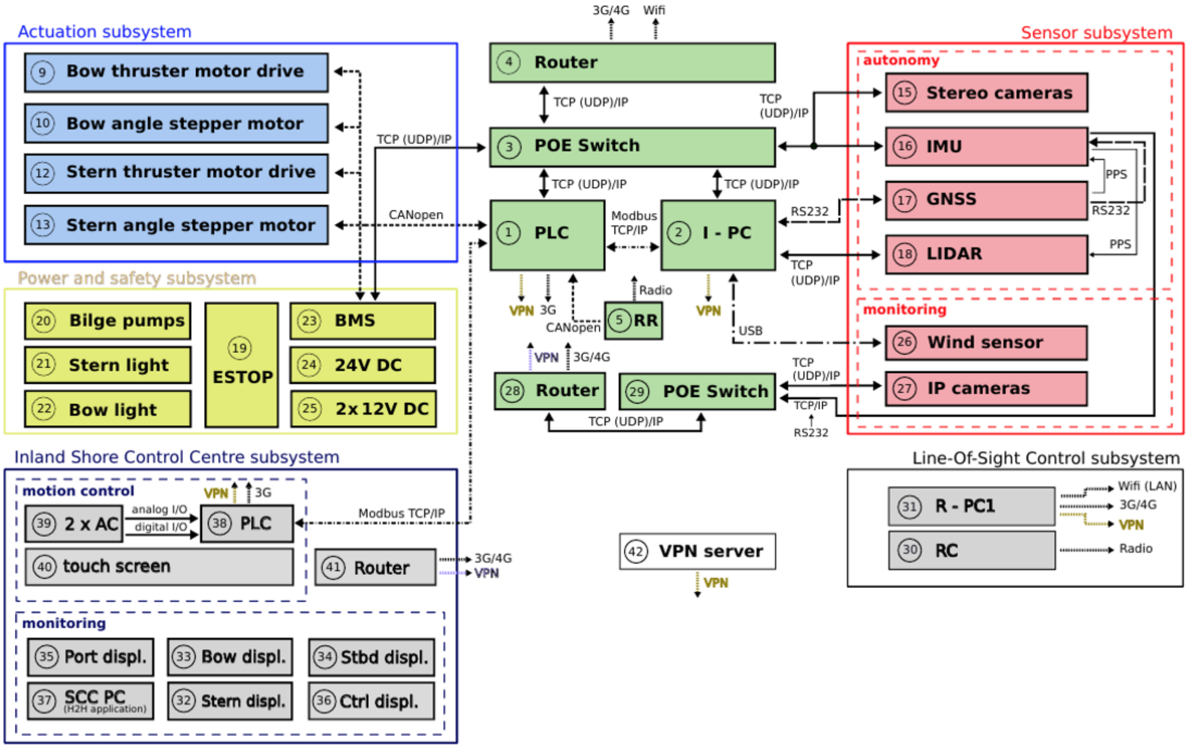


Figure 33: Overview of communication between different sub-systems installed on Cogge and its surroundings

5 Modelling and Simulation

5.1 Modelling and simulation capabilities

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., Synchro-modality).

The 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.

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.

Data is a very important part of setting up simulation scenarios. When we analyse the transport flows of inland waterway transport it is most often done in relative comparison to road transport. The road network supported 77.4% (Eurostat, 2020) of the freight transport and 92.3% (EU-stats, 2017) 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.

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 the journeys.

In order to achieve this goal, diverse inputs are 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) and from an emission monitoring project that has recently started called ‘IWT Footprinting’ with the objective of measuring emissions on representative IWT vessels in the Netherlands. 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.

