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Article *in* Journal of Physics Conference Series · October 2024

DOI: 10.1088/1742-6596/2867/1/012018

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Abstract. Small inland waterways offer considerable capacity for modal shift of cargo transport. Revitalization of smaller inland waterways, however, may require new vessel designs as most of the existing small vessels are outdated and incompatible with the present state of the technology development and the current commercial and regulatory requirements. This paper investigates the possibilities for modernization of small inland vessel designs and offers a systematic analysis of impact of “automation” and “zero-emission propulsion technology” on reference designs of standard European inland cargo vessels of CEMT classes I, II, III, and IV. The adopted level of automation enables the vessels to be remotely operated without human crew onboard, whereas the adopted zero-emission propulsion concept is based on electrification of the powertrain. The paper identifies the impacts of the modernization on general arrangement, cargo capacity, safety, structural design, etc. and indicates the vessel classes which could be the most promising candidates for the design of a future small autonomous inland ships.

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 densely populated areas. However, the existing inland cargo vessels suitable for such waterways are relatively old and outdated and may not be able to respond to the contemporary market and regulatory requirements.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. This paper attempts to answer how much the original designs may be affected by the introduction of novel technologies.

Small inland waterways considered in this paper 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 (for classification of inland waterways in Europe see CEMT, 1992). To increase cost-efficiency and address the labor 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 diminish the climate impact of the vessels (and facilitate automation), a zero-emission propulsion solution via electrification is to be implemented. The major differences between the modified and the reference designs in terms of general arrangement, cargo type and cargo capacity, safety requirements, structural design, outfitting, energy and propulsion system, are identified and their impacts are assessed.

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** 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. It follows that most of the vessels suitable for the waterways considered in this paper are at least 45 years old.

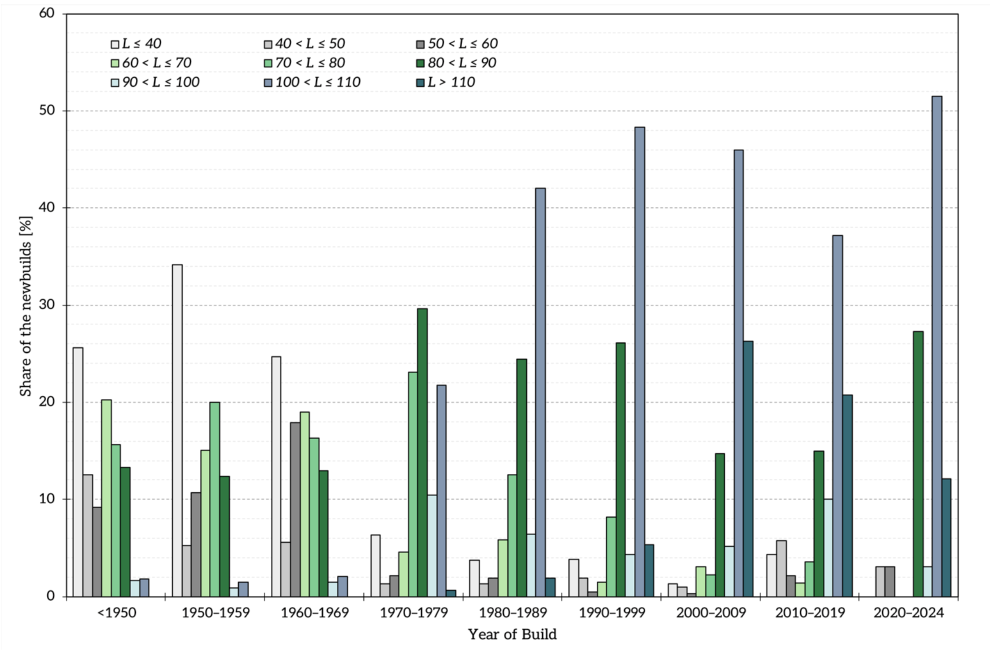

Figure 1. Evolution of the Western European inland fleet of general cargo vessels

1.2 A 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 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.

2. Approach

The analysis is conducted using the original designs of the relevant CEMT classes of ships, made in Western Germany in the 1950s, as the reference (sample) vessels. Generic CAD models of the reference designs (**Figure 2**) are used to examine and visualize the modifications which are a consequence of automation and electrification of the vessels. The analysis is performed in several steps whereby a major modernization intervention is introduced within each step.

