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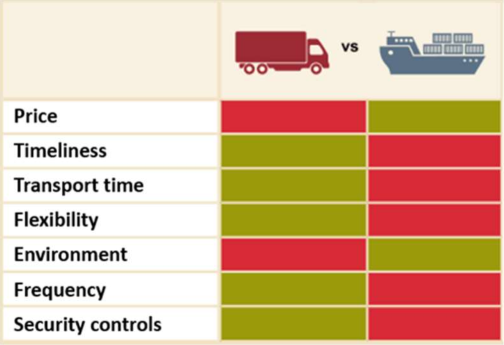
Abstract. The European maritime transport policy recognizes the importance of the waterborne transport systems as key elements for sustainable growth in Europe. A major goal is to transfer more than 50% of road transport to rail or waterways within 2050. To meet this challenge waterway transport needs to get more attractive and overcome its disadvantages. Therefore, it is necessary to develop new knowledge and technology and find a completely new approach to short sea and inland waterways shipping. A key element in this is automation of ships, ports and administrative tasks aligned to requirements of different European regions. One main goal in the AEGIS project is to increase the efficiency of the waterways transport with the use of higher degrees of automation corresponding with new and smaller ship types to reduce costs and secure higher frequency by feeders and provide multimodal green logistics solutions combining short sea shipping with rail and road transport.

1. Introduction

The European Union [1] and the Norwegian Government [2] recognized the importance of waterborne transportation systems for sustainable growth in Europe. The main goal of the AEGIS Project is to shift road transport to waterborne transport thus reducing road congestions and pollution.

In general, waterborne transportation can be very energy efficient especially when using new vessel types with zero or low emission propulsion systems to reach an emission, dust and noise free transport system.



	🚚 vs	🚢
Price	🟥	🟩
Timeliness	🟩	🟥
Transport time	🟩	🟥
Flexibility	🟩	🟥
Environment	🟥	🟩
Frequency	🟩	🟥
Security controls	🟩	🟥

Figure 1 Why Norwegian short sea transport fails to compete with trucks. [3]

Figure 1 summarizes the conclusions on why short sea waterborne transport today cannot compete efficiently with trucks, from the Auditor General in Norway [3]. Ship transport is generally cheaper, is able to transport heavy loads and more tonnage compared to trucks and is friendlier to the environment. On the other side, truck transport offers more service quality and is more flexible on short routes.

The AEGIS project develops a transport system with more and smaller vessels to increase frequency, differentiate speeds, reduce terminal costs and reducing port times. Furthermore, smaller vessels increase reliability and resilience and automated cargo handling as well as standardized cargo units will reduce problems (e.g., human errors) and transhipment costs. The advantage by using and establishing remotely controlled vessels, is the possibility to operate a fleet of vessels from a remote control centre and therefore be more flexible and efficient.

This paper mainly focuses on the development of the new advanced, efficient and green vessel designs (section 4), beforehand the three real life use cases of the project (subsections 2.1-2.3), policy measurements (subsection 2.4) and key performance indicators (KPI) for the vessel development (subsection 2.5) are introduced. In addition, the definition of vessel autonomy for this project as well as autonomous vessel operations are discussed (section 3). In the end, a conclusion and an outlook is presented (section 5).

2. Requirements and Objectives

2.1. Use-case A

Use case A in the AEGIS project refers to a maritime transport corridor from the west coast of Norway down to the continent, that in our case is the port of Rotterdam as destination.

It also includes local transport in Norway, serving the smaller ports in the Trondheimsfjorden region where a transshipment terminal is planned to be at Sandstad in the island Hitra. The use case has three important elements to consider, which is the baseline in this paper:

1. Local transport between smaller ports in the Trondheimsfjorden region operated by a daughter vessel
2. Terminal activities and operations, which differ with different terminal sizes, spanning from the smallest self-served ports to medium-size ports and the large ports in Europe, such as in Rotterdam
3. Short-sea transport from Norway to the large ports in Europe (Rotterdam)

From the studies we consider that there will be different autonomy levels, where we are following the four-degree levels defined by IMO [4], as presented in section 3.2.

When investigating the autonomous transport system, the focus has been mainly on the following parts:

- The autonomous ship with different autonomy levels. In the use case there are two different ship concepts; a mother vessel (see subsection 4.1.1) sailing the short-sea segment and daughter vessels (see subsection 4.1.2) operating locally in Norway.
- There is also a particular focus on crane operations, and land-based autonomous solutions such as terminal tractors and reach stackers.
- An onshore Remote Control Centre (RCC) and its role in supporting the ships and terminals.
- Interaction between ships and automated port services, and specifically regarding solutions for safe berthing and mooring.
- Communication between ships, control centres and crew in logistic operations.

