Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101136257

AUTOFLEX

[D4.1] DESIGN IMPACTS

Work Package	WP4	Developing small automated zero-emission vessels
Lead Author	DST	Igor Bačkalov
Co-Author(s)		Hans-Christoph Burmeister, Ljubisav Isidorović, Justin Jasa, Marko Josipović, Kristoffer Kloch, Vladimir Krasilnikov, Stefan Krause, Kamyar Maleki Bagherabadi, Denys Mateienko, Håvard Nordahl, Nathalie Reinach
Dissemination Level	PU	R
Date / Project Month	27.11.2024 PM 11	Start of the Project: 01.01.2024 Duration: 36 Months

DELIVERABLE INFORMATION

This Deliverable has been provided by members of the AUTOFLEX consortium and is intended as input to the development of autonomous and flexible inland waterway vessels and respective business models. The content of this publication has been reviewed and accepted by the members of the AUTOFLEX consortium. However, not necessarily every aspect of it represents the view of each individual member of the AUTOFLEX consortium.

While the information contained in the document is believed to be accurate, AUTOFLEX participants make no warranty of any kind with regard to this material including, but not limited to the implied warranties of merchantability and fitness for a particular purpose. None of the AUTOFLEX participants, their officers, employees, or agents shall be responsible for, liable in negligence, or otherwise howsoever in respect of any inaccuracy or omission herein. Without derogating from the generality of the foregoing neither of AUTOFLEX participants, their officers, employees or agents shall be liable for any direct, indirect, or consequential loss or damage caused by or arising from any information advice or inaccuracy or omission herein.

The material in this publication can be reproduced provided that a proper reference is made to the title of this publication and the AUTOFLEX project.

An example for reference of this Deliverable is given here:

Bačkalov, Igor; 'AUTOFLEX Deliverable D4.1 – Design Impacts'; Revision 1.0; Nov. 2024

Document History		
07.07.2024	Version 0.1	First draft, for review
24.07.2024	Version 0.2	Review by Alexandros Koimtzoglou (NTUA)
23.09.2024	Version 0.3	Second draft, submitted to the Coordinator
27.11.2024	Version 1.0	To be submitted to the European Commission

Funded by
the European Union

Grant Agreement:
101136257

EXECUTIVE SUMMARY

This Deliverable presents the research done within the scope of the Task 4.1, titled "Impacts of automation and zero-emission propulsion on inland vessel design". The project AUTOFLEX focuses on reactivation of smaller inland waterways using the small, flexible, zero-emission inland vessels without crew on board. However, in the first stages of the project, the term "small" is still undefined. Therefore, this deliverable offers a systematic overview of the modifications of the reference designs of CEMT classes I, II, III, and IV ships, that is, the vessels whose length is between (approximately) 35 m and 85 m.

The research was conducted in several steps, whereby each step implied a (potentially) major modification (modernization) of the reference ship designs:

1. To facilitate automation of cargo handling, the reference designs – general cargo / dry bulk carriers – were converted into containerships.
2. To achieve zero-emission propulsion and facilitate automation of ship machinery, conventional diesel engines were replaced by electric propulsion which uses swappable battery packs (stored in shipping containers) as the source of energy. To address manoeuvrability in challenging navigation conditions, the conventional single propellers were replaced by twin azimuth thrusters.
3. To address the labour market constraints and improve the attractiveness of the service provided by the small vessels, the remote-control system was implemented.

In each of the steps, it was verified how the introduced modifications affect the common naval architecture disciplines, including general arrangement, weight and space requirements, cargo capacity, safety, structural design, energy systems, etc. Recent publications and projects were reviewed to include the information relevant to the design impacts considered. State-of-the-art naval architecture software, CAD tools, and in-house mathematical models were used in assessment of impacts of modernization steps on the reference designs. The relevant regulatory aspects were considered in each step.

The research was complemented by interviews conducted with experts, addressing two specific aspects: energy efficiency of small inland vessels (which pertains to hydrodynamics of the vessels and the selection of propulsion and steering systems), and the ship operator's perspective (which pertains to the relevance of the technologies and design solutions investigated in this Task for efficient operations of "small" inland vessels).

In addition to identifying the impacts of the novel technologies on standard designs, the findings indicate the vessel classes which could be the most promising candidates for the design of the future small autonomous inland ships. The outcomes of the Task 4.1, presented in this Deliverable, shall serve as a basis for the research to be performed within Task 4.2 which deals with the development of small uncrewed vessel concepts.

The research presented in this Deliverable is a joint effort of partners involved in the Task 4.1 (DST, SO, ISE) with the contributions of other partners participating in WP4 (FHG, DFDS) and the interviewed experts (Benjamin Friedhoff and Jelle van Koevorden). The review of the Deliverable was performed by NTUA.

Funded by the European Union

Grant Agreement: 101136257

TABLE OF CONTENTS

Funded by the European Union

Grant Agreement: 101136257

TABLE OF FIGURES

Funded by the European Union

Grant Agreement: 101136257

TABLE OF TABLES

Funded by
the European Union

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol / Abbreviation	Description
B	Ship beam [m]
C_B	Block coefficient [–]
d	Ship draught [m]
GM	Metacentric height [m]
h_a	Minimum height under bridges [m]
h_w	Water depth [m]
L	Ship length [m]
L_{BP}	Ship length between perpendiculars [m]
m_{cargo}	Mass of cargo [t]
m_{DWT}	Mass of deadweight [t]
m_{TEU}	Average mass of TEU [t]
n_{TEU}	Number of TEU [–]
n_{tiers}	Number of container tiers [–]
P_2	Median engine power [kW]
P_{avg}	Average engine power [kW]
VCG_{cargo}	Vertical centre of gravity of cargo [m]
η_{HOLD}	Space utilization of cargo hold [–]
φ	Heeling angle [°]

ADN	European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways
CCNR	Central Commission for the Navigation of the Rhine
CEMT	Conférence européenne des ministres des Transports
CPP	Controllable pitch propeller
DOF	Degrees of freedom
EEDI	Energy Efficiency Design Index
ES-TRIN	European Standard Laying Down Technical Requirements for Inland Navigation Vessels
FEU	Forty-foot equivalent unit
TEU	Twenty-foot equivalent unit
WP	Work package

Funded by the European Union

Grant Agreement: 101136257

1 INTRODUCTION

Small inland waterways in Europe are presently underutilized and, thus, offer a considerable capacity for modal shift of cargo transport. Using the small inland waterways, cargo can be brought closer to end-users by means of waterborne transport. Such a service has to be reliable, flexible, efficient, and commercially viable to be attractive for cargo owners and freight forwarders. In addition, its environmental footprint should be low, considering that small inland waterways often penetrate into densely populated areas. However, the existing inland cargo vessels suitable for such waterways are relatively old and outdated, hence they may not be able to respond to the contemporary market and regulatory requirements. Therefore, the reactivation of small inland waterways requires new vessels whose designs may have to considerably deviate from the original ones. The research, presented in this Deliverable, attempts to answer how much the original designs may be affected by the introduction of novel technologies.

Small inland waterways considered in this Deliverable comprise all waterways up to and including CEMT class IV, which can accommodate ships of up to 85 m in length and 9.5 m in beam (maximum dimensions of ships for small inland waterways are reported in Table 1-1; for detailed overview of classification of inland waterways in Europe see CEMT (1992). Such a decision is based on the fact that the “small” inland vessels (which are in focus of AUTOFLEX) are still not defined at the present stage of the project.

To increase cost-efficiency and address the labour market constraints (primarily ageing and shortage of the qualified ship personnel as reported in CCNR, 2024), operational modes based on remote control of vessels, which require a high level of automation of ship functions, are considered. To reduce the climate impact of the vessels and diminish the emissions of atmospheric pollutants (in line with the targets set in Roadmap of the Central Commission for the navigation of the Rhine for reducing inland navigation emissions, see CCNR, 2022a) and facilitate automation, a zero-emission propulsion solution via electrification is to be implemented. For each of the considered CEMT class, a sample vessel (the “reference design”) is selected and “modernized” by implementing the described technologies. The major differences between the “modernized” and the “reference” designs in terms of general arrangement, cargo capacity, safety requirements, structural design, outfitting, energy and propulsion system, are identified and the performance of the implemented changes is assessed.

Table 1-1: Main particulars of self-propelled vessels which could be accommodated by inland waterways of CEMT classes I to IV.

CEMT class	L [m]	B [m]	d [m]	m_{DWT} [t]	h_a [m]
I	38.5	5.05	1.8–2.2	250–400	4
II	50–55	6.6	2.5	400–650	4–5
III	67–80	8.2	2.5	650–1000	4–5
IV	80–85	9.5	2.5	1000–1500	5.25 or 7

It should be noted that the vessel design (which would comprise hydrodynamic optimization of the hull, thorough weight estimation, detailed structural design, elaboration of machinery beyond the main components, etc.) is not within the scope of Task 4.1. The ship design aims to attain certain objectives that follow from the so-called “owner’s requirements” (normally comprising cargo type, cargo capacity, speed, endurance, etc.) which may lead to adoption of specific technologies. The analysis performed in Task 4.1 employs a reverse approach: it is investigated how a given design may be affected by introduction of the specific, pre-selected technologies. The analysis is, however, considered to be sufficiently robust to identify the major design impacts and detect possible opportunities and challenges which could be of importance to the development of concepts in Task 4.2.

1.1 EVOLUTION OF EUROPEAN INLAND CARGO FLEET

The evolution of inland fleet in Western Europe has been previously addressed by e.g. van Hassel (2011), Bačkalov et al. (2014), and Dahlke-Wallat et al. (2020). Figure 1-1 shows the evolution of the inland dry cargo fleet in Western Europe, based on the data of 6380 general cargo ships built in period 1897–2024. Until the end of the 1960s, the fleet was dominated by small vessels; the vessels longer than 110 m were non-existent, while around 16% of the newbuilt vessels had lengths between 80 m and 110 m. Considerable changes in the composition of the fleet took place in course of the 1970s. Nearly 62% of the vessels built in this period had lengths between 80 m and 110 m, while vessels in length of up to 80 m comprised less than 15% of the newbuilds. The first vessels longer than 110 m were also built in the 1970s. After the 1970s, the large vessels dominated the market: between 44% and 72% of the vessels built in the subsequent decades were longer than 100 m. The share of the newbuild vessels of the length below 80 m declined from 25% in the 1980s to 6% in the 2020s. Only two such vessels were built since 2020. In fact, 95% of the vessels below 80 m in length were built before the 1980s.

The same data may be presented in terms of number of vessels built in the observed period (Figure 1-2), which gives an additional insight into the dry cargo fleet evolution. While the total number of newbuilt dry cargo vessels decreased over time (e.g. from 1647 ships built in the 1960s, down to 140 in the 2010s), the average deadweight of the vessels increased (from 833 t in the 1960s, up to over 2600 t in the 2010s). While more than 500 vessels whose length was up to 40 m were built in the 1950s, merely six new vessels of that size were built in the 2010s.

If the analysis is narrowed down to the general cargo vessels of classes CEMT I to CEMT IV (2879 vessels in total) i.e., the vessels intended for the “small inland waterways”, it may be observed that, as of the 1970s until the end of the 20th century, the newbuilt “small vessels” were almost exclusively the CEMT IV ships (Figure 1-3). A revival of the classes I, II, and III may seem to have taken place during the first two decades of the 21st century. However, the actual number of newbuilt vessels built since 2000 is very low, as it may be observed from Figure 1-4.

It follows that most of the vessels suitable for the inland waterways considered in AUTOFLEX are at least 45 years old. It should be noted, however, that the year of build may not be sufficiently indicative of the vessel’s condition, because many inland vessels have been extensively retrofitted at least once in their lifetime. The retrofit may include a change of the drivetrain, fitting of a bow thruster, lengthening of the mid-body (and even a widening

Funded by the European Union

of the ship), single hull to double hull conversion, introduction of novel navigation systems and sensing devices, or a combination thereof.

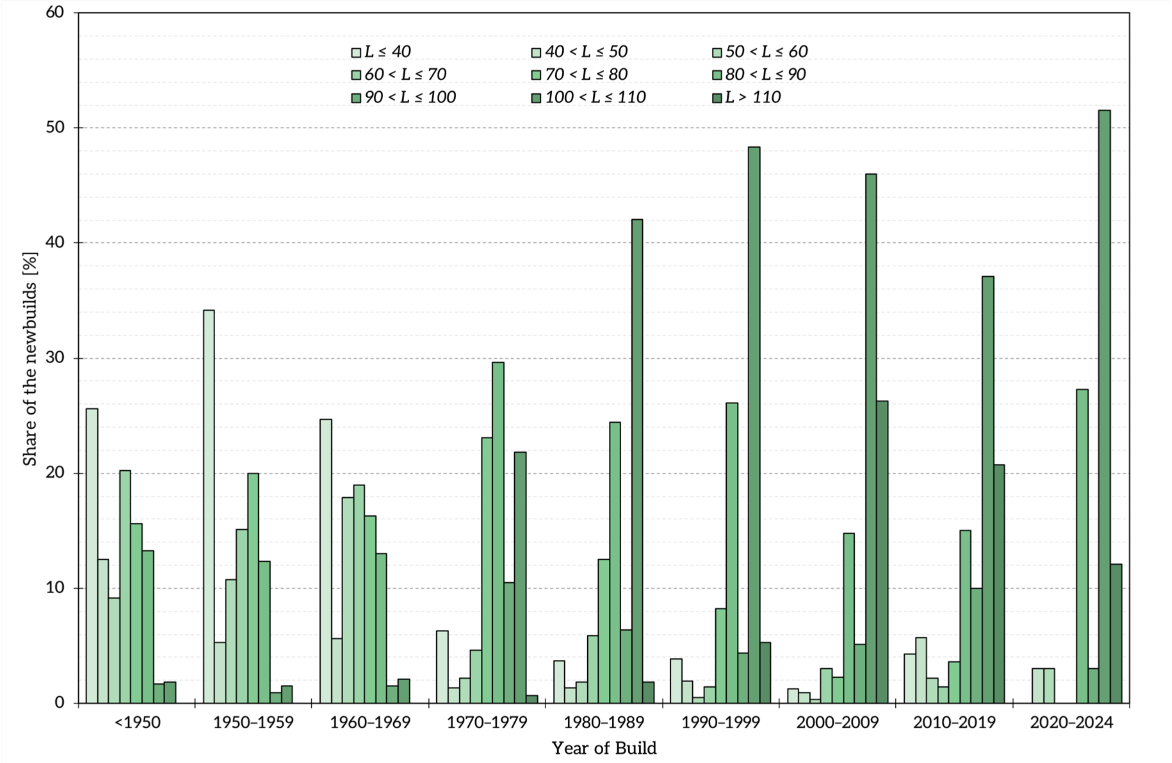


Figure 1-1: Evolution of the Western European inland fleet of general cargo vessels: share of the vessels built in period 1897–2024, broken down by ship length.