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 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.

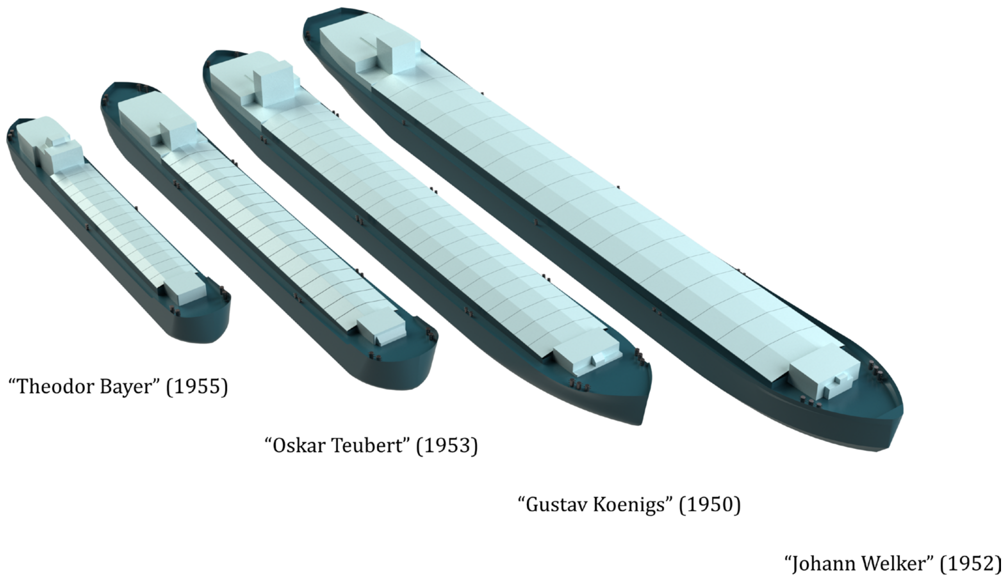

Figure 2. Generic CAD models of reference designs of CEMT classes I, II, III and IV

Table 1. Main features of the sample vessels.

Sample vessel	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-centered elements of ship architecture (i.e., wheelhouse, superstructures, and life-saving appliances) and implementation of an autonomous navigation system. Such interventions should be preceded by the implementation of technologies which enable automation of other main ship functions in addition to navigation: cargo handling, propulsion, mooring, communication, etc. 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. The introduction of the zero-emission propulsion 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”. 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.

3. Shift from bulk cargo to containerized cargo

As previously pointed out, the sample vessels were not intended for carrying the containerized cargo. An analysis of container-carrying capabilities of the considered original designs is given in **Table 2**, where η_{HOLD} and m_{TEU} stand for the space utilization (cargo hold space utilized by the containers as a share of the total space available in the cargo hold) and average mass of twenty-foot equivalent unit (TEU) containers, respectively (m_{cargo} divided by the number of TEU, n_{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.

Table 2. Cargo space and cargo weight capacity utilization of original designs of the sample vessels.

Sample vessel	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

The conversion of the sample vessels to containerships may have several goals. The number of containers carried at the design draught should be maximized. In addition, the containers should be neither too light nor too heavy, i.e. the vessel should be well-balanced, which is a specific challenge for inland container vessels (see 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 which allow for loading of an even number of TEU bays. 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. Some of the designs given in **Table 1** could be lengthened, but not widened as their beams are already at the maximum values as per definitions of the CEMT classes.

The container loading capacity of the sample CEMT II vessel could be substantially improved by modifying the dimensions of the cargo hold only. In other cases, however, the designs have to be extensively altered. Curiously, the reference CEMT I and III class designs have excessive cargo capacity which cannot be utilized when the vessels carry unitized cargo: neither the widths nor the lengths of their cargo holds are suitable for loading of a natural number of TEUs. On the other hand, these vessels cannot be widened as they already reach the limitations of the respective CEMT classes. Thus, the modification of these two reference designs to containerships implies a reduction of some of their main dimensions which is an unorthodox measure in inland navigation. Finally, lengthening the CEMT IV design by 5 m would enable an even number of TEU bays to be loaded. The main particulars of the sample designs after the first modernization step are given in **Table 3**. The improvement of container-carrying efficiency is reported in **Table 4**.