Figure 2 Proposed daughter scenarios for use case A.

Use case A has proposed to look into four different daughter scenarios, as shown in Figure 2. Each of the four scenarios has different cargo volume potential and requirements related to weather conditions and terminals to be visited. While scenarios a), b) and d) have constant cargo flows, the scenario c) will be more varying and maybe also on-demand. Different vessel requirements have been proposed for the four scenarios. For scenario a) the daughter vessel with capacity 60 TEUs is relevant, for scenario b) and c) the barge solution will be the best suited alternative, as these also can be used as temporary storage of cargo. The last scenario, d), might need a bigger and more seaworthy vessel as the daughter with capacity 160 TEUs.

Scenario b) relates to transport of goods from the island Frøya to Hitra with barges and further to Rotterdam with a short sea container liner.

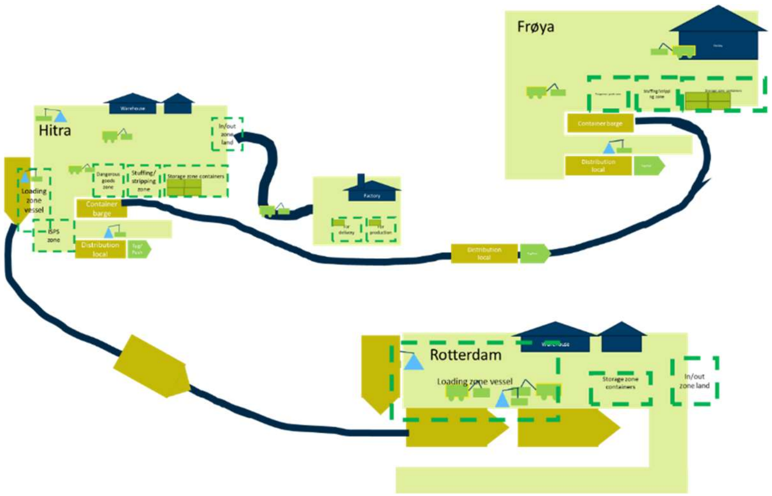


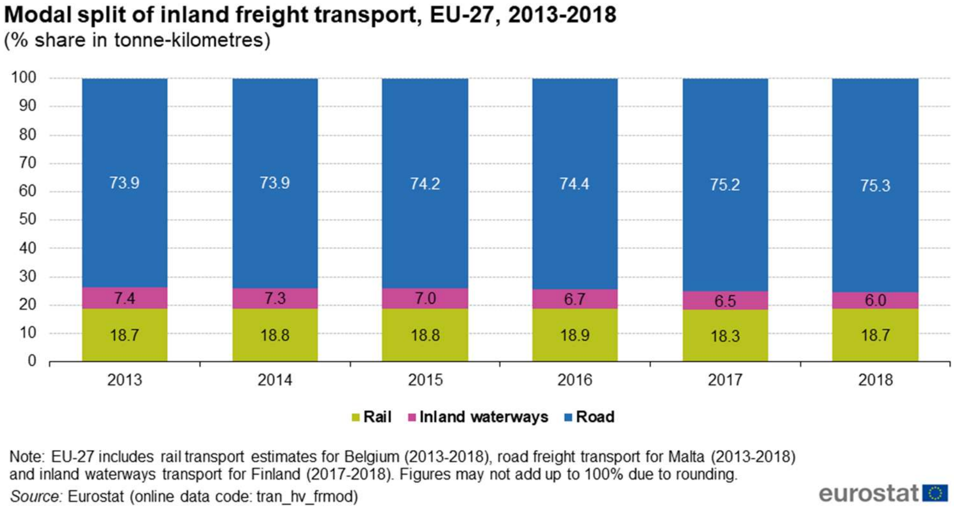
Figure 3 Proposed transport chain in use case A.

As can be read from Figure 3, there are three main parts in this value chain: 1) the production site at Frøya, 2) the terminal operations at Sandstad (Hitra), 3) the arrival terminal in Rotterdam. Regarding autonomy there can be different levels implemented in the individual parts, varying from level 1 to 3 (4 is probably far into the future). The mother short-sea vessel is realistically at a level 1 (maximum 2), whereas the barges will be at level 3. Cargo handling and other terminal related equipment will also be automated and should aim at an autonomy level of at least 2.