Funded by the European Union

Grant Agreement: 101136257

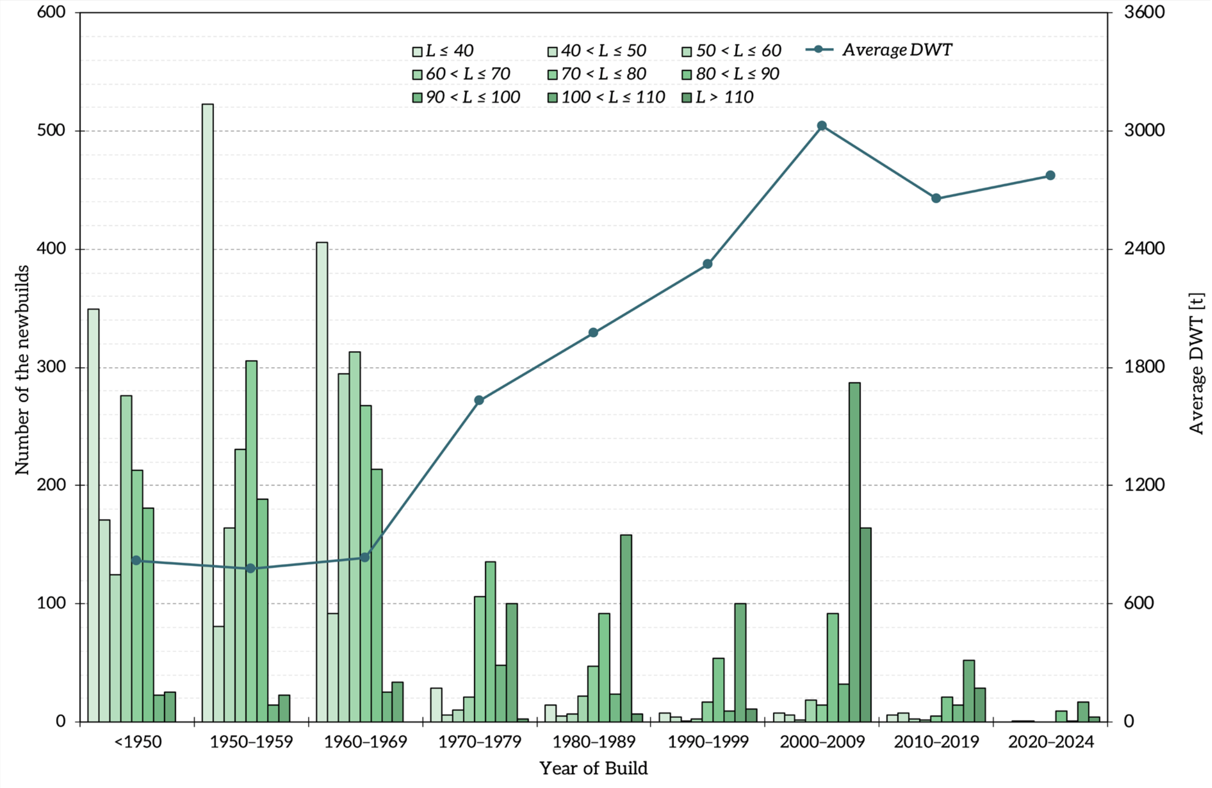


Figure 1-2: Evolution of the Western European inland fleet of general cargo vessels: number of the vessels built in period 1897–2024, broken down by ship length.

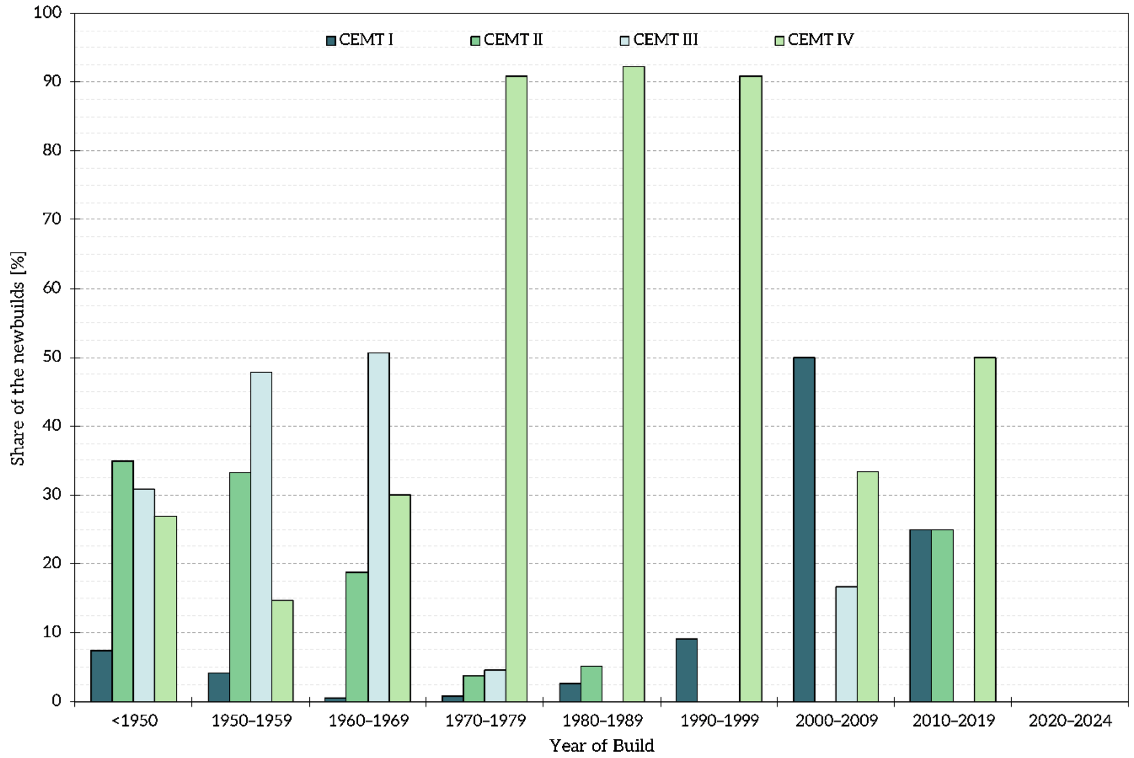


Figure 1-3: Evolution of the Western European inland fleet of “small” general cargo vessels: share of the vessels built in period 1897–2024, broken down CEMT class.

Funded by the European Union

Grant Agreement: 101136257

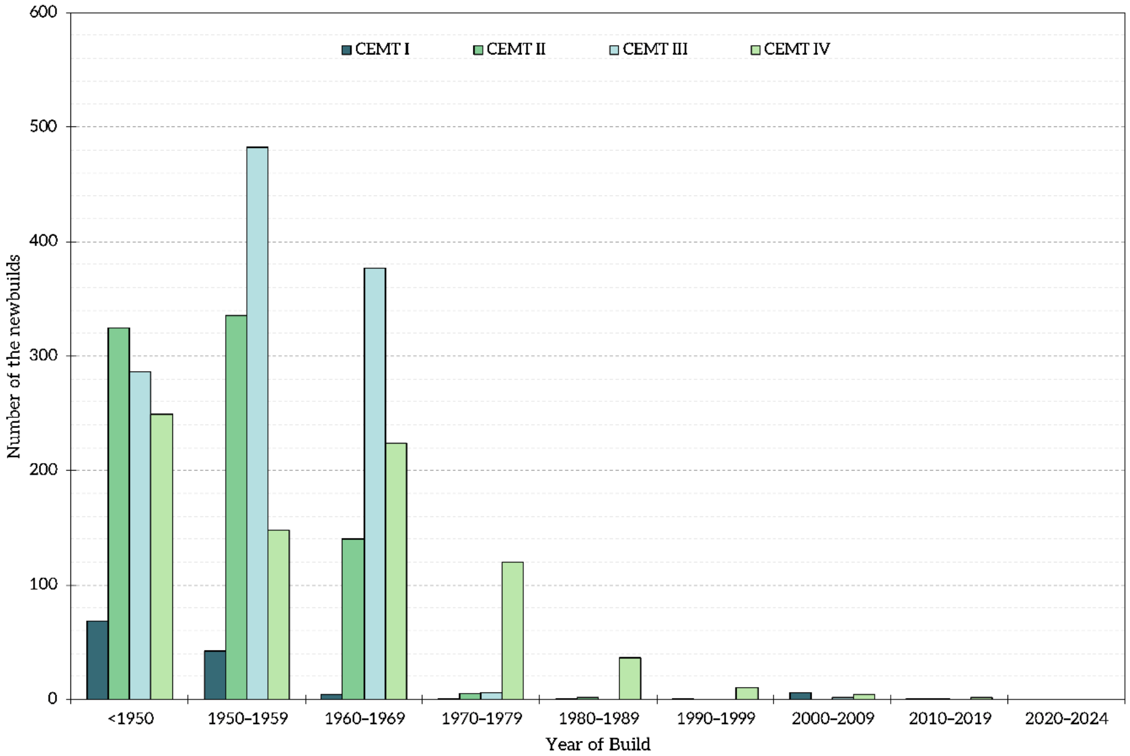


Figure 1-4: Evolution of the Western European inland fleet of “small” general cargo vessels: number of the vessels built in period 1897–2024, broken down by CEMT class.

Therefore, even some very old vessels may have been considerably modernized. This Deliverable, however, focuses on assessment of impacts of modernization on reference design, rather than on retrofit possibilities. In addition, the extent of modernization of the existing small vessels cannot be fully evaluated (as it is going to be demonstrated) which makes it difficult to assess whether the standard designs could be successfully adapted to highly automated ships or not. Finally (and most importantly), the main particulars may have a much greater effect on ship performance than specific ship systems, especially if the type of cargo is changed, as is the case in this analysis.

1.2 REVIEW OF RESEARCH ON IMPACTS OF AUTOMATION ON SHIP DESIGN

Impacts of high levels of automation on ship design have seldom been addressed and almost never in a holistic manner. Gudmestad (2022) indicated the main challenges to ship design brought about by autonomous shipping. de Vos and Hekkenberg (2020) and de Vos et al. (2020) discussed the possibility to reduce the required subdivision index (stipulated by the probabilistic damage stability rules) for unmanned seagoing ships. Abaei and Hekkenberg (2020), Abaei et al. (2021), and Abaei et al. (2022) studied the reliability of machinery in unattended machinery spaces on autonomous ships. Ait Allal et al. (2019) investigated opportunities (created by the absence of human operators) for reduction of energy consumption on autonomous ships. Gribkovskaia et al. (2019) analyzed the influence of main ship particulars, with a specific focus on block coefficient, on efficiency of autonomous

Funded by the European Union

Grant Agreement: 101136257

ships for coastal and short-sea shipping. Some guidelines for design of short-sea ships with various levels of crew reduction, including unmanned ships, were given by Kooij et al. (2021). However, none of the aforementioned studies dealt with the design of inland vessels.

Funded by
the European Union
Grant Agreement:
101136257

2 METHODOLOGY

The analysis is conducted using the original designs of the relevant CEMT classes of ships as the reference (sample) vessels. The designs, which were made in Western Germany in the 1950s (that is, well before the CEMT classes were officially established) were first known as "Theodor Bayer" (corresponding to CEMT class I), "Oskar Teubert" (corresponding to CEMT class II), "Gustav Koenigs" (corresponding to CEMT class III), and "Johan Welker" (corresponding to CEMT class IV). The principal benefit of using the original designs is the availability of the relevant information (including general arrangements of the vessels, structural drawings, weight estimations, etc.). The downside, however, might be that each of the original designs features unique characteristics which may differ from the other existing vessels within the same CEMT class. Consequently, the observed impacts may not be the same for all the vessels in one class.

To examine and visualize the modifications which are a consequence of automation and electrification of the vessels the generic CAD models of the reference designs (Figure) are built. The analysis is performed in several steps whereby within each step a major modernization intervention is introduced.

2.1 REFERENCE DESIGNS

Main features of the reference designs: length (L), beam (B), draught (d), block coefficient (C_B), and mass of cargo (m_{cargo}) are given in Table 2-1. All sample vessels are powered by diesel engines and have two rudders mounted behind a single propeller. None of the vessels have a bow thruster. Apart from the inner bottom, the vessels have single hull structures. The vessels have cargo holds with hatch covers and could be designated as general cargo / dry bulk ships.