GHG emissions are directly related to the consumption of fuel. Table 4 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 4: Share in estimated tonne-kilometre performance and average fuel consumption of the main fleet families

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

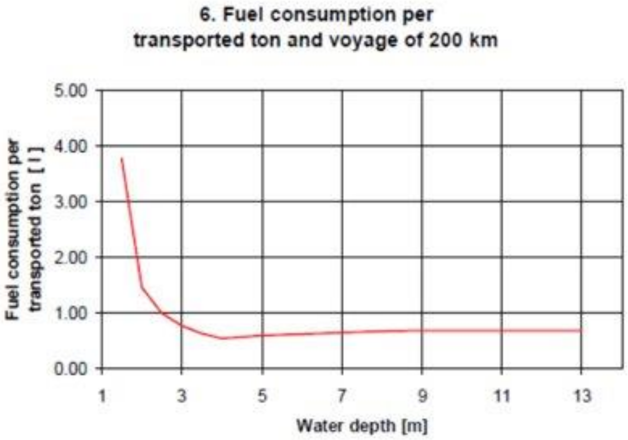


Figure 34: Correlation between vessel fuel consumption and water depth

As well 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 34 shows the correlation between vessel fuel consumption and water depth.

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.

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 35 has been the basis for collecting data on vessel types, operational characteristics, and fuel consumption.