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

Sample vessel	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 4. Cargo space and cargo weight capacity utilization of the reference designs following the modifications aimed at improvement of container loading efficiency.

Sample vessel	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	95.6	14.9

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

The consequences of conversion of the sample vessels to container carriers 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). The calculations, however, show that the CEMT I vessel (as given in **Table 3**) cannot fulfil the intact stability rules for any realistic vertical center of gravity of the cargo even with one container tier. Thus, further analysis of the CEMT I vessel is redundant.

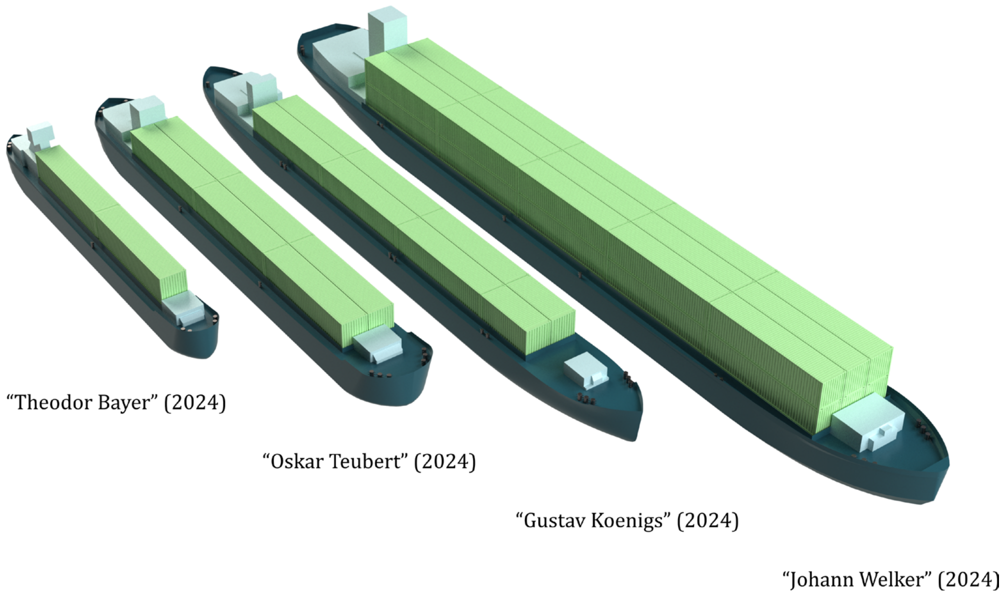

Figure 3. Generic CAD models of reference designs of CEMT classes I, II, III and IV following the modifications aimed at improvement of container loading efficiency.

4. Implementation of zero-emission propulsion via electrification

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.

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 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, and vibrations, and provides additional space at the aft of the ship.

Another modification of the reference designs is the adoption of twin-screw arrangement which allows for smaller propeller diameters, 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 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 and in harbors, the vessels would be equipped with low noise, bow tunnel thrusters. Energy would be supplied by at least two swappable battery packs (in line with the current ES-TRIN requirements for two independent energy sources) in TEU containers. The main features of the adopted propulsion and steering systems are reported in **Table 5**.

Table 5. 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
Type of bow thruster	Tunnel thruster	Tunnel thruster	Tunnel thruster
Power of bow thruster	115 kW	165 kW	220 kW

5. Implementation of remote control

The foreseen remote-control package consists of four main systems: situational awareness system (SAS), autonomous navigation system (ANS), remote control system (RCS), and connectivity system (CS). SAS consists of sensing devices, data processing, sensor fusion and prediction. 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. RCS presents the essential data to the remote human operator. CS provides a redundant link for communication between the unmanned vessel and RCS.

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), (a) could be placed between "Remote Control" and "Constrained Autonomous", while (b) corresponds to "Constrained Autonomous".[1] In terms of classification proposed by the Central Commission for the Navigation of the Rhine (see CCNR, 2022), (a) may correspond to CCNR level 3 ("Conditional Automation"), while (b) could be regarded as either CCNR level 4 ("High automation") or 5 ("Autonomous").