Funded by the European Union

Grant Agreement: 101136257

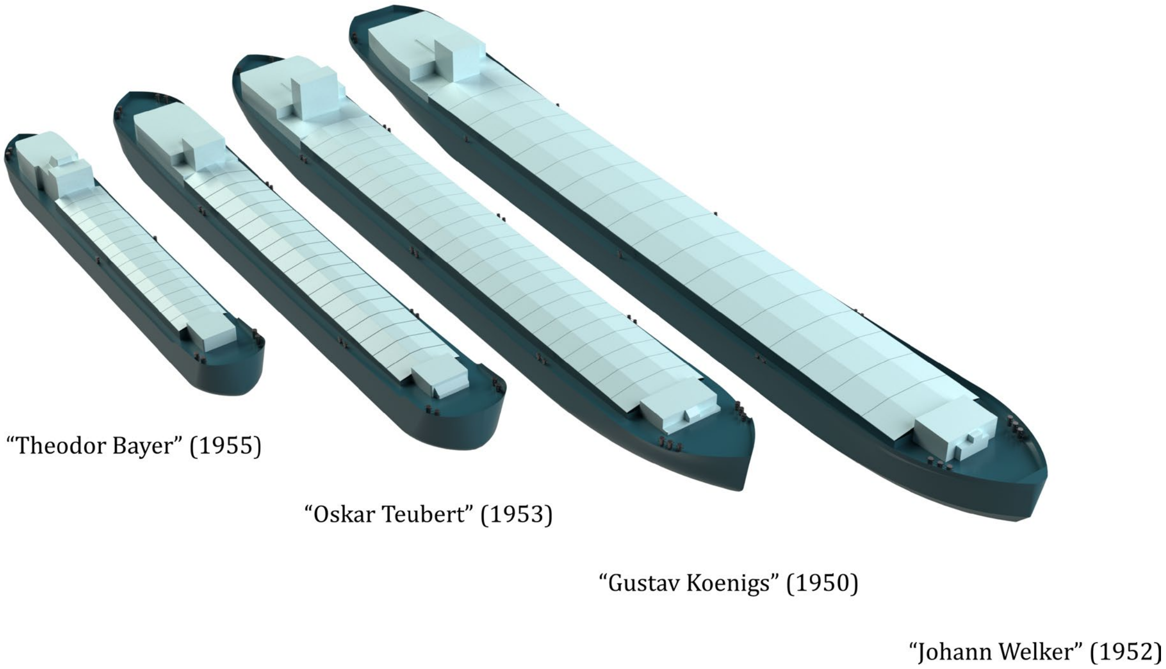


Figure 2-1: Generic CAD models of reference designs of CEMT classes I, II, III and IV.

Table 2-1: Main features of the reference designs.

Reference design	**CEMT class**	L [m]	B [m]	d [m]	C_B	m_{cargo} [t]
“Theodor Bayer” (1955)	I	38.5	5.05	2	0.922	221
“Oskar Teubert” (1953)	II	53	6.3	2	0.923	403
“Gustav Koenigs” (1950)	III	67	8.2	2	0.849	645
“Johann Welker” (1952)	IV	80	9.5	2.5	0.852	1289

2.2 MODERNIZATION STEPS

The introduction of remote control on ships without permanent human operators on board may require ample measures which include, but are not limited to, removal of human-centred elements of ship architecture and implementation of an autonomous navigation system. Such interventions should be preceded by the implementation of technologies which facilitate automation of other main ship functions in addition to navigation: cargo handling, propulsion, mooring, communication, etc. Therefore, the analysis will be carried out in several steps, whereby each step addresses one major design modification.

1) Firstly, to facilitate the automation of cargo handling, the designs should be adapted so that the vessels can (efficiently) carry unitized cargo, such as shipping containers. Considering that the sample vessels were designed two decades before the advent of containerization, it may be expected that the necessary modifications could have

a considerable impact on the design, including a possible modification of the main particulars. Obviously, this may affect virtually all design aspects.

2) In the next step, the zero-emission propulsion is introduced, which in the considered case entails electrification based on swappable containerized battery packs as energy sources. This implies a new drivetrain, and a (complete) makeover of the machinery space and the “fuel system”. Such changes may affect the general arrangement of the ships, the distribution of the masses (and, thus, ship buoyancy and stability) and manoeuvrability.
3) As a final step towards an operational mode based on remote control, a range of safety functions normally executed by human operators onboard has to be taken over by the (appropriate) systems. On the other hand, a range of human-centred ship design requirements become unnecessary on the remotely controlled ships, whereby the major impacts do include removal of the wheelhouse, superstructures and life-saving appliances but may extend beyond the obvious. Therefore, the introduction of remote control will be the last step in the considered modernization process.

The adopted methodology allows us to distinguish between the impacts of different modifications. The sequence of steps also reflects the expected course of modernization of inland vessels, whereby the change of the propulsion system would precede the operations without human operators onboard. Hence, this Deliverable may provide basic guidelines for a gradual modernization of small inland cargo vessels.

Funded by
the European Union

Grant Agreement:
101136257

3 SHIFT FROM BULK CARGO TO CONTAINERIZED CARGO

As previously pointed out, the sample vessels were not intended for carrying the containers. This becomes apparent from Figure 3-1, Figure (a), Figure (a), Figure 3-4 (a), and Figure 3-5 (a) which show the utilization of the cargo holds of the reference designs when the twenty-foot equivalent unit (TEU) containers are loaded. In addition, considering that the reference designs feature single hulls, certain cargo space beneath the deck is "lost", as it cannot be used for loading the containers (see red shading in Figure 3-1, Figure 3-2 (b), Figure (b), Figure (b), and Figure (b)).

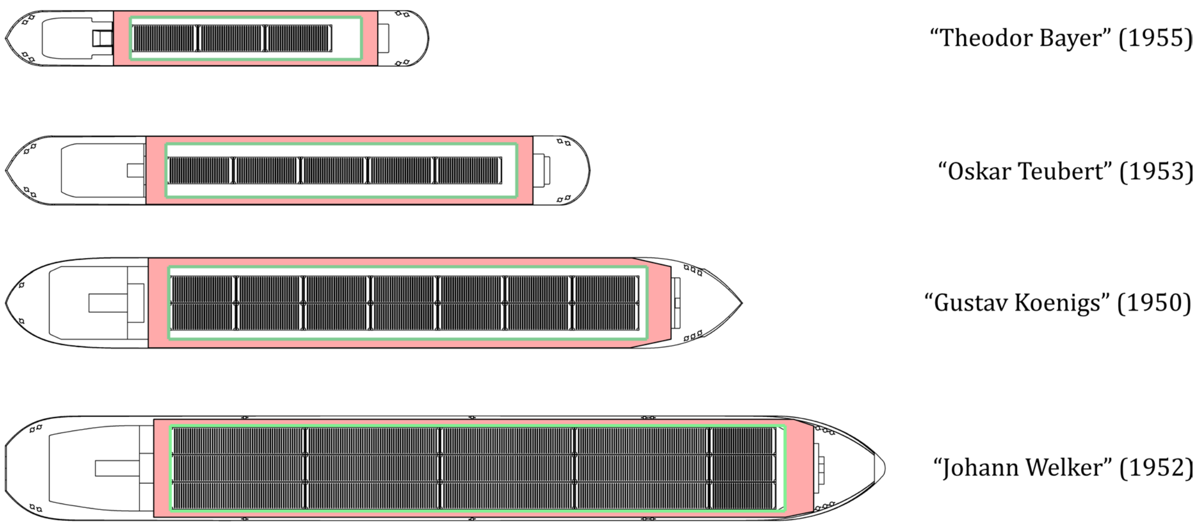


Figure 3-1: Cargo space utilization of original designs of the sample vessels when loading containers. Green lines represent the position of hatch openings. Red shading represents the "lost" space in the cargo hold.

An analysis of container-carrying capabilities of the considered original designs is given in Table 3-1, where η_{HOLD} stands for the space utilization:

$$\eta_{HOLD} = \frac{A_{cargo}}{A_{TEU}}$$

where, A_{cargo} is the area of the cargo hold bounded by the length and the breadth of the hatch opening (excluding the area corresponding to the red shaded parts of the cargo hold in Figure) and A_{TEU} is the area of the cargo hold which can be covered by the TEU containers. m_{TEU} stands for the average mass of TEU containers:

$$m_{TEU} = \frac{m_{cargo}}{n_{TEU}}$$

where, n_{TEU} is the number of TEU which can be loaded in the cargo hold. As the cargo space is underutilized (except in case of the CEMT IV vessel), the average mass of TEU significantly exceeds the maximum possible mass of a TEU unit in case of CEMT I and CEMT II sample vessels, while the CEMT III vessel would have to carry heavy containers to maximize the capacity utilization.

(a) (b)

Figure 3-2: “Theodor Bayer” (1955) (CEMT I reference design): a) cargo space utilization when loading containers, b) “lost” cargo space beneath the deck.

(a) (b)

Figure 3-3: “Oskar Teubert” (1953) (CEMT II reference design): a) cargo space utilization when loading containers, b) “lost” cargo space beneath the deck.

(a) (b)

Figure 3-4: “Gustav Koenigs” (1950) (CEMT III reference design): a) cargo space utilization when loading containers, b) “lost” cargo space beneath the deck.

(a) (b)

Figure 3-5: “Johann Welker” (1952) (CEMT IV reference design): a) cargo space utilization when loading containers, b) “lost” cargo space beneath the deck.

Funded by the European Union

Grant Agreement: 101136257

Table 3-1: Cargo space and cargo weight capacity utilization of original designs of the sample vessels.

Reference design	TEU/tier	n_{tiers}	n_{TEU}	η_{HOLD} [%]	m_{TEU} [t]
“Theodor Bayer” (1955)	3	1 or 2	3 or 6	51	73.7 or 36.8
“Oskar Teubert” (1953)	5	2	10	47	40.3
“Gustav Koenigs” (1950)	14	2	28	72	23
“Johann Welker” (1952)	27	3	81	91	15.9

Therefore, the designs should be modified to improve the container-carrying capacity with respect to both space and weight utilization. In other words, the general cargo vessels should be converted to containerships. The conversion to containerships may have several goals. The number of containers carried at the design draught should be maximized which may require the modification of the hull structure and the cargo hold dimensions. In addition, the containers should be neither too light nor too heavy, i.e. the vessel should be well-balanced at its design draught, which may be a specific challenge for inland container vessels (Hofman, 2006). Another set of goals is related to flexibility in operation: the cargo space capacity should be also fully utilized when loading forty-foot equivalent unit (FEU) containers only, which translates to a requirement for cargo hold dimensions allowing for loading of an even number of TEU bays. An option to load the containers with dangerous cargo could be beneficial as well. On the other hand, an overall design constraint is defined by the maximum dimensions (primarily *L* and *B*) of the vessels which could be accommodated by the considered waterways. Therefore, the main dimensions of some of the designs given in Table 3-2 could not be increased as they already have the maximum values as per definitions of the CEMT classes. The following impacts of containerization of the reference designs are observed.

1) The reference design of CEMT I vessel has excessive cargo capacity which cannot be utilized if the vessel carries unitized cargo: neither the width nor the length of the cargo hold is suitable for loading of a natural number of TEUs. However, the vessel can be neither lengthened nor widened as its *L* and *B* already reach the limitations of the respective CEMT classes. The remaining possibility is a reduction of beam (to make the cargo hold suitable for containers) and draught (to reduce the deadweight).
2) The container loading capacity of the sample CEMT II vessel could be substantially improved by modifying the dimensions of the cargo hold only, without altering the main dimensions of the ship.
3) Similarly to the CEMT I reference design, the CEMT III vessel “suffers” from both the cargo capacity that cannot be used when loading containers and the inability to increase the beam without stepping out of the boundaries of the class. The vessel may be lengthened, but this would not solve the inadequacy of the cargo hold. Additionally, the lengthening might penalize the design, considering that the length is the “most expensive” ship dimension. In this case, the beam of the vessel is reduced to make the vessel suitable for loading two container rows.
4) As for the CEMT IV design, it already has a high η_{HOLD} and a value of m_{TEU} which reflects a well-balanced design (see Table 3-1). Nevertheless, the lengthening of the

Funded by the European Union

vessel by 5 m would enable an additional TEU bay to be loaded. This would result in 10 TEU bays, allowing for loading of five FEU bays.

Thus, the CEMT II and CEMT IV sample vessels could be successfully converted to containerships with relatively moderate interventions. The CEMT I and CEMT III designs, however, have to be extensively altered, including a reduction of some of their main dimensions, which is a highly unorthodox measure in inland ship design. The main particulars of the sample designs after the first modernization step are given in Table 3-2. The improvement of container-carrying efficiency is reported in Table 3-3. Considering that the cargo holds are tailored to natural number of bays and rows, the cargo space capacity utilization η_{HOLD} is 100% by default (except in case of CEMT IV design where four TEUs cannot be fitted in the "corners" of the lowest tier). In addition, the average m_{TEU} is closer to the values which can be expected in practice. Generic CAD models of reference designs, modified so as to improve the container loading efficiency, are given in Figure .