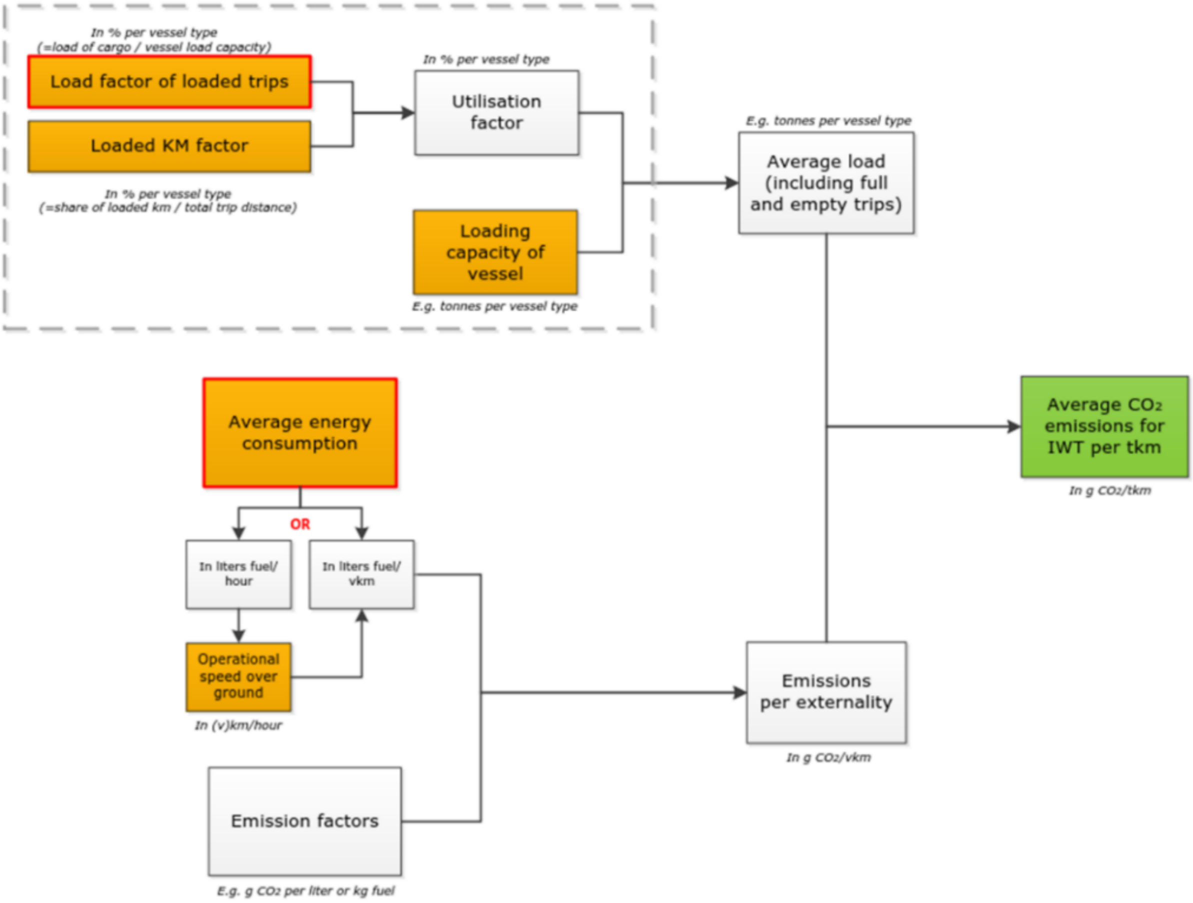
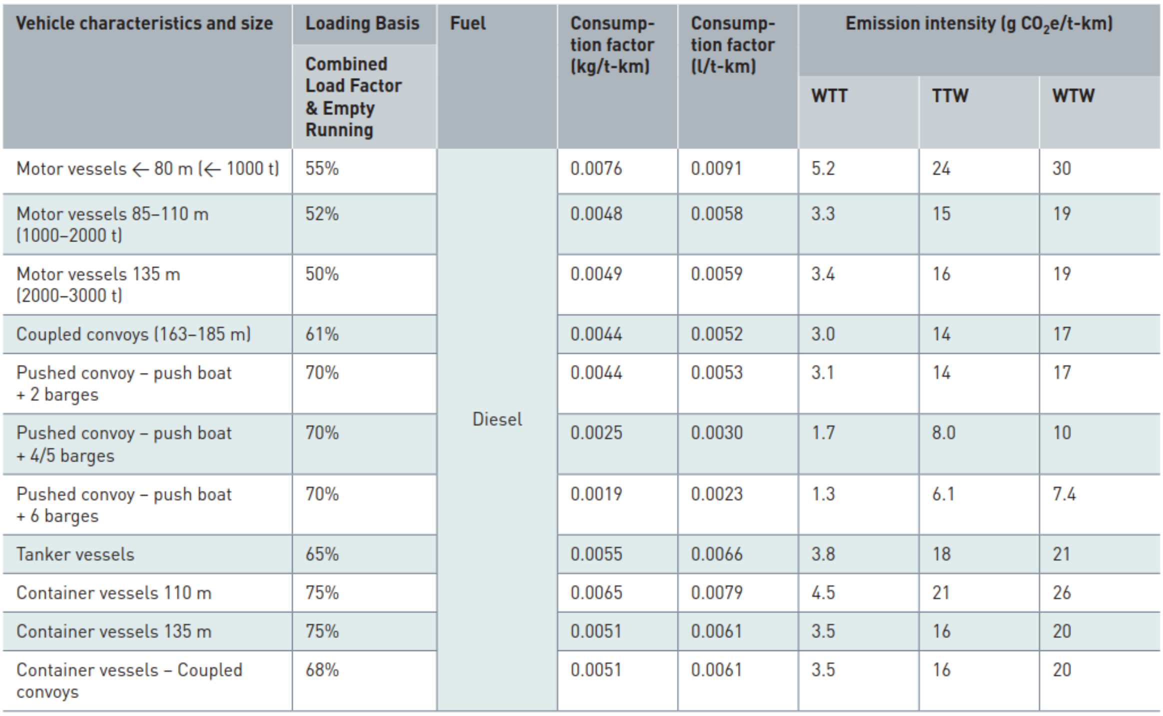


Figure 35: Data collection framework for estimating GHG emissions for IWT (Source: STC-NESTRA)

In Table 5 an overview is given of the GHG emission factors per representative vessel classes (fleet families) in Europe. This information can be used for simulation purposed to showcase impacts of IW-NET application scenarios.

Table 5: Inland waterways transport emission intensity factors



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

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.

Finally, to measure the impact of IWT on the global distribution network different KPIs (Key Performance Indicator) are used.

Focusing on the environmental part, these are the main KPIs (see Table 6):

Table 6: Examples of KPI

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...)