2.2. Use-case B

For the purposes of AEGIS Use Case B, with its focus on the inland shipping interface in Belgium and Netherlands, a few important mental framings must be considered before engaging with developing a prospective green, autonomous waterborne transportation system on the inland waterways in Europe in general and in Belgium and the Netherlands in particular.

First, it is worth noting that the purpose of the AEGIS Use Case B autonomous transport system and its focus on RoRo transportation by the inland waterways is not to directly compete with existing LoLo services in the region, but instead to convert existing trucking services unto the inland waterways in the area. This becomes evident when looking at the existing modes of inland freight transportation. According to Eurostat [5], of all the inland freight transport in Europe, the inland waterways constitute a mere 6% of inland freight – a number that has been decreasing yearly from 2013 to 2018 (see Figure 4). In contrast, inland freight transportation by road constitutes more than 75% of the total inland freight – a number that has been increasing yearly from 2013 to 2018.



Modal split of inland freight transport, EU-27, 2013-2018
(% share in tonne-kilometres)

Note: EU-27 includes rail transport estimates for Belgium (2013-2018), road freight transport for Malta (2013-2018) and inland waterways transport for Finland (2017-2018). Figures may not add up to 100% due to rounding.
Source: Eurostat (online data code: tran_hv_frmod)

Figure 4 Modal split of inland freight transport, 2013-2018. [5]

Nevertheless, the trucking sector is facing some significant challenges that may see the increase in alternative modes of transport. One of these challenges is the growing congestion on the road infrastructure which negatively influences both speed, reliability, cost-effectivity, sustainability of landborne freight transport as well as the social mobility in the area in general. For the Netherlands, a steady increase in congestion over the past years has been registered and a 35% increase in travel time loss on roads from 2017 to 2023 is predicted [6]. This would place an even heavier burden on the road transport infrastructure in the area and consequently the distribution of cargo out of the Dutch ports. The same problem of congestion is present in Belgium also, where especially the areas around the ports of Antwerp, Ghent and the capital Brussels are facing 83%, 64% and 23% increases in hours lost in congested traffic respectively (see Figure 5) [7].

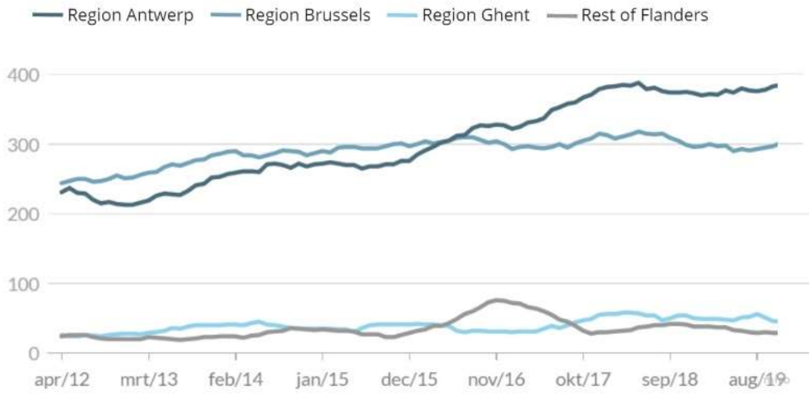


Figure 5 Lost vehicle kilometrehours per working day in the Flemish regions (rolling annual average). [7]

Based on the above, the AEGIS Use Case B predicts an ample opportunity to convert some of this roadborne freight into waterborne freight regardless of whether this comes through the modes of either LoLo or RoRo. This leads back to the point of departure, i.e. that the primary focus is not to convert freight from a LoLo based system unto a RoRo based system, but instead to convert the roadborne freight system unto a waterborne freight system.

Second, when looking at transport systems in general and on multimodal transportation in particular one has to differentiate between the so-called direct runs (A-B), or milk runs (A-B-C…). A direct run is, as the name may indicate, a direct route between two points with no intermediate stops. For this type of route, the vessel will be completely unloaded of cargo at the destination port and potentially reloaded for cargo to travel with the vessel back to the departure port. This means that the cargo onboard the vessel would not necessarily have to be stowed in a particular commercial fashion, as all inbound cargo will be unloaded and subsequently all outbound cargo will be loaded at every single port stay. A milk run is a route with two end points and one to multiple stops along the route between the two end points. For this type of route, the vessel will not necessarily be completely unloaded at every intermediate stop nor will there necessarily be loaded any cargo back on the vessel at the given stop. In the end points, however, the unloading of cargo often follows that of a direct run, but the loading of the cargo must obey by strict commercial planning orders with regards to the destination of every single cargo unit. If one imagines a route from Port of Rotterdam to the Port of Ghent, the two types of routes can be exemplified shown in Figure 6.