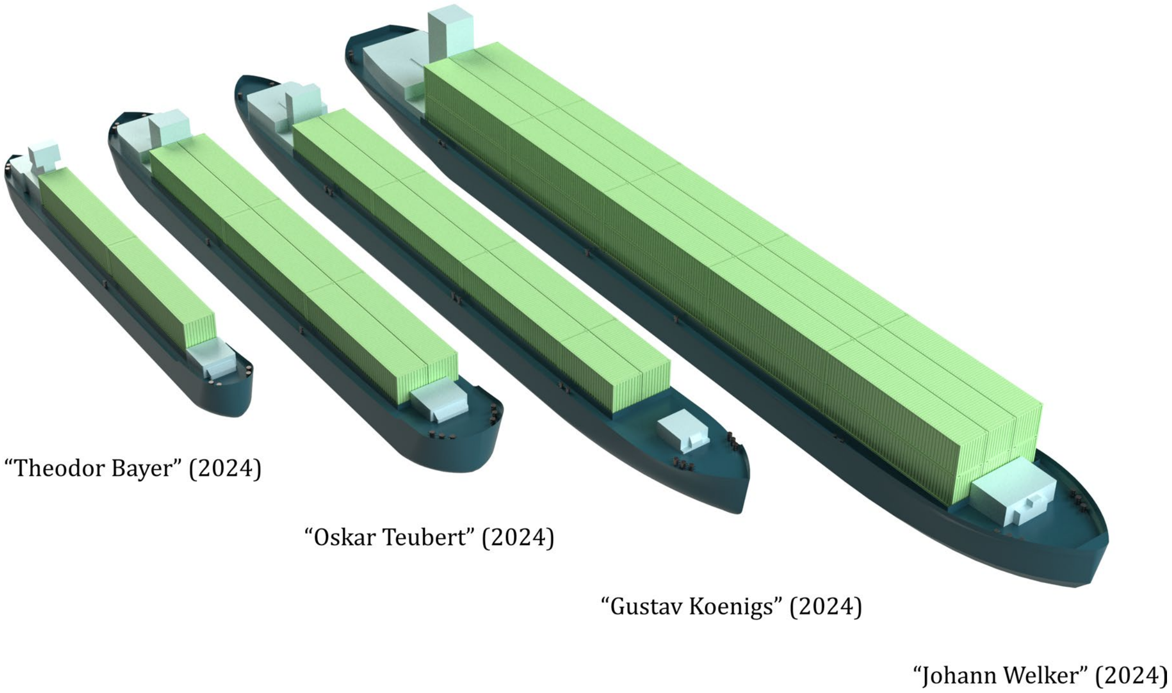


Figure 3-6: Generic CAD models of reference designs of CEMT classes I, II, III and IV following the modifications aimed at improvement of container loading efficiency.

Funded by the European Union

Table 3-2: Main features of the reference designs following the modifications aimed at improvement of container loading efficiency.

Reference design	CEMT class	L [m]	B [m]	d [m]	C_B	m_{cargo} [t]
"Theodor Bayer" (2024)	I	38.5	3.74	1.5	0.912	69
"Oskar Teubert" (2024)	II	53	6.3	2	0.923	400
"Gustav Koenigs" (2024)	III	67	6.3	2	0.847	463
"Johann Welker" (2024)	IV	85	9.5	2.5	0.861	1279

Table 3-3: Cargo space and cargo weight capacity utilization of the reference designs following the modifications aimed at improvement of container loading efficiency.

Reference design	TEU/tier	n_{tiers}	n_{TEU}	η_{HOLD} [%]	m_{TEU} [t]
"Theodor Bayer" (2024)	4	1 or 2	4 or 8	100	17.3 or 8.6
"Oskar Teubert" (2024)	12	2	24	100	16.7
"Gustav Koenigs" (2024)	14	2	28	100	16.5
"Johann Welker" (2024)	30*	3	86	86.7	14.9

* Except in the lowest tier, where 26 TEUs may be accommodated.

The consequences of conversion of the sample vessels to container carriers are multifaceted and go well beyond the removal of hatch covers. The intact stability of the vessels should comply with the requirements for containerships of the European technical standards for inland vessels ES-TRIN (CESNI, 2023) [ES-TRIN Ch. 27, Article 27.02]. The calculations, however, show that the CEMT I vessel (as given in Table 3-4) cannot fulfil the intact stability rules for any realistic vertical centre of gravity of the cargo even with a single container tier (Table 3-3). Thus, further analysis of the CEMT I vessel is redundant.

The possibility of carrying dangerous cargo implies that the vessels are subject to damage stability requirements put forward by the ADN regulations (UNECE, 2023). This results in additional watertight subdivision of the hulls including the conversion to (full) double hull: a considerable change considering the original structural design of the reference vessels. Even though the damage stability calculations at this instance cannot be performed with sufficient accuracy (due to the lack of detailed design information) the results do indicate that the compliance with the relevant requirements may be challenging.

Funded by the European Union

Grant Agreement: 101136257

Table 3-4: Compliance of the reference designs with intact stability regulations for inland container vessels following the modifications aimed at improvement of container loading efficiency.

Reference design	**Required**	**Attained**	**Status**	**VCG_{cargo}**
"Theodor Bayer" (2024)	$GM \geq 1$ m	$GM = 0.456$ m	✗	0 m
	$\varphi < 5°$	$\varphi = 7.74°$	✗	
"Oskar Teubert" (2024)	$GM \geq 1$ m	$GM = 1$ m	✓	1.565 m
	$\varphi < 5°$	$\varphi = 3.15°$	✓	
"Theodor Bayer" (2024)	$GM \geq 1$ m	$GM = 1$ m	✓	1.513 m
	$\varphi < 5°$	$\varphi = 1.89°$	✓	
"Johann Welker" (2024)	$GM \geq 1$ m	$GM = 1$ m	✓	3.486 m
	$\varphi < 5°$	$\varphi = 2.33°$	✓	

Funded by
the European Union

4 IMPLEMENTATION OF ZERO-EMISSION PROPULSION

There are different paths towards zero-emission propulsion in inland navigation: Dahlke-Wallat et al. (2020) use seven criteria (technology readiness level, volume, weight, capital expenditures, operational expenditures, range, and emission reduction potential) to assess the viability of greening technologies for inland vessels of different types and sizes. Additionally, there is a wide variety of solutions for propulsion and steering in inland navigation (see e.g. VBW, 2016). The viability of a vessel drivetrain may be assessed using multiple criteria, including controllability, maintainability, and maneuverability (Geertsma et al., 2017). In view of the foreseen operational areas (small waterways which may penetrate urban and suburban communities) and modes (without human operators on board), the propulsion and steering solutions for the considered vessels should fulfil several requirements. The systems should provide an efficient response to varying power demand as well as adequate maneuvering performance, including operation in shallow waters, in proximity of riverbanks and other vessels, and at low speeds. The environmental performance of the vessels should be improved, in terms of effects on climate and air quality, and radiated noise. Finally, the adopted system should facilitate the automation of the vessel navigation and remote control of the machinery. Thus, this Section investigates the options for modification of the drivetrain of the reference designs.

Sizing of the drivetrain, that is, deciding on the engine power, the number and the features of the propulsors, fuel capacity, etc. is normally based on the “owner’s requirements” which specify the operational area, the speed and the endurance of the vessel. Such information, however, is neither at disposal in this Task nor it is within its scope. Therefore, the propulsion and steering systems will be selected taking into account both the aforementioned criteria relevant for the foreseen operational profiles of AUTOFLEX vessels, and the present fleet. Consequently, the required characteristics of the drivetrain are to be determined based on the literature and the available statistical data for existing ships.

Electric propulsion is typically regarded as the preferred solution for autonomous ships, due to its high fault tolerance, reduced need for maintenance, and inexpensive redundancy. Reduced radiated noise is another advantage from the point of view of the present analysis. Azimuth pushing ducted thrusters, which represent a combined propulsion and steering device, are considered to be a suitable option for electric propulsion. They provide propulsion efficiency comparable to conventional ducted propellers with rudders, but with superior maneuverability, including low-speed operation, dynamic positioning, full propulsion power available for maneuvering and 360° degrees steering. The absence of shaft line reduces mechanical losses, noise, as well as vibrations, and also provides additional space at the aft part of the ship. Regarding the latter, the so-called “L-drive” configuration with the vertically mounted electric motor is the most attractive one, as it eliminates the need of the upper gearbox present in the more conventional “Z-drive” configuration.

Another possible modification of the reference designs is the adoption of twin-screw arrangement instead of the single propeller. Twin-screw arrangement allows for smaller propeller diameters to be used, reducing the risk of the propeller ventilation in low water levels. In addition, the wake field of a twin-screw vessel is more uniform which results in

Funded by
the European Union

reductions of unsteady loads, unsteady cavitation, pressure fluctuations and noise. Twin-screw arrangement also provides redundancy in case of a failure of one of the propulsors.

To improve maneuverability at low speeds, in restricted areas, in harbors, and near temporary cargo terminals, the vessels would be equipped with bow tunnel thrusters. In view of the radiated noise requirements [ES-TRIN Ch. 32, Article 32.02] and the foreseen operational areas, the selected bow thrusters should have low noise levels.

4.1 PROPULSION AND MANEUVERING SYSTEM

To arrive at practical recommendations regarding the modernization of the propulsion and maneuvering systems of the reference designs, the data on the CEMT II to CEMT IV class vessels (which were used to describe the evolution of the fleet in Section 1.1) were analyzed to obtain the statistical parameters of the main engine power and the average power of tunnel thrusters. The average and median power of main engines (P_{avg} and P_2, respectively) are reported in Table 4-1. In addition, the upper and lower quartiles, and minimum and maximum values found in the datasets are reported in Figure . (The outliers in the datasets – typically engine powers which considerably exceed the maxima – are also reported in Figure .) For the sake of comparison, the "approximate" main engine power of the vessels according to the report VBW (2016) is also reported in Table 4-1.[1] It is to be noted that, even though the database comprises over 2750 ships, the information on the power of main engines is not available for more than 25% of vessels. This is especially valid for CEMT II class, where the relevant information is not available for almost 40% of ships. On the other hand, there is a significant discrepancy between the statistical values of the engine power derived from the database and the information reported in VBW (2016). It is thus difficult to pinpoint typical powers of main engines of "small" inland vessels.

Another possibility is to establish the trends in power of engines installed on the vessels of examined CEMT classes and to refer to e.g. the most recently built ships (which could indicate the general preferences of the shipowners). The evolution of the total power of main engines is visualized in Figure (CEMT II), Figure 4-3 (CEMT III), and Figure 4-4 (CEMT IV). However, there are no apparent trends which could indicate the relations between the year of build and engine power. Almost any power (within the typical power range of a specific vessel class) may be found on the vessels (of that class) built over several decades.

Table 4-1: Power of main engines on "small" inland vessels: statistical values and the "approximate" power reported in the literature.

CEMT class	Total No.	Information on main engine power		P_{avg} [kW]	P_2 [kW]	P [kW]*
		Yes	No			
II	807	510	297	198	191	-
III	1154	867	287	440	412	580
IV	794	623	171	613	597	750

*According to VBW (2016)

---

[1] Nevertheless, it is unclear how this "approximate" engine power reported in VBW (2016) was derived.

Funded by the European Union
Grant Agreement: 101136257

A similar analysis has been performed to determine the typical power of bow thrusters (see Table 4-2 and Figure 4-5). For nearly 50% of the vessels given in the database, it cannot be established whether a bow thruster has been installed or not (which confirms that it is difficult to establish the actual extent of modernization of "small" vessels). This share is as high as 72% for CEMT II vessels. However, the majority of the existing CEMT III and CEMT IV vessels do feature a bow thruster. The information on the power of bow thrusters is also only partly available, which further emphasizes the difficulty to formulate the specifics of the propulsion and steering systems based on the existing vessels. Nevertheless, such an outcome is not surprising. The vessels within a certain class may have different operational profiles and may operate in line with the different business cases, which, consequently, may require different powering and maneuvering capabilities.

Table 4-2: Average power of bow thrusters on "small" inland vessels

CEMT class	Total No.	Bow thruster			Information on bow thruster power		P_{tavg} [kW]
		Yes	No	No info	Yes	No	
II	807	152	72	583	110	32	103
III	1154	669	63	422	500	148	158
IV	794	484	44	266	362	116	211

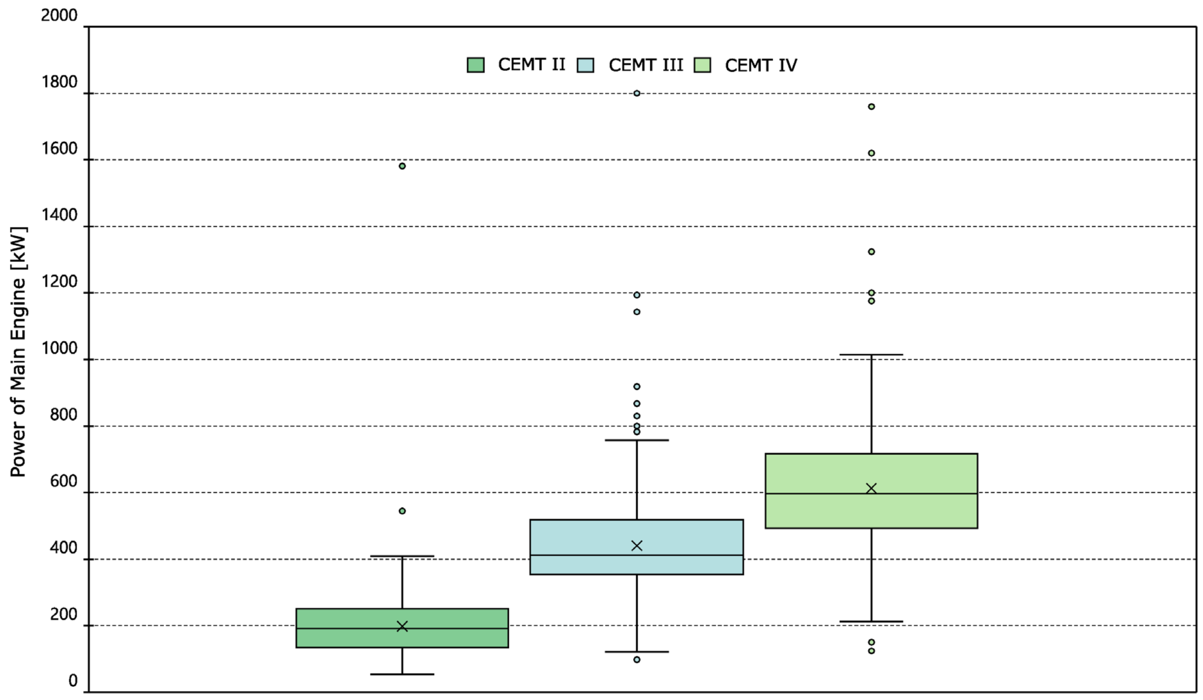


Figure 4-1: Statistical analysis of the power of main engines of CEMT II, III and IV vessels. Crosses correspond to average values. Circles correspond to outliers in the datasets.