5.2 Example for Danube Application Scenario

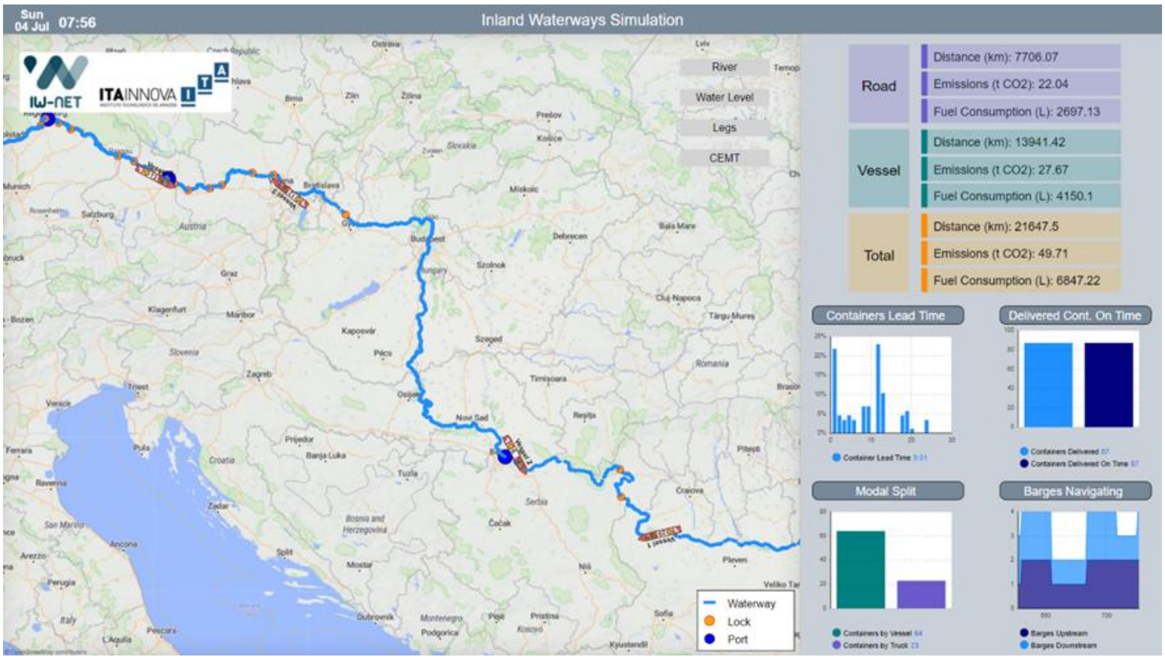
The objective of the model in this application scenario is to analyse different container distribution strategies along the Danube River corridor, including navigable inland waterways and road-based alternatives. Road transport strategy, vessel transport FIFO strategy and revenue management optimisation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

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

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

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 (see simulation runtime screen Figure 36) as well as different KPIs dynamically (delivered containers, lead time, distance, fuel consumption, emissions, etc.).



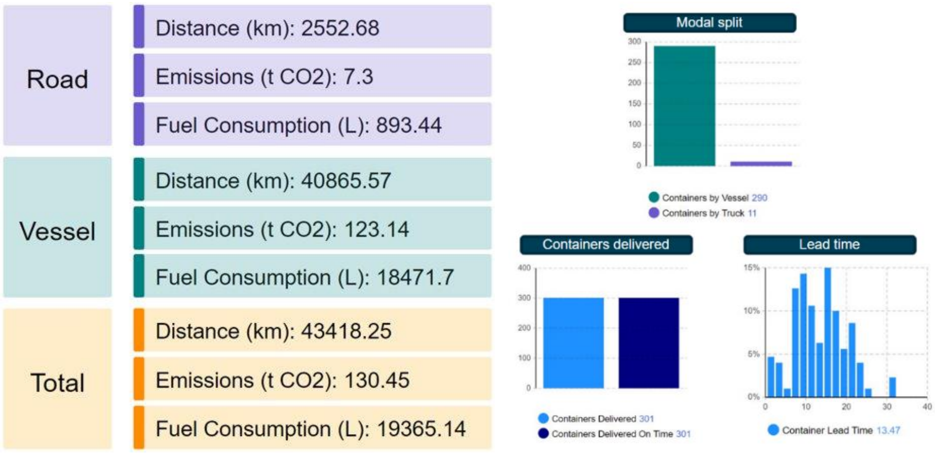
Road
Distance (km): 7706.07
Emissions (t CO2): 22.04
Fuel Consumption (L): 2697.13