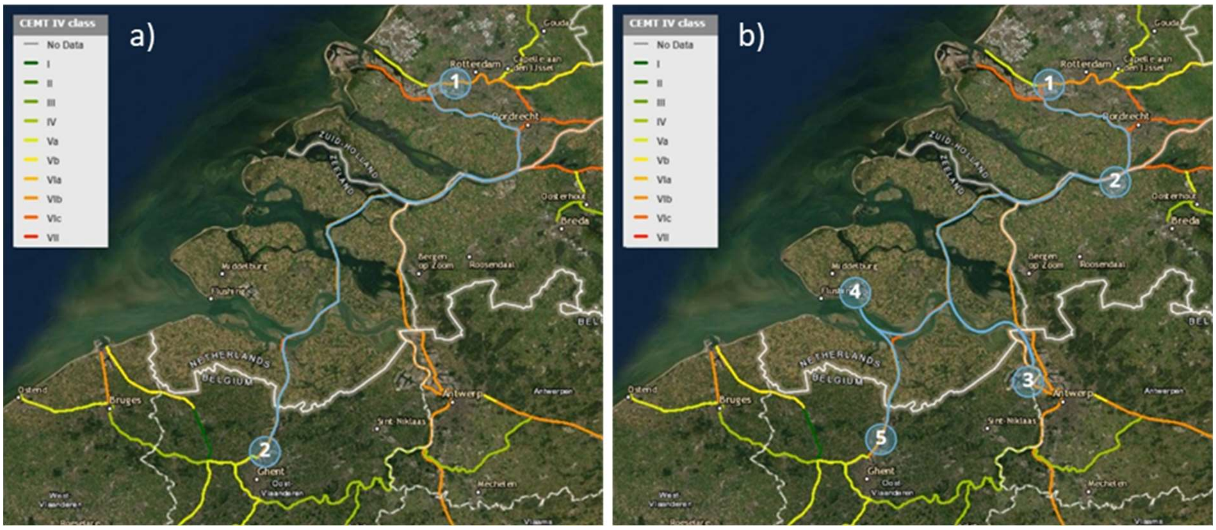


Figure 6 Hypothetical route between port of Rotterdam and Port of Ghent on the inland waterways depicted as a direct run a) and a milk run b).

The two types of routes each offer different advantages and challenges. A direct run offers high cargo volumes to be transported between two given points as fast as possible, but in turn requires that a sufficiently high cargo volume exist between the two points. A milk run instead offers connectivity to terminals with smaller cargo volumes that in themselves could not substantiate a direct run, but at the cost of longer transportation time between the end points due to the multiple stops. A milk run further requires complex planning of the loading and unloading séance in order to have access to the given cargo units destined for unloading at the given port without spending excess resources and time on restoring the cargo units destined for later ports. The direct run does not have this issue. This later point is of utmost importance with regards to establishing a RoRo transport system for the purposes of AEGIS Use Case B. As RoRo vessel normally load and unload through an access point at either the vessel's stern or bow, it becomes difficult to access every cargo unit separately. For a RoRo vessel to be able to engage in effective milk run solutions, new vessel design giving access to as many sperate cargo units as possible must be invented.

One potential way of achieving this is through side loading and unloading of the vessel, instead of stern or bow loading. This requires that the RoRo cargo is places in a transversal direction on the vessel as opposed to the normal longitudinal direction that is common on both RoRo and LoLo vessels of today. Requiring transversal stowage of cargo does however place some rather stringent requirements on the width of the vessel – a requirement that is one of the main restrictors on the inland waterways. A standard, standalone DFDS box trailer measure around 14 meters in length. Including space for various cargo lashing appliances, this would potentially require that a barge with transversal stowage of trailers should have a minimum width of approximately 16 meters. Consequently, for a RoRo barge to be installed in a milk run route and provide the ability to have direct access to as many single cargo units onboard as possible, it would only be able to travel on inland waterways of CEMT Class of VIa or above. In contrast, a RoRo barge installed on a direct run would not be restrained by this width requirement, as there would be no need for side loading and unloading and the trailers could thus be positioned in a longitudinal fashion. To this extend, a standard, standalone DFDS trailer is around 2,5 meters wide and with an additional allowance for lashing would possibly take up to 3 meters transversally allowing for multiple trailers to stand side by side.