From the point of view of ship design, the implementation of the remote control opens the possibility for removal of the wheelhouse, accommodation, and other elements of human-centered design which 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. On the other hand, sensing devices (cameras, radars, lidars, etc.) take a prominent place on deck (**Figure 4**).

[1] 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.

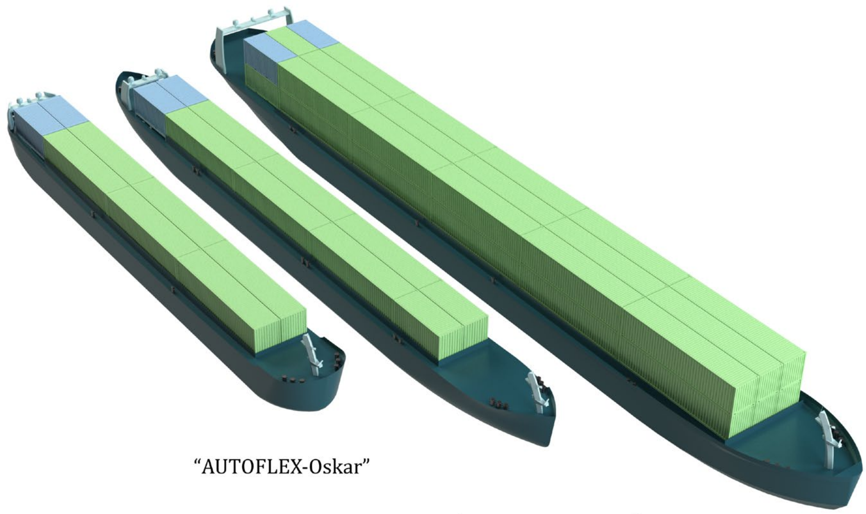

Figure 4. Generic CAD models of reference designs of CEMT classes I, II, III and IV following the modifications aimed at improvement of container loading efficiency, and implementation of zero-emission propulsion and remote control. Blue containers represent swappable battery packs.

6. Discussion

There are different paths towards zero-emission propulsion in inland navigation, as emphasized by Dahlke-Wallat et al. (2020). Hence, additional measures and/or alternatives to the solution adopted in this paper may be considered. Such solutions include hull form optimization aimed at increase of energy efficiency (e.g. the lowering of the block coefficient, which is inherently high in inland vessels, see **Table 1**) and decrease of operational ship speed ("slow steaming"). Both measures are meant to reduce the power demand which may be particularly important for ships utilizing the technologies with lower energy density, such as the battery-powered designs examined in this paper. Reduction of the power demand translates to reduction of investment costs which may be critical for economic viability of novel designs for small inland waterways.

It was shown that the removal of human-centered elements, such as the wheelhouse, may be an advantage of remotely controlled vessels, from the ship design point of view. However, the components of the remote-control package should be placed in a dedicated space protected from major hazards. Using the existing ship technology definitions such a space could be designated as the "control center". ES-TRIN regulations define control center 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 requirements found in the technical standards for inland ships, which impede introduction of remotely operated 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. Thus, following the removal of the wheelhouse, its safety functionalities should be transferred to a remote location as well. This results in 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. Hence, 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.

7. Conclusions

The paper presents 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 waterways 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 the paper was not to propose novel designs, but rather to identify the major impacts that the considered modernization may have on the reference designs. Thus, 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 may provide basic guidelines for a gradual modernization of small inland vessels.

It was demonstrated that the impacts may vary considerably. More specifically, the following impacts on individual reference designs were identified.

- 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.
- 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. The remote-control operation mode without human operators on board enabled adding two TEU slots which can be used for placing the containerized battery packs. This facilitates electrification of the drivetrain without compromising the cargo capacity.
- The conversion of the CEMT III design from a general cargo ship to a container vessel led to a significant loss of payload and suboptimal space utilization. The design can be modernized by implementing the described zero-emission propulsion and remote-control concepts (which provides space for the battery packs), but the potential benefits of the modernization are not obvious. However, it was clear that 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.
- 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 paper has shown 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.

Acknowledgments

The paper presents the outcomes of early stages of research done within the framework of the project AUTOFLEX (AUTOnomous small and FLEXible vessels) which received funding from the European Union Horizon Europe Programme under the Grant Agreement 101136257.

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