Funded by the European Union

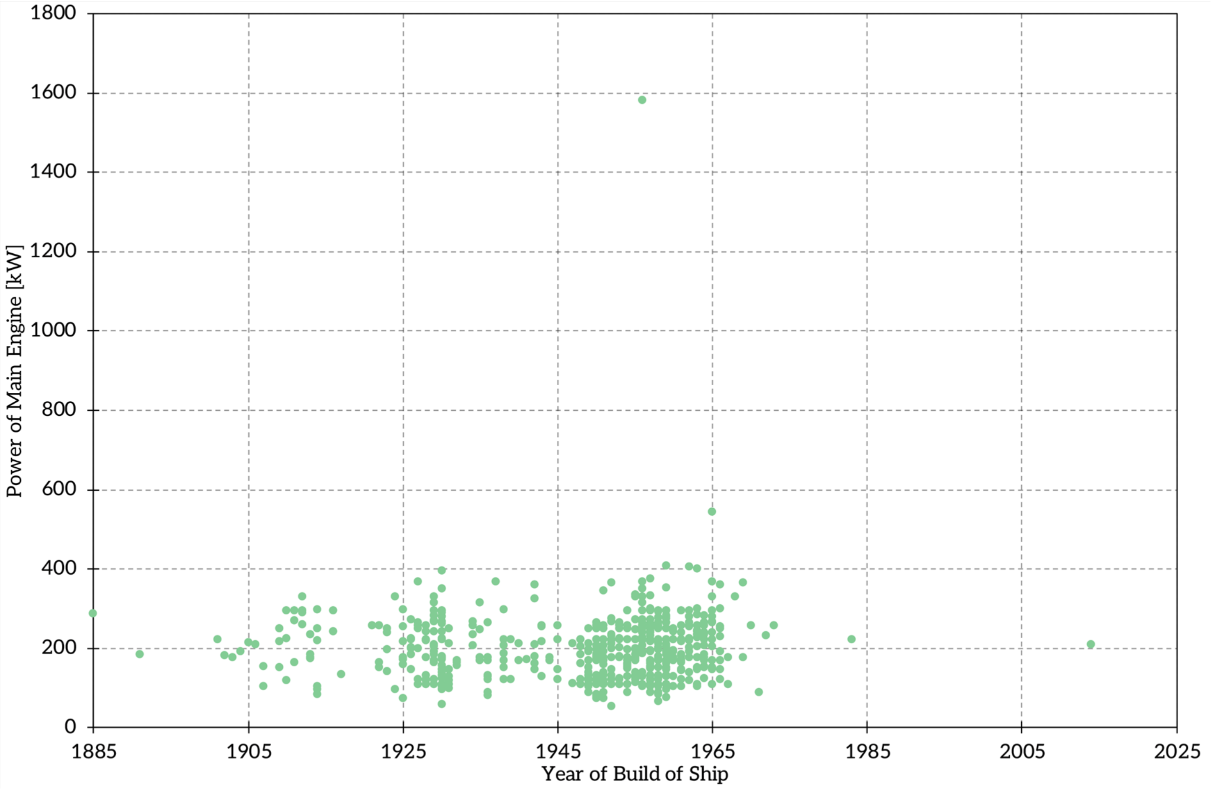


Figure 4-2: Evolution of the (total) power of main engines of CEMT II class vessels.

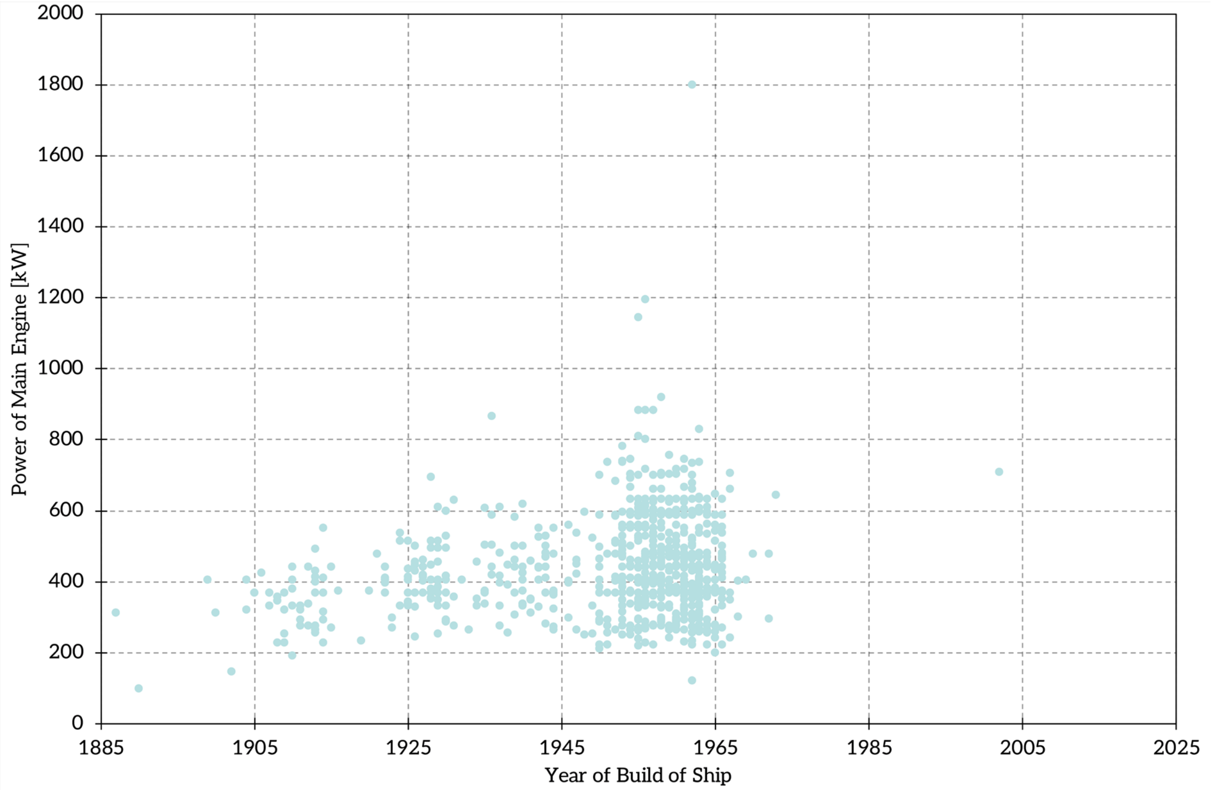


Figure 4-3: Evolution of the (total) power of main engines of CEMT III class vessels.

Funded by
the European Union

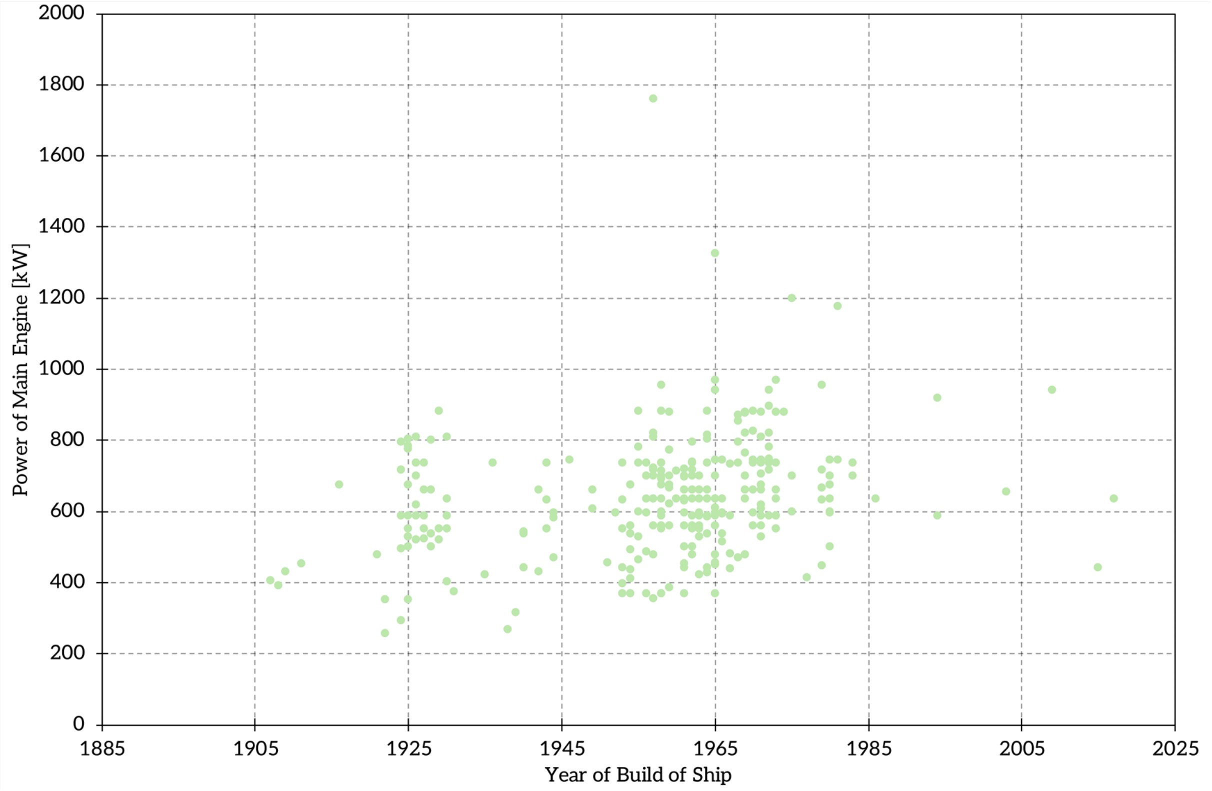


Figure 4-4: Evolution of the (total) power of main engines of CEMT IV class vessels.

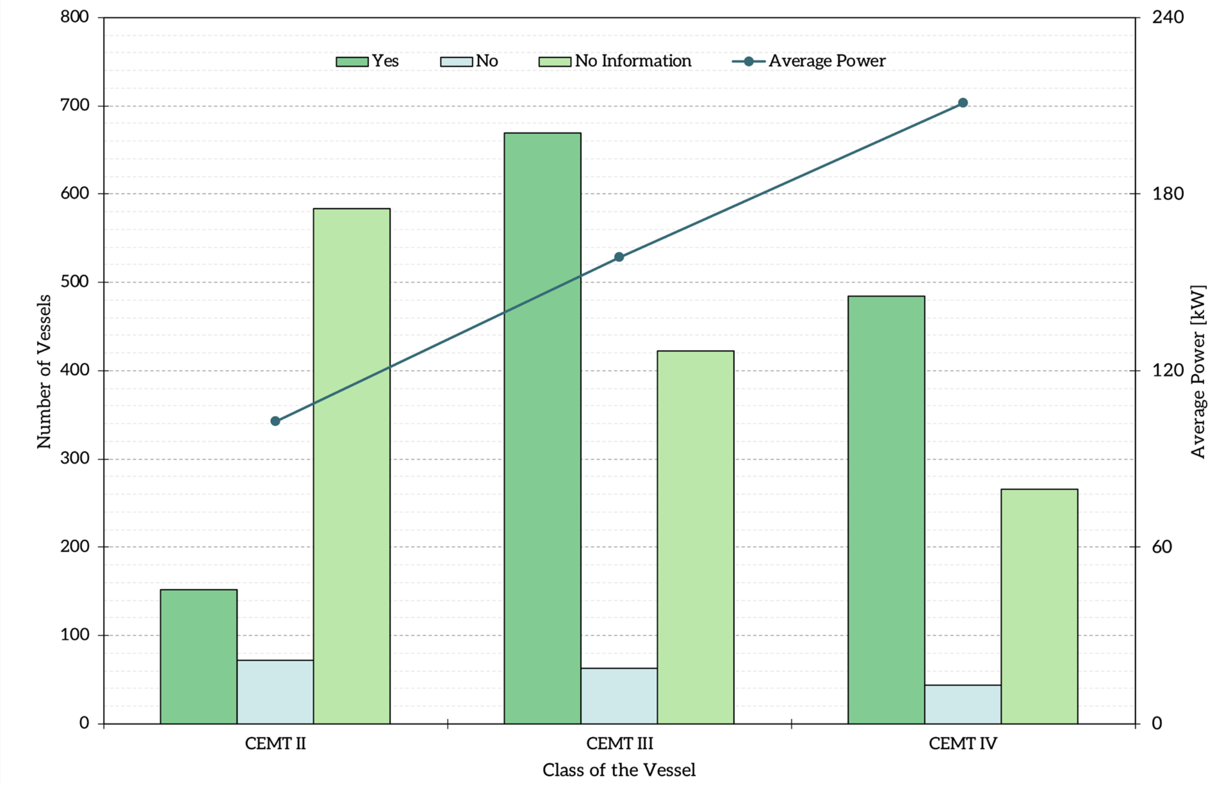


Figure 4-5: Bow thrusters on “small” inland vessels: availability and average power.