Third, it is worth noting the concept of autonomous transport systems as opposed to autonomous transport legs, where making autonomous legs of the transportation instead of an entire autonomous system would likely create significant issues further down the transportation chain. An example of such could be establishing an autonomous LoLo barge which would only be able to visit terminals which would allow for its visiting and more importantly its cargo operation, i.e. terminals with a given level of infrastructural investments. It is true that LoLo vessels could bring their own cargo cranes, by which they could load and unload cargo themselves, but investments must still be made with regards to replacing pure containers unto trailers, i.e. by using so-called reachstackers. It is hard to imagine a solution where these could travel with the vessel itself as trucks often arrive at different times in a terminal and would not be able to load the containers unto their trailers themselves. Looking at the DFDS terminals in the region, it is observed that the cargoes for a given route arrives at the terminal rather sporadically over multiple hours and potentially days. Consequently, an autonomous LoLo barge that carries its own reachstackers would potentially have to wait prolonged periods of time for the trucks to arrive or alternatively leave the containers as they are on the terminal floor. If the former is chosen, a LoLo solution would be extremely slow and cost inefficient. If latter is chosen, the continuous hinterland transportation of the container is potentially hindered by the need to somehow reload the container unto a trailer for a truck to drive off with (see Figure 7).

Figure 7 LoLo cargo operations (simplified).

In contrast, RoRo vessels could also bring their own cargo equipment, a so-called tugmasters, that could live onboard the vessel and undertake the cargo operation whenever the vessel is moored in a terminal. This means that upon the unloading of the vessel, the cargo would already be standing on a rolling platform ready for last mile distribution by trucks that merely need to connect to the trailer and drive off into the hinterland. The same logic applies when a truck is coming to a terminal with a cargo, where the truck merely has to disconnect the trailer with the cargo. Below, Figure 8 shows this simplified in comparison to cargo operations for LoLo transportation systems in Figure 7.

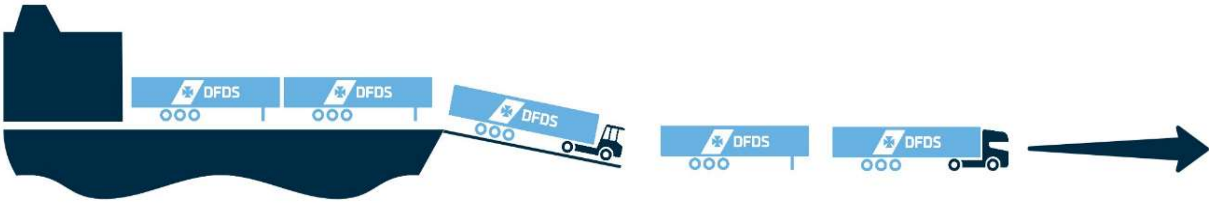


Figure 8 RoRo cargo operations (simplified).

To summarise, the continued work in the AEGIS Use Case B and the autonomous transport system that it aims to create builds on the following mental frames:

1. The autonomous inland RoRo transportation option is first and foremost about creating an alternative to inland truck transportation – not directly to inland LoLo transportation. The increasing congestion in the Dutch and Belgian regions may create an ample opportunity to convert roadborne transportation to waterborne transportation.
2. An autonomous inland RoRo barge would encounter width requirements if installed on a milk run as direct access to each individual cargo would necessitate a vessel width of 16 meters and hence an inland waterway of at least CEMT Class of VIa – a CEMT Class which is not widely available in the Benelux region. An autonomous inland RoRo barge would not face same

width requirements if installed on a direct run, which in turn require a certain minimum of cargo volumes to be transported.

3. It is important to consider the full transport system and not only a single transport leg. In this regard, RoRo transportation offers better opportunities to call smaller terminal with no to limited infrastructural investments than LoLo transportation, which does require some level of infrastructural investments. This also creates an opportunity for RoRo vessels to visit infrastructures which would not traditionally be considered a port or a terminal.

The vessel designs for use-case B are required to be able to operate on west European inland waterways (IWW) which are defined by CEMT (Conference of European Ministers of Transport) classes. In addition, the vessels are supposed to only transport trailers as RoRo. There will be no truck drivers or crew on-board as the autonomy level is required to be very high and to safe space and weight on the vessels.