Vessel
Distance (km): 13941.42
Emissions (t CO2): 27.67
Fuel Consumption (L): 4150.1

Total
Distance (km): 21647.5
Emissions (t CO2): 49.71
Fuel Consumption (L): 6847.22

Figure 36: 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 37 and Figure 38 respectively.

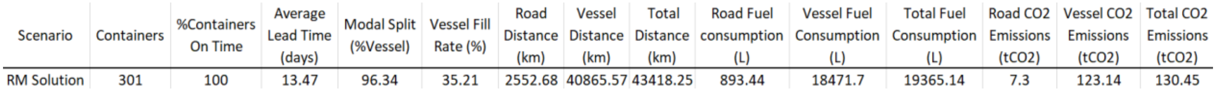


Road
Distance (km): 2552.68
Emissions (t CO2): 7.3
Fuel Consumption (L): 893.44

Vessel
Distance (km): 40865.57
Emissions (t CO2): 123.14
Fuel Consumption (L): 18471.7

Total
Distance (km): 43418.25
Emissions (t CO2): 130.45
Fuel Consumption (L): 19365.14

Figure 37: 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 38: 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 7.

Table 7: 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 Conclusions

The work in T3.1 provides the categorisation and analysis of Inland Waterway vessels, focussing on a “single vessel”. The output of this task is a set of components and a taxonomy which for the modelling of the various vessel parameters to be used for simulation (WP1 and the Living Lab).

Research was performed on interoperability in vessels with the final aim to introduce solutions and deliver innovations to for automated navigation. All T3.1 research outputs are being tested in the IW-NET use cases and specifically in the Application Scenario AS3 of the Living Lab which is about the deployment of innovative IW fleet including autonomous vessels for urban distribution, for smart, safe, and efficient vessel operations.

Consequently, the vessel and fleet components analysed and discussed in the work performed, aim to provide a basis for extending simulation-based impact assessment on key vessel innovations for specific corridors, while the taxonomies, and corresponding technologies developed in T3.1 are expected to provide the modelling basis for simulation-based assessments delivering automation supported solutions and smart waterway systems, resulting to cost-effective operations. Specific aspects considered were the Vessel Geometry, hull types, deck types for bulk, tankers, or custom decks, the Actuation systems including different propulsion types and different energy options aiming to environmentally friendly solutions. Specific attention was given to the on-board sensor systems, for improved autonomy and manoeuvrability. The Aspects of Vessel Interoperability and Situational Awareness were studied with regard to applicable standards and current state of art solutions. The work output is connected with the Application, hence application experiments have been performed in simulation.

Various "single vessel" technologies are being explored in the Living Lab of the IW-NET project also carried over, incorporated in the development of barges to be used for urban scenarios.

By means of carefully weighing the added values of each separate technological innovation, the work presented in this document leads to devising an incremental approach towards sustainable interoperability between multiple vessels. As such, it tries to answer the question "which innovations are productive to not only allow for increased single vessel automation, but also to enable a smart, sustainable IWT supply chain?”

The simulation components and libraries developed in WP1 and enriched in WP3 integrate elements of the vessel technologies and characteristics taxonomies, supporting:

- Ship Management: Vessel lifecycle management, fleet management
- Navigation Management: Safety, greening
- Port operations: productivity improvements, SC-coordination
- Customers: Tracking Services/SC visibility improvements

These simulations will be configured in detailed and tested within AS3, modelling the impact of innovations to urban scenarios, as they apply to the vessel actuation subsystem and the corresponding manoeuvrability improvements, the impact of raising the level of autonomy, and the interface capabilities, among many other factors.