Funded by the European Union

Grant Agreement: 101136257

The main features of the adopted propulsion and steering systems are reported in Table 4-3. Herein, the focus was on the standard products available from propulsion system suppliers: Schottel RudderPropellers (SRP), Brunvoll Azimuth Ducted Thrusters, Brunvoll Standard and LowNoise Tunnel Thrusters. The speed ranges are taken from the VBW (2016). The adopted powers of the main propulsors are higher than the values given in Table 4-1 (and even higher than the upper quartiles reported in Figure 4-1). Although they are still in the range of the engine powers found on the existing vessels, it is to be noted that the power adopted for the CEMT II vessel is very close to the maximum value of the corresponding data set. A justification may be found in the fact that the selected propulsors include the power needed for both the propulsion and the steering. The adopted bow thrusters feature powers which are in line with the average values reported in Table 4-2. The analysis of nominal criteria against developed ventilation of tunnel thrusters indicates that, for the design draughts of 2÷2.5 m (corresponding CEMT II, II and IV vessels), tunnels having the diameter of 0.8÷0.85 m are suitable. In general, tunnel thrusters equipped with controllable pitch propellers (CPP) are preferred as they allow to better optimize thruster performance to varying loading and submergence conditions.

Table 4-3: Main features of the adopted propulsion and steering systems

Sample vessel	**"AUTOFLEX-Oskar"**	**"AUTOFLEX-Gustav"**	**"AUTOFLEX-Johann"**
Speed	12–14 km/h	14–16 km/h	15–18 km/h
Type of main propulsor	Ducted azimuth thruster	Ducted azimuth thruster	Ducted azimuth thruster
No. of main propulsors	2	2	2
Power of propulsors	380 kW	630 kW	800 kW
Propeller diameter	0.85 m	1.1 m	1.3 m
Standard product	SRP 100	SRP 150	SRP 180 or AUP/AWP63*
Type of bow thruster	Tunnel thruster	Tunnel thruster	Tunnel thruster
Power of bow thruster	115 kW	165 kW	220 kW
Standard product	Brunvoll FU 37	Brunvoll FU 37	Brunvoll FU 37

* Brunvoll AUP/AWP63 also offers a CPP option, but at a larger propeller diameter

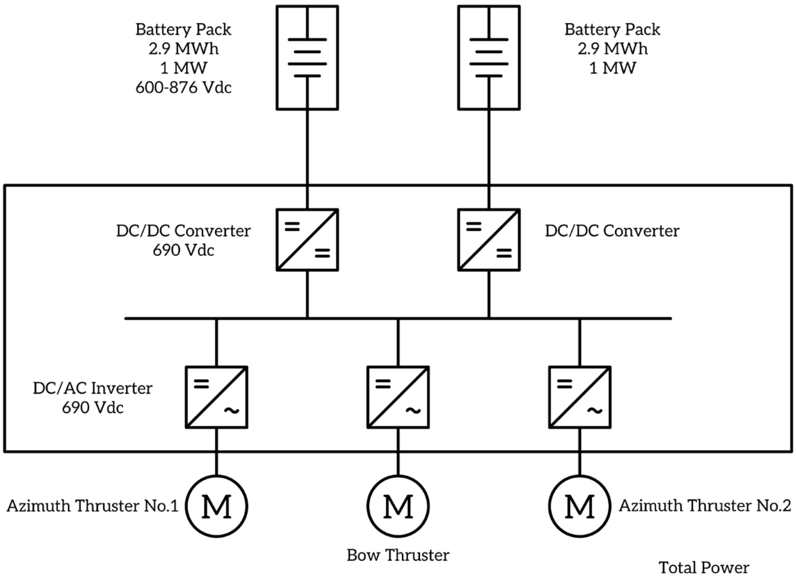
4.2 POWERTRAIN CONCEPT

The powertrain transfers the stored chemical energy of batteries through electrical converters to thrusters. In the design process, key parameters such as power system configuration, redundancy, total efficiency, space, and weight must be carefully considered. Typically, a power system comprises converters that integrate batteries with the switchboard and inverters that connect thrusters to the switchboards as drivers (Xu et al., 2022). Integration of electrical converters in marine applications can employ either AC or

Funded by the European Union

DC schemes. Notably, DC switchboard architecture has gained significant attention in recent years due to its compatibility with DC power suppliers, particularly for battery-powered systems (Haxhiu et al., 2022). The selection of electrical converters is influenced by factors such as redundancy, power range, voltage line, and heavy-duty loading.

In this work, after sizing the thrusters, the power required by propulsors is determined for each of the four examined vessel classes. The suggested single-line diagram is shown in Figure 4-6. Energy is to be supplied by at least two swappable battery packs in TEU containers, in line with the ES-TRIN requirements for two independent energy sources [ES-TRIN Ch. 11, Article 11.01]. Furthermore, ES-TRIN regulations necessitate selecting converters and inverters by considering temporary overloading, alongside the power and current range of drivers [ES-TRIN Ch. 11, Article 11.03]. Based on these considerations, two DC/DC converters are selected so that in case of failure of one battery pack, the other can supply the demanded power to the thrusters. Inverters, responsible for the motor drive in different operations, are selected for each class with overloading considerations.



				Total Power
CEMT I	140 [kW]	75 [kW]	140 [kW]	335 [kW]
CEMT II	190 [kW]	115 [kW]	190 [kW]	495 [kW]
CEMT III	315 [kW]	165 [kW]	315 [kW]	795 [kW]
CEMT IV	400 [kW]	220 [kW]	400 [kW]	1020 [kW]

Figure 4-6: Single-line diagram of machinery and power plant configuration for four examined vessel classes

In the selection of electrical converters, standard products (ABB ASC880 multi-drive modules) are considered, taking into account the power range, voltage and temporary overload. Additionally, according to ES-TRIN, redundancy of the cooling system is required [ES-TRIN Ch. 11, Article 11.03]. Therefore, each converter and inverter have independent air-cooling in the cabinets, ensuring that a cooling system failure does not lead to an entire system shutdown. The weight and space requirements of the proposed drivetrain were also considered to ensure that the systems could be fit into the modified designs.

Funded by the European Union

4.3 ASSESSMENT OF MANEUVERABILITY

Assessment of maneuverability of the sample vessels in real operational conditions (which may include shallow and restricted waters) is not possible at the present stage due to the lack of detailed design information. Instead, a relative comparison of maneuvering capabilities of reference designs before and after each of the first two steps of modernization is made in line with the requirements of the technical standards for inland vessels in Europe (CESNI, 2023) which, inter alia, require checking of the turning capacity and the ability to perform evasive maneuvers. The maneuverability was tested in simulations using the 3 degrees-of-freedom (sway-surge-yaw) mathematical model developed by Jasa (2022). The open water characteristics of azimuth thrusters used in the analysis were obtained experimentally at SINTEF Ocean (Koushan, 2007; Berchiche et al., 2018). The main particulars of propeller, duct and pod used in the experiments, as well a summary of test conditions, are reported in Table 7-1 in Appendix B.

Turning circle tests were conducted in deep water at an initial speed of 13 km/h with the limiting rudder angle (or azimuth heading) of 35°. Evasive maneuvers were also conducted in deep water at initial speed of 13 km/h, the limiting rudder angle (or azimuth heading) of 20° and a yaw rate of 20°/min. The outcome of the turning capacity simulations is reported in Figure 4-7. Time corresponding to the end of an evasive maneuver t_4 (used as a criterion in CESNI, 2023) is reported in Table 4-4.

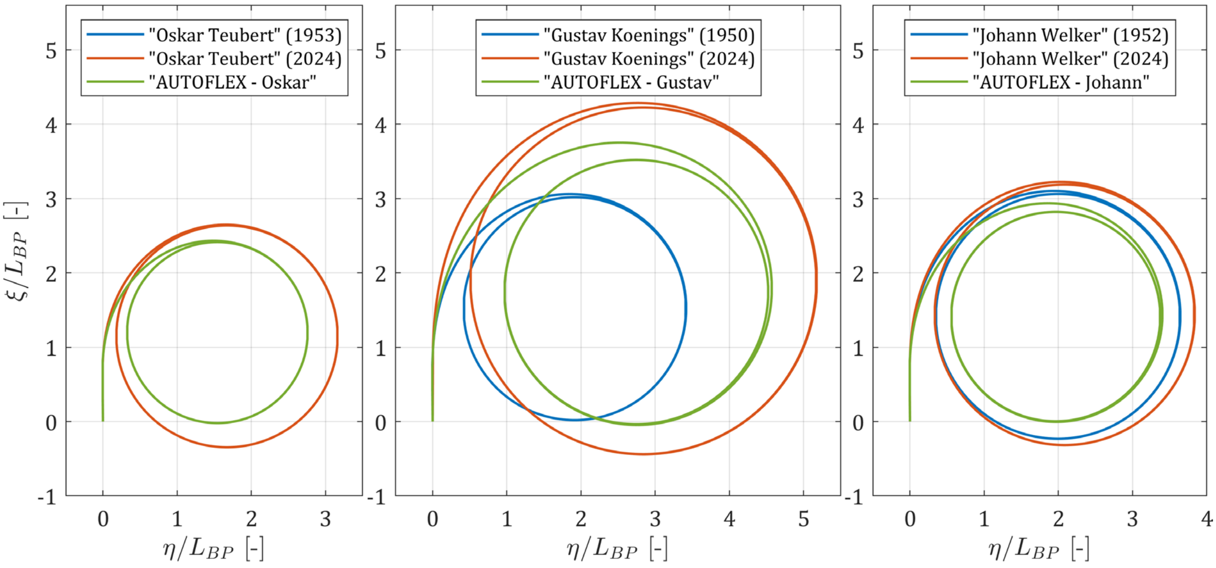


Figure 4-7: Comparison of turning capacity of reference designs before and after the modifications

Based on the results of simulations, it may be concluded that the turning capacity of the sample vessels generally improves with the twin ducted azimuth thruster arrangement. Even larger improvements are expected during the operation at lower speeds, where the efficiency of conventional rudders is reduced. However, while the turning capacity of the CEMT II and IV vessels also improves in comparison to the performance of the original reference designs, the turning circle parameters of the CEMT III vessel worsen when compared to the reference design. Such an outcome is a consequence of modification of main particulars of the vessel in an effort to improve its container-carrying capacity.

Funded by the European Union
Grant Agreement: 101136257

Table 4-4: Time attained at the end of evasive manoeuvre.

CEMT II	t_4 [s]	CEMT III	t_4 [s]	CEMT IV	t_4 [s]
“Oskar Teubert” (1953)	14	“Gustav Koenigs” (1950)	21.4	“Johann Welker” (1952)	27.8
“Oskar Teubert” (2024)	14	“Gustav Koenigs” (2024)	42.1	“Johann Welker” (2024)	33.2
“AUTOFLEX-Oskar”	13.8	“AUTOFLEX-Gustav”	31.2	“AUTOFLEX-Johann”	29.6

Regarding the evasive maneuver, the performance of the CEMT II vessel marginally improves after the change of the drivetrain. The azimuth thrusters fail to fully compensate for impairment of the evasive maneuver performance caused by the change of main dimensions of CEMT III and IV vessels in the first modernization step. Nevertheless, all vessels comply with the applicable ES-TRIN regulations which require $t_4 \leq 110$ s for self-propelled vessels whose dimensions (L x B) are up to 110 m x 11.45 m, in relative water depth $h_w/d > 2$ [ES-TRIN Instructions for the application of the technical standard, Part II, ESI-II-4].

The 3 DOF mathematical model used in the analysis does not include the roll motion, which may be of importance for inland container vessels, considering that the containers are generally not fixed, and that the heeling moments due to turning (especially if combined with the wind gusts) may lead to the loss of cargo.

Funded by the European Union

Grant Agreement: 101136257

5 IMPLEMENTATION OF REMOTE CONTROL

5.1 DESCRIPTION OF THE SYSTEM

The remote-control package to be used in AUTOFLEX project is supplied by the project partner Maritime Robotics (MR). The package consists of four main systems:

- situational awareness system (SAS)
- autonomous navigation system (ANS)
- remote control system (RCS)
- connectivity system (CS).

SAS is provided by the MR product SeaSight and it consists of sensing devices, data processing, sensor fusion and prediction. The output of SAS is used by the ANS MR product SeaControl as the basis for decision-making; ANS handles mission planning, guidance, and control within its given operational envelope. Based on the predefined mission, it generates trajectories for navigation. It includes a collision avoidance system that avoids static and dynamic objects, while adhering to the navigation rules. It also continuously assesses the situation by classifying navigation hazards and quantifying risks. ANS has interfaces to the lower-level conventional control systems such as autopilot, dynamic positioning, and thruster controllers. Maneuvers are thus done by controlling the setpoints to these controllers. RCS presents the essential data to the remote human operator. CS provides a redundant link for communication between the unmanned vessel and RCS.

5.2 CONSIDERED AUTONOMY LEVELS

Two main autonomy levels are considered:

(a) the system proposes an action and requests confirmation from the human operator before initiating the action, and
(b) the system executes the actions autonomously, while keeping the operator informed on the decisions.

The described autonomy levels could be categorized differently, depending on the classification used. Following Rødseth et al. (2022):

- Level (a) could be placed between “Remote Control” and “Constrained Autonomous”.
- Level (b) corresponds to “Constrained Autonomous”.

The ambiguity related to the autonomy level (a) is a consequence of the fact that the definitions in Rødseth et al. (2022) do not include automation systems that will generate proposed actions and execute them if confirmed by the operator.

In terms of classification proposed by the Central Commission for the Navigation of the Rhine (CCNR, 2022b):

- Level (a) may correspond to CCNR level 3 (“Conditional Automation”)
- Level (b) could be regarded as either CCNR level 4 (“High automation”) or 5 (“Autonomous”).