Regarding the different scenarios and the existing IWW, different sizes are proposed to be developed. The first size is to fit the CEMT class II waterways with a capacity of about 10 Trailers, the second to fit CEMT class IV waterways with a capacity of about 20 trailers and the third vessel is required to be able to store the trailers transversal to the sailing directions which results in a vessel fitting the CEMT class VIb.

2.3. Use-case C

The main purpose of the two Danish ports is to develop Blueprints for 1) a Multipurpose terminal in a small port (Vordingborg) and 2) an Intermodal Automatic Green Terminal in a medium size port (Aalborg) as mean to move cargo from road transport to short-sea shipping. This is a way to support the fulfilment of the EU 2030 and 2050 targets for reduction in CO2 emissions.

To move goods from one modality to another is not straightforward: Road transports have historically been highly competitive on price, flexibility, and time. Thus, the challenge for short sea shipping is as far as possible to match road transport on price and set-up systems that through clever planning, can compensate for the need for high flexibility. This entails a focus on goods types where speedy deliverables are less important, as well as focusing on how to reduce the last mile deliverable costs. Collectively, this is to ensure that the short sea shipping transport mode is not outcompeted by road transport. Short-sea shipping (or rail for that matter) has a major advantage to road transport in relation support the green transition and facilitate a carbon neutral transport sector in Europe by 2050. To achieve this highly ambitious target it is important in parallel to optimize and green every step in the value chain. The ports can play an import role in improving terminal design and goods flow on land to increase efficiency. Nevertheless, without also reducing shipping costs, it is unlikely that short sea shipping will become a major player in the green transformation. Thus, new vessel designs, and increased automatizations will be cornerstones for short-sea shipping to increase its market share of movements of goods in Europe.

We conducted a detailed study and estimation of the gross volume of goods that can be shifted from road transport to short-sea-shipping within Denmark more precisely between Northern Jutland and Zealand (other regions not included due to distance, cf. Figure 9). Currently the total goods between these regions (road) are approximately 1 million tons, where the conversion potential is estimated to be around 177.500 tons, which equals approximately 10.000 trips per year.

We combined these findings with international goods, and, based on all the analyses (scenarios with reduced conversion probabilities), it was estimated that the potential gross volume of goods that can be shifted from road transport to Short-sea-shipping within and to/from Denmark is approximately 5 million tons yearly, or about 18% of the relevant goods by truck. It is again important to note that this is provided that any short-sea-shipping solution would be on par or cheaper than a competing direct road solution.

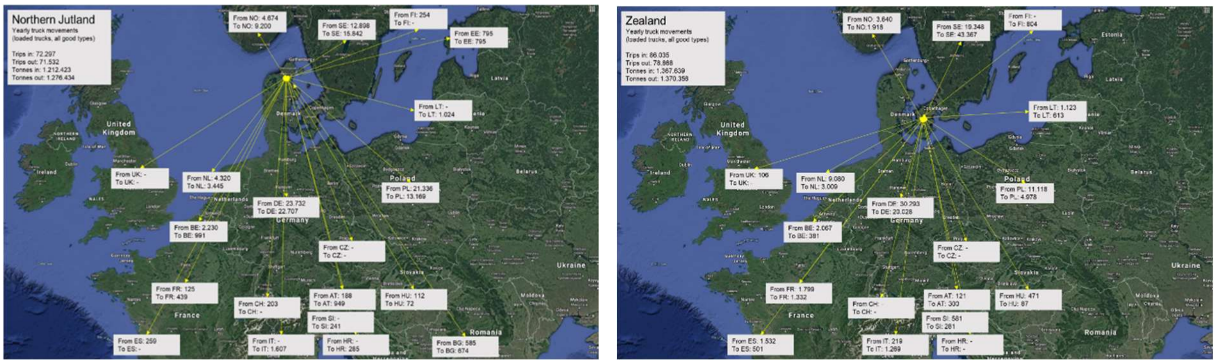


Figure 9 International road transport to/from the regions of Northern Jutland and Zealand. [8]

Presently, Port of Aalborg is called by a feeder line connecting Aalborg to Bremerhaven and Hamburg on a weekly basis, whereas the Port of Vordingborg presently is not connected to the container network. The feeder vessels have a capacity of 1000-1200 TEU and this vessel size is considered optimal but need to be improved in terms efficiency and autonomy to be competitive to road transport. As a Gantry crane constitutes a significant part of CAPEX costs for a medium size container terminal, it will be particularly important to explore onboard crane solutions.