7 References

[1] G. Peeters, R. Boonen, P. Slaets and M. Vanierschot, *Towards unmanned inland shipping,* 2021.

[2] G. Peeters, M. Kotze, M. R. Afzal, T. Catoor, S. Van Baelen, P. Geenen, M. Vanierschot, R. Boonen and P. Slaets, "An Unmanned Inland Cargo Vessel: Design, Build and Experiments," *Ocean Engineering,* vol. 201, no. 107056, 2020.

[3] ECMT Council of Ministers, "Resolution no. 92/2 on new classification of inland waterways," in *European Conference of Ministers of Transport*, Athens, 1992.

[4] E. V. Lewis, Principles of Naval Architecture - Volume I - Stability and Strength, Society of Naval Architects and Marine Engineers (SNAME), 1988.

[5] A. Molland, S. Turnock and D. Hudson, Ship Resistance and Propulsion, Cambridge University Press, 2011.

[6] J. Liu, R. Hekkenberg, E. Rotteveel and H. Hopman, "Literature review on evaluation and prediction methods of inland vessel manoeuvrability," *Ocean Engineering,* vol. 106, pp. 458-471, 2015.

[7] G. Peeters, M. R. Afzal, M. Vanierschot, R. Boonen and P. Slaets, "Model Structures and Identification for Fully Embedded Thrusters: 360-Degrees-Steerable Steering-Grid and Four-Channel Thrusters," *Journal of Marine Science and Engineering,* vol. 8, no. 3, pp. 1-27, 2020.

[8] E. M. S. Agency, "Study on electrical energy storage for ships," 2020.

[9] S. Van Baelen, H. Shin, G. Peeters, M. R. Afzal, G. Yayla and P. Slaets, "Preliminary results on increased situational awareness for inland vessels using onboard LiDAR," in *Global Oceans 2020*, Singapore - U.S. Gulf Coast, 2020.

[10] G. Delefortrie, K. Eloot, E. Lataire, W. Van Hoydonck and M. Vantorre, "Captive Model Tests Based 6 DOF Shallow Water Manoeuvring Model," in *4th MASHCON*, Hamburg (Germany), 2016.

[11] C. Chen, G. Delefortrie and E. Lataire, "Effects of water depth and speed on ship motion control from medium deep to very shallow water," *Ocean Engineering,* vol. 231, no. 109102, 2021.

[12] G. Peeters, S. Van Baelen, G. Yayla, T. Catoor, M. R. Afzal, C. Christofakis, R. Louw, Y. Singh, M. Vanierschot, R. Boonen and P. Slaets, "Decoupled Hydodynamic Models and Their Outdoor Identification for an Unmanned Inland Cargo Vessel with Embedded Fully Rotatable Thrusters," *Journal of Marine Science and Engineering,* vol. 8, no. 11, pp. 1-30, 2020.

[13] S. Van Baelen, G. Peeters, H. Bruyninckx, P. Slaets and P. Pilozzi, "Dynamic Semantic World Models and Increased Situational Awareness for Highly Automated Inland Waterway Transport," *Frontiers in Robotics and AI,* vol. 8, 2022.

[14] C. Sys and T. Vanelslander, Future Challenges for Inland Navigation: a scientific appraisal of the consequences of possible strategic and economic developments up to 2030, Antwerp: University Press Antwerp, 2011.

[15] G. Peeters, G. Yayla, T. Catoor, S. Van Baelen, M. R. Afzal, C. Christofakis, S. Storms, R. Boonen and P. Slaets, "An Inland Shore Control Centre for Monitoring or Controlling Unmanned Inland Cargo Vessels," *Journal of Marine Science and Engineering,* vol. 8, no. 10, pp. 1-27, 2020.

[16] Ø. J. Rødseth and H. Nordahl, "Definition of autonomy levels for merchant ships," Norwegian Forum for Autonomous Ships, 2017.

[17] E. C. o. M. o. Transport, "Resolution no. 92/2 On new classification of inland waterways," Athens, 1992.