Funded by the European Union

Grant Agreement: 101136257

In this case, the ambiguity related to the autonomy level (b) is related to the scope of the foreseen remote-control package. Namely, even though in both CCNR level 4 and CCNR level 5, the system is fully in charge of decision-making, level 4 is limited to "context-specific" situations, that is, to specified scenarios taking place in "well known" environments. On the other hand, level 5 entails "unconditional performance" of the system, without restriction, in both routine and emergency tasks. In addition, it is worth mentioning that the CCNR taxonomy (which refers to levels of automation rather than autonomy) does not make an explicit relation to remote control; thus, according to CCNR, remote control may be executed at any level of automation (except level 0).

Finally, according to a more general categorization of technical systems given by Sheridan and Verplank (1978):

- Level (a) may be placed at level 5
- Level (b) may be placed at level 6 or 7.

The given examples show that, for the time being at least, there is a lack of uniformity among the existing taxonomies of ship autonomy, and even the lack of a common terminology. From the point of view of the vessel design in the AUTOFLEX project (in particular as regards the design to be performed in Tasks 4.2 and 4.3), this fact has to be acknowledged and the operational mode based on the remote control should be precisely defined, rather than expressed in terms of some of the existing classifications.

5.3 IMPACT OF THE CONSIDERED REMOTE CONTROL SYSTEM ON SHIP DESIGN

From the point of view of ship design, the implementation of the considered remote control opens the possibility for removal of the wheelhouse, accommodation, and other elements of human-centered design, which may allow for additional space and/or weight available for the cargo. (Some elements of the human-centered design would probably have to be retained, for the purposes of maintenance and inspection.) On the other hand, sensing devices (cameras, radars, lidars, etc.) take a prominent place on deck. Indeed, removal of the superstructures enables loading of two additional TEUs on the CEMT II and III vessels, providing space for swappable battery packs without reducing the cargo capacity, and as much as six additional TEUs on the CEMT IV vessel (Figure 5-1). The components of the remote-control package should be placed in a dedicated space protected from major hazards; the position of such a space should also ensure good connectivity. Using the existing ship technology definitions such a space could be designated as the "control center". ES-TRIN regulations define control center [ES-TRIN Ch. 1, Article 1.01] as:

> "a wheelhouse, an area which contains an emergency electrical power plant or parts thereof or an area with a center permanently occupied by shipboard personnel or crew members, such as for fire alarm system, remote controls of doors or fire dampers".

Therefore, even though the wheelhouse in its present appearance may be removed from the vessel, a part of its functions has to remain on board.

On the other hand, the regulatory gap analysis presented by Bačkalov (2020) has shown that the ES-TRIN and ADN requirements which impede introduction of remotely operated

Funded by the European Union

vessels are predominantly related to the wheelhouse, where most of the information necessary for safe handling of the ship in routine and emergency operations should be directed, and from where a range of safety functions should be executed. Accordingly, removal of the wheelhouse from inland vessels implies the loss of the “global safety center” of the ship (Bačkalov, 2020). Notwithstanding that the present regulatory framework for inland navigation does not foresee such a possibility, the safety functionalities of the wheelhouse should be transferred to the remote location as well. This translates to a requirement for a high-capacity link for real-time transmission of information pertaining not only to navigation, but also to monitoring of cargo, hull integrity, machinery, etc. and management of the related functions. Thus, it turns out that the wheelhouse actually cannot be fully removed but rather relocated and distributed (in terms of both functionalities and space it normally occupies) between the vessel and remote operator’s locale.

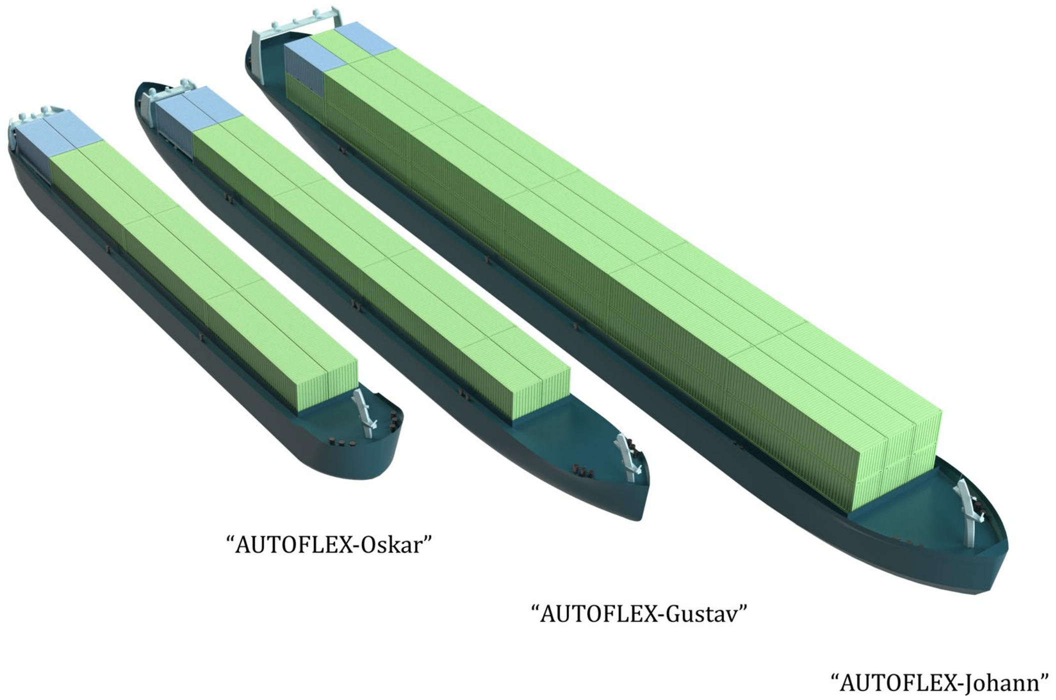


Figure 5-1: Generic CAD models of reference designs of CEMT classes II, III and IV following the modifications aimed at improvement of container loading efficiency, and implementation of zero-emission propulsion and remote control. Blue containers represent swappable battery packs.

Funded by the European Union

6 CONCLUSIONS

This Deliverable presented a systematic analysis of a possible modernization of standard designs of “small” vessels typical for Western European inland waterways, motivated by the potential for reactivation of the small waterway network. The modernization steps included modification of general cargo vessels to container carriers, implementation of a zero-emission propulsion concept based on electrification of the drivetrain, and introduction of remote control of the ship without permanent human crew onboard. The analysis was performed on the reference designs of CEMT I, II, III and IV vessels originally established in the 1950s. The limits of the CEMT classes (maximum length and beam of vessels) were adopted as design constraints. The goal of the research presented in this Deliverable was not to propose novel designs, but rather to identify the major impacts that the considered modernization may have on the reference designs. The technologies introduced in the modernization steps were pre-selected, assuming that they could facilitate the overall goals of the project AUTOFLEX. In other words, the modernization technologies were not the solutions selected as an outcome of the design process. In that sense, hydrodynamic optimization of the hull, detailed structural design, thorough weight calculations, elaboration of machinery beyond the main components, etc. were out of scope of the analysis. On the other hand, the analysis was done in steps which enabled understanding of overall impacts of each of the technologies considered; thus, it may provide basic guidelines for a gradual modernization of small inland vessels.

It was demonstrated that the impacts may vary considerably both in terms of interventions required to accommodate the considered novel technologies and in terms of achieved performance in course of modernization. More specifically, the following impacts on individual reference designs were identified.

1) The modification of CEMT I reference design to a container carrier proved to be unsuccessful as the vessel could not comply with the intact stability criteria for container carriers, which rendered the analysis of the further modernization steps superfluous.
2) The CEMT II reference design required the least modifications. Relatively modest changes of ship structure resulted in full utilization of the cargo hold and well-balanced container-carrying ability, without a loss of payload. Following the modification of the propulsion and steering system, the maneuvering performance of the vessel improved in terms of turning capacity and was virtually unaffected in terms of ability to perform the evasive maneuvers. The remote-control operation mode without human operators on board enabled adding two TEU slots which can be used for placing the containerized swappable battery packs. This facilitates electrification of the drivetrain without compromising the cargo capacity.
3) The conversion of the CEMT III design from a general cargo ship to a container vessel led to a significant loss of payload, suboptimal space utilization and impairment of maneuvering capabilities. The design can be modernized by implementing the described zero-emission propulsion and remote-control concepts (which somewhat improves maneuverability and provides space for the battery packs), but the potential benefits of the modernization are not obvious. However, it was clear that

Funded by the European Union

the hull form optimization (which was not considered in this analysis) would lead to an increase of cargo capacity and an improved space arrangement. Thus, to understand the potential for modernization of the CEMT III reference design a more detailed analysis should be performed.

4) The adaptation of the CEMT IV reference design to a containership and the implementation of the remote control both resulted in container-carrying capacity gains. Similarly to CEMT II and III vessels, electrification of the drivetrain is facilitated by automation, as some of the additional container slots may be used for battery packs.

The research shows that the influence of disrupting technologies and operation modes on ship design has to be analyzed and comprehended in a systematic and holistic manner, by considering all major aspects of ship as a complex system and a crucial component within the larger ecosystem of shipping and logistics. Focusing on a single feature of ship design may result in a limited or even false understanding of the impacts of automation and zero-emission propulsion on design of inland vessels.

Finally, the research was complemented with the insights gained through the interviews conducted with the experts in two very different, yet very much connected fields: ship hydrodynamics and ship management. The interview with the ship hydrodynamics expert stressed the importance of the hydrodynamic optimization of the hull form from the energy efficiency point of view and provided some guidelines for such an optimization. Furthermore, it was advised to reexamine the vessel speeds in view of decreasing the power demand (“slow steaming”), and to strive for simpler, more robust and more cost-effective propulsion solutions. The interview with the ship operator confirmed the need for automation and electrification of inland vessels but revealed that in fact the ships with cargo capacity at the upper limit of the designs examined in this Task (CEMT IV) are regarded as “small” vessels. Thus, the expert interviews provide a basis for a critical analysis of the modernization steps considered in this Deliverable. Such a critical analysis should form an important part of the design process to be performed in the subsequent Tasks, in particular Task 4.2 and Task 4.3.

Funded by the European Union

7 REFERENCES

Abaei, M.M., Hekkenberg, R., BahooToroody, A., 2021. A multinomial process tree for reliability assessment of machinery in autonomous ships. Reliability Engineering & System Safety 210, 107484. https://doi.org/10.1016/j.ress.2021.107484

Abaei, M.M., Hekkenberg, R., BahooToroody, A., Banda, O.V., van Gelder, P., 2022. A probabilistic model to evaluate the resilience of unattended machinery plants in autonomous ships. Reliability Engineering & System Safety 219, 108176. https://doi.org/10.1016/j.ress.2021.108176

Abaei, M.M., Hekkenberg, R.G., 2020. A Method to Assess the Reliability of the Machinery on Autonomous Ships. Presented at the 19th Conference on Computer and IT Applications in the Maritime Industries, Pontignano.

Ait Allal, A., Mansouri, K., Youssfi, M., Qbadou, M., 2019. Toward a Study of Environmental Impact of Shipping Industry and Proposal of Alternative Solutions, in: Ezziyyani, M. (Ed.), Advanced Intelligent Systems for Sustainable Development (AI2SD'2018). Springer International Publishing, Cham, pp. 245–256. https://doi.org/10.1007/978-3-030-11881-5_21

Bačkalov, I., 2020. Safety of autonomous inland vessels: An analysis of regulatory barriers in the present technical standards in Europe. Safety Science 128, 104763. https://doi.org/10.1016/j.ssci.2020.104763

Bačkalov, I., Radojčić, D., Molter, L., Wilcke, T., van der Meij, K., Simić, A., Gille, J., 2014. Extending the life of a ship by extending her length: Technical and economic assessment of lengthening of inland vessels. Presented at the 7th International Conference on European Inland Waterway Navigation (EIWN 2014), Budapest.

Berchiche, N., Krasilnikov, V.I., Koushan, K., 2018. Numerical Analysis of Azimuth Propulsor Performance in Seaways: Influence of Oblique Inflow and Free Surface. Journal of Marine Science and Engineering 6, 37. https://doi.org/10.3390/jmse6020037

CCNR, 2024. Thematic report: the labour market of the European inland navigation sector. Central Commission for the Navigation of the Rhine, Strasbourg.

CCNR, 2022a. CCNR Roadmap for reducing inland navigation emissions. Central Commission for the Navigation of the Rhine, Strasbourg.

CCNR, 2022b. Automated navigation: International definition of levels of automation in inland navigation. Central Commission for the Navigation of the Rhine, Strasbourg.

CEMT, 1992. Resolution No. 92/2 on New classification of inland waterways.

CESNI, 2023. European Standard Laying Down Technical Requirements for Inland Navigation Vessels (ES TRIN).

Dahlke-Wallat, F., Friedhoff, B., Martens, S., 2020. Assessment of technologies in view of zero-emission IWT (No. 2293). DST – Development Centre for Ship Technology and Transport Systems, Duisburg.

de Vos, J., Hekkenberg, R.G., 2020. Towards Safety Regulations for the Design of Autonomous Ships. Presented at the 19th Conference on Computer and IT Applications in the Maritime Industries, Pontignano.

de Vos, J., Hekkenberg, R.G., Koelman, H.J., 2020. Damage stability requirements for autonomous ships based on equivalent safety. Safety Science 130, 104865. https://doi.org/10.1016/j.ssci.2020.104865

Funded by the European Union

DST, 2017. Evaluating the energy requirement of inland vessels using energy efficiency indices (No. 2252). DST – Development Centre for Ship Technology and Transport Systems, Duisburg.