Neither Aalborg nor Vordingborg are on a regular basis called by RoRo vessels. We conducted analyses of relevant activities, potential capital expenditures, operating expenditures, potential goods volumes, as well as developed new costing and pricing models for terminal operators and port authorities respectively. Initially, 12 scenarios have been considered showing that the minimum threshold of an economically viable port call to any of the ports would be 2 calls per week with a 50-trailer RoRo vessel (80 % utilization). We additionally examined 10 scenarios considering the notion of a multipurpose terminal in a small port, where the same terminal area could be used for multiple purposes throughout a week. A RoRo connection would be economically viable at even 1 call per week. The national calling (Aalborg-Copenhagen) showed substantial economic benefit of short-sea-shipping solutions over the road alternative. The international calling (Klaipeda-Vordingborg) similarly showed economic promise. However, the example similarly showed that increased vessel transport time (48 hours), offsets the economic benefit, and also potential market attractiveness, of having seabound solutions that stretch over longer distances, with only a 50-trailer vessel capacity. This finding gives interesting perspectives in min-max thresholds of sea distances and provide important guidance for potential vessel designs for UC-C.

Regarding the different challenges in use case C, the vessel designs are supposed to be as different as them. Therefore, the vessel designs are proposed to be medium sized and combine SSS and IWW shipping. The first design is required to transport only containers with a capacity of about 120-130 TEU with low draught and an on-board handling system. A second design is required to be more flexible in the kind of cargo it is transporting. Therefore, a vessel able to transport bulk as well as containers with the same properties as the first vessel design is proposed. Additionally, a third vessel design is required to be able to fit the RoRo transport needs of the customers operating in the area of use case C. Therefore, synergies are considered from vessel designs from use case B. The capacity is required to be about 50-60 trailers stored transversal to the sailing direction.

2.4. Governance and policy support of the Areas

Shipping is a global industry which is subject to regulatory standards developed under the International Maritime Organization (IMO), a specialized agency of the United Nations. The rules and standards developed at the IMO apply to design, construction, equipment, operation and manning of vessels. The IMO also plays a regulatory role with respect to environmental protection, namely by determining pollution standards. Furthermore, the IMO also impacts on the efficiency of ships, for example via the mandatory Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). Under international law, states do not find many avenues to depart from IMO regulations, as they are expected to be the result of a consensual compromise. However, there are some avenues for coastal states to develop more stringent norms, especially when enforcing them at port.

Although the IMO has been working on the introduction of digital technology into shipping, regulating Maritime Autonomous Surface Ships (MASS) is a relatively recent endeavor. In 2017 the IMO begun scoping ways to determine how safe, secure and environmentally sound MASS operations might be addressed in IMO legal instruments. The challenge is to identify all existing treaties affected by the introduction of different levels of autonomy and to either redraft them or interpret them consistently. In this early scoping exercise, four degrees of autonomy were considered: crewed ship with automated processes and decision support (Degree One); remotely controlled ship with seafarers on board (Degree Two); remotely controlled ship without seafarers on board (Degree Three); and fully autonomous ship (Degree Four). Each one of these degrees would require different regulatory work, and eventually Degree Three and Four would require a revision of more structural treaties on the law of the sea which did not consider the possibility of unmanned vessels.

A few examples may showcase the gaps between existing instruments and forthcoming technical developments. UNCLOS requires all ships to be in charge of a master and officers who possess appropriate qualifications. SOLAS obliges the master to render or provide assistance to persons in distress at sea. FAL obliges the master to ensure the “security, general health, welfare and safety of the stowaway while he/she is on board, including providing him/her with adequate provisioning, accommodation, proper medical attention and sanitary facilities”. Without a human on board, would the flag state be violating international law? Furthermore, COLREG also presuppose a human involvement. It remains to be decided how to interpret the phrases ““not under command” or “restricted in her ability to maneuver” if MASS is introduced without adequate legal revisions.

The AEGIS concept focuses on SSS and IWT, which in principle allows for some more leeway from the existing regulatory scenario. Test sites were created by national maritime authorities, for example in Norway and Denmark, to assist in the development of these technical solutions, and this was made possible within the international legal framework. However for a capital intensive industry such as shipping, taking risks with regulatory unknowns is not an option. And thus, at least for international journeys, more clarity is required.

The AEGIS project is seeking to identify these regulatory avenues to propose regional approaches that fit the use-case scenarios. Considering that the project seeks to develop routes that are not mere cabotage but that link up small terminals to larger transshipment hubs, international law would still apply. That notwithstanding, it is a hypothesis that the EU may seek to facilitate navigation of vessels with advanced technology which is not yet regulated under the IMO.

A less experimental route is the development of policy measures to support SSS without considering the introduction of MASS. The EU has failed in the past to make maritime transport more appealing and it does not seem that lack of IMO regulation was the cause of it. Policy support in this case may have to do with looking at the incentive structures provided to road and rail transport. Environmental policy has developed since the early days of EU Marco Polo programs designed to foster maritime transport and thus it is possible that new avenues are made existent today to support private actors in shifting from road to sea. Yet for that it is important for policy makers to take into consideration the need of private actors for clear and foreseeable rules so that long-term management strategies can emerge.

All in all, the challenges associated with AEGIS from a law and policy perspective relate to the international nature of the maritime space. This makes it relatively easier for UC-C and UC-B to move forward, as port development and inland waterway transport are more heavily ingrained in national jurisdiction. With what regards SSS, and the development of new vessels, there remains a structural challenge which requires political will and legal imagination.

2.5. Key performance indicators for the vessel design

Whatever solutions are contemplated in AEGIS, it is imperative to assess them in a holistic fashion, so as to capture the effects of all conceivable cross-linkages and inter-dependencies and hopefully obtain what we call “win-win” solutions. This analysis and evaluation are carried out in a comprehensive Cost Benefit Analysis (CBA) and environmental assessment including also social aspects. To that effect, we have developed a comprehensive set of Key Performance Indicators (KPIs) in order to assess any solutions further contemplated in AEGIS. KPIs represent the criteria under which the set of solutions developed under AEGIS will be evaluated. They include criteria grouped under the following classes:

- Economic KPIs, including cost, profit, logistical efficiency and others
- Environmental KPIs, including GHG and other emissions
- Social KPIs, including safety, security, externalities and others

The KPIs are aimed to be measurable, concise and compact, relevant, unambiguous and easily understood. Appendix A presents a list of the most important KPIs.

3. Autonomy in vessel designs

3.1. Definition of autonomy for this project

Autonomous operations are widely studied and various defined. The range of defined autonomy levels vary from four autonomy levels introduced in subsection 2.4 [9] to seven [10] defined by the Lloyd’s register. Further, Ø. Rødseth defined in one of his publications [11] two different areas of automation on ships, operational and bridge autonomy level. This results into a 4x3 matrix to describe different scenarios. By the definition of Lloyd’s Register [10], the different autonomy levels are also categorised in groups to describe manned, remote, automated, and fully autonomous ships in a more detailed way.

This project will discuss the level of autonomy for new designed vessel concepts regarding the definition by the International Maritime Organisation (IMO). Therefore, four levels of autonomy are defined as followed [9]:

- Degree one: vessel with automated processes and decision support and crew on board to control vessel systems and functions. Operations may be automated and at time be unsupervised.
- Degree two: vessel remotely controlled and operated from another location but with crew available on board to take control.
- Degree three: vessel remotely controlled and operated without crew on board.
- Degree four: vessel operates fully autonomous and is able to make decisions and determine actions by itself.

3.2. Autonomous vessel operation

For the developed vessel designs, the degree of autonomy will be developed towards a higher level. The benefits of autonomous operations will take effect at low levels but become more important at high levels.

Autonomous sailing and vessel operations can be described with several actions that need to be performed for secure and safe sailing. First steps are condition detection and condition analysis. Further steps are action planning, action execution and action control. After executing these steps, the circle of actions is reapplied. For these actions, appropriate sensors and fast decision algorithms are needed. The more and divers the sensors are installed on the vessel, the better and more secure will be the condition detection and action control. Appropriate sensors are optical sensors, e.g. camera and LIDAR (light imaging, detection and ranging) systems as well as other sensors, e.g. radar, etc. Additionally, sensors and technology for GNSS (global national satellite system) are essential for autonomous sailing.

The main benefit for autonomous vessel operations is the increase of safety by eliminating the human error, which causes over 75% of accidents on ships, according to Bureau Veritas [12]. Simultaneously, the operational costs are lower due to less or no crew on board, following that during vessel design it is possible to use the space more efficiently without needing any crew accommodation. Another benefit for autonomous vessels is the efficient use of fuel considering environmental influences like weather conditions and