Geertsma, R.D., Negenborn, R.R., Visser, K., Hopman, J.J., 2017. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. Applied Energy 194, 30–54. https://doi.org/10.1016/j.apenergy.2017.02.060

Gribkovskaia, V., Borgen, H., Holte, E.A., Lindstad, E., Nordahl, H., 2019. Autonomous ships for coastal and short-sea shipping. Presented at the SNAME Maritime Convention, OnePetro.

Gudmestad, O.T., 2022. Modern ship design. Presented at the 15th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS 2022), Dubrovnik, pp. 66–72.

Haxhiu, A., Abdelhakim, A., Kanerva, S., Bogen, J., 2022. Electric Power Integration Schemes of the Hybrid Fuel Cells and Batteries-Fed Marine Vessels—An Overview. IEEE Transactions on Transportation Electrification 8, 1885–1905. https://doi.org/10.1109/TTE.2021.3126100

Hofman, M., 2006. Inland container vessel: optimal characteristics for a specified waterway. Presented at the International Conference on Coastal Ships and Inland Waterways II, London.

Jasa, J., 2022. Manoeuvring simulations of inland vessels and assessment of wind effects under navigational constraints (M.Sc. Thesis). University of Trieste, Trieste.

Kooij, C., Hekkenberg, R.G., Vos, J. de, Abaei, M.M., 2021. NOVIMAR Deliverable 4.5: Guidelines for design of vessels with reduced crewing levels. Delft University of Technology, Delft.

Koushan, K., 2007. Dynamics of Propeller Blade and Duct Loading on Ventilated Thrusters in Dynamic Positioning Mode.

Rødseth, Ø.J., Wennersberg, L.A.L., Nordahl, H., 2022. Levels of autonomy for ships. J. Phys.: Conf. Ser. 2311, 012018. https://doi.org/10.1088/1742-6596/2311/1/012018

Sheridan, T.B., Verplank, W.L., 1978. Human and Computer Control of Undersea Teleoperators. Massachusetts Institute of Technology, Cambridge, Massachusetts.

UNECE, 2023. European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN).

van Hassel, E., 2011. Developing a Small Barge Convoy System to reactivate the use of the small inland waterway network (Ph.D. Thesis). University of Antwerp, Antwerp.

VBW, 2016. Driving dynamics of inland vessels: Vessel behaviour on European inland waterways and waterway infrastructure with special respect to German waterways. Karlsruhe.

Xu, L., Guerrero, J.M., Lashab, A., Wei, B., Bazmohammadi, N., Vasquez, J.C., Abusorrah, A., 2022. A Review of DC Shipboard Microgrids—Part I: Power Architectures, Energy Storage, and Power Converters. IEEE Transactions on Power Electronics 37, 5155–5172. https://doi.org/10.1109/TPEL.2021.3128417

Funded by the European Union

Grant Agreement: 101136257

A. APPENDIX: EXPERT INTERVIEWS

A.1 ENERGY EFFICIENCY OF SMALL INLAND VESSELS

Benjamin Friedhoff, Head of Department of Experiments, Fleet Modernization, and Emissions (DST) is a naval architect and an expert in shallow water hydrodynamics.

The transport of goods by ship is known for its high energy efficiency. Large quantities and masses of goods are transported not only in intercontinental ocean shipping, but also in intracontinental coastal and inland shipping with its intermodal competition. Ships benefit from their size and correspondingly high deadweight tonnage due to Archimedean buoyancy. The specific power demand, given e.g. in kW/t, depends not only on the size of the ship but also to a large extent on its speed. Here, the speed is not so much to be considered as absolute value, but scales to a large extent with the size of the ship due to hydrodynamic phenomena. Accordingly, ships can best utilise their energy efficiency advantages if they are as large as possible (see Figure 7-1) with an exemplary baseline of Energy Efficiency Design Index for inland vessels) and travel slowly. However, as AUTOFLEX is dedicated to the development of small vessels, maximising efficiency is of paramount importance. Only by rigorously optimising the design and operation an ecological advantage over road transport can be achieved.

In addition to environmental performance, holistic optimisation is required for economic viability. Today crew costs are considered as a key limiter for profitability of small cargo vessels. With the aimed high level of automation of the AUTOFLEX vessels other cost elements will come into the focus. These are mainly energy costs for fuels or charging batteries, costs for energy storage (tanks or batteries) and the equipment costs for propulsion and manoeuvring devices. All these costs are reduced as a consequence of hydrodynamic and operational optimisation. The smaller the power demand, the less power is required for the energy converters and the less energy capacity needs to be carried in tanks and/or batteries, or the higher the range of autonomy. For low- or zero-emission drivetrains and technologies with lower energy density this is even more important than for conventional drivetrains. Investment costs for energy converters and energy containment will have a significant impact on economic viability.

Fortunately, the great pressure to optimise coincides with optimisation potentials that are significantly greater than it is the case with large ships, particularly in terms of hydrodynamics. When specifying the propeller diameter in ship design, a compromise usually has to be made for large inland vessels. Large propellers go hand in hand with greater efficiency, but also increase the minimum draught required for safe navigation. An increase in minimum draught, however, can trigger a reverse modal shift when the transport performance drops with water depth. This is less critical with small ships.

A further design constraint to improve the resilience against low-water periods for larger ships is absent for small craft. To increase cargo capacity at minimum draught and with overall dimensions limited by lock sizes, conventional inland ships have very full forms with extremely small bilge radius and the lowest possible centre of buoyancy. Though straight hull plating offers lower building costs, a quick return on investment by reduced investment costs for the equipment and lower operational costs is very likely with low- or zero-emission drivetrains.

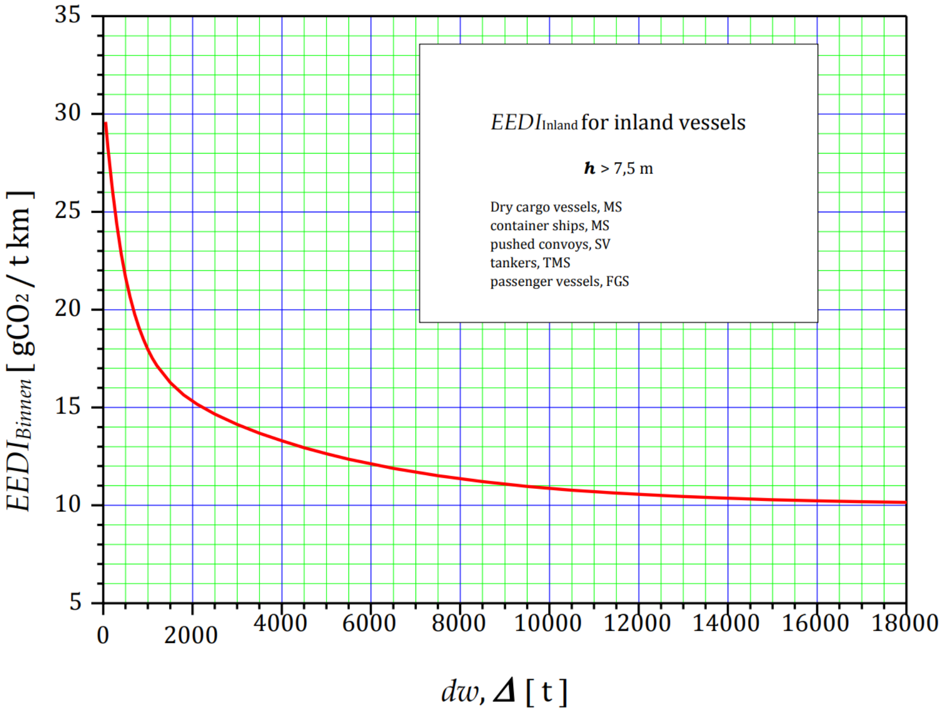


Figure 7-1: $EEDI_{Binnen}$ trend line for inland vessels (from DST, 2017)

Therefore, the following recommendations are given:

- optimise ship lines with a moderate block coefficient,
- investigate the potential of reduced width/draught ratios,
- check the limits of slow steaming without interfering with surrounding traffic,
- minimise the power capacity and complexity of propulsion and manoeuvring devices,
- aim for simplest and robust equipment like one conventional shaft propulsion and twin rudders plus a steering grid in the bow,
- ensure manoeuvrability with proactive control strategies.

Funded by the European Union

Grant Agreement: 101136257

A.2 SHIP OPERATOR'S VIEW OF THE VESSEL DESIGN

Jelle van Koevorden, Managing & Route Director (DFDS Ferry) oversees development of the DFDS Multimodal terminal in Ghent.

With respect to inland vessels, DFDS do not operate vessels smaller than CEMT class Va. Inland vessels operated by DFDS are exclusively standard containerships. With respect to the type of the cargo carried, most of the containers (around 90%) are FEU units. TEU containers are mainly utilized for steel and heavy bulk goods. The dangerous goods may be found in less than 5% of containers. A business case for a Ro-Ro vessel may exist as well, considering the current lack of capacity in the road transport. Ideally, a vessel should be capable of carrying “mixed” cargo: vehicles / trailers on lower deck(s) which would be loaded over a stern ramp, and containers on an upper deck which would be handled by e.g., reach stackers. A Ro-Ro container vessel (i.e. a vessel on which the containers would be handled horizontally) is not considered as a viable option; the cassettes which need to be used as intermediary devices reduce the payload and increase the handling costs in view of the expensive dock labour. The double-ended Ro-Ro design would not bring any added value considering the typical length of voyages. A business case for smaller vessels may exist (in waterway networks which penetrate the hinterland); the desired cargo capacity is in range of 48 FEU / 50 trailers / 60 vehicles (per deck).

Electrification is regarded as the most cost-effective innovative propulsion solution in terms of attaining climate neutrality goals. The type of electrification (i.e., fixed or swappable battery) however, may depend on a number of parameters including business models, evolution of the battery prices, technological advancements in battery charging, and the availability of the charging stations. Fixed, higher capacity batteries on vessels, combined with the fast-charging technology, are regarded as a more viable solution compared to swappable batteries. Nevertheless, the current lack of charging infrastructure in ports like Antwerp and Rotterdam prevents such developments.

Automation and remote control are driven by a shortage of qualified personnel willing to work on board ships. The hurdles in finding an adequate crew are making it difficult for ship operators to decide whether to opt for owning or long-term chartering of the vessels (in the latter case, crewing is not the responsibility of the operator). In conclusion, innovation and, specifically, the energy infrastructure, play a major role in ensuring the sustainability of inland waterway transport.

Funded by the European Union

B. APPENDIX: MAIN PARTICULARS OF THE GENERIC AZIMUTH DUCTED PUSH THRUSTER AND TEST CONDITIONS

Table 7-1: Main particulars of the SO Generic Azimuth Ducted Push Thruster

Propeller	P1374
Type	Controllable Pitch Propeller
Diameter in model scale	0.25 m
Hub ratio	0.24
Number of blades	4
Blade area ratio, Ae/Ao	0.6
Pitch ratio	1.1
Reference chord length	0.3879
Total skew angle	23°
Duct	D-136
Type	Base 19A, w/o diffusor
Length diameter ratio	0.5
Distance from duct LE to propeller plane	0.5
Pod housing	
Type	SINTEF Ocean stock push unit for ducted thrusters, w/o brackets
Gondola length	0.723
Distance from pod steering axis to propeller plane	0.471
Strut chord length	0.333
Strut max relative thickness	0.503
Test conditions in open water	
Heading angles	[-90°; +90°]
Pitch settings (*P/D*)	-0.5; -0.3; 0.0; 0.3; 0.5; 0.6; 0.9; 1.0
Propeller RPS	6÷11 Hz

Funded by the European Union

Grant Agreement: 101136257

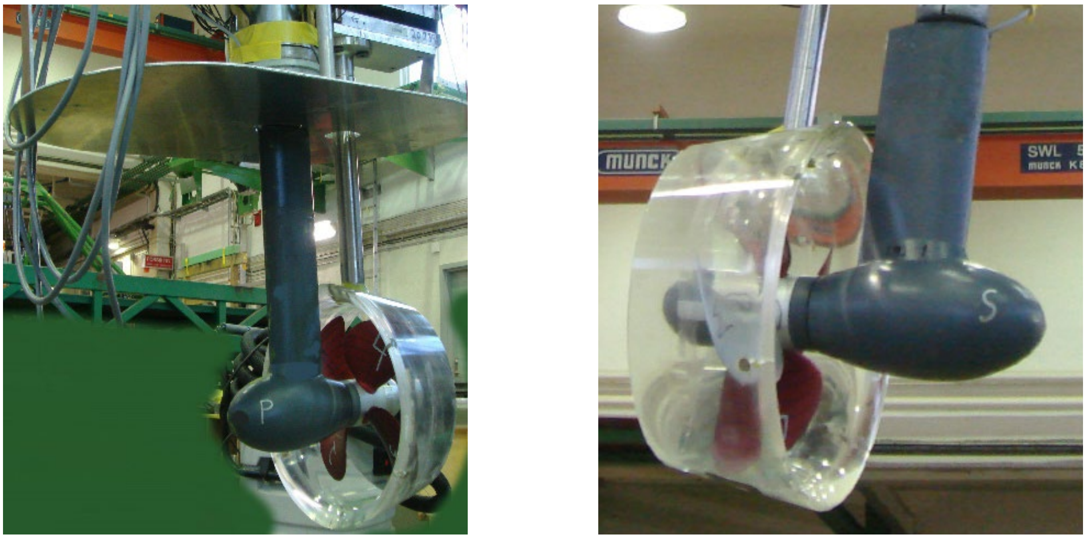


Figure 7-2: General view of the SO Generic Azimuth Ducted Push Thruster

Funded by the European Union

Grant Agreement: 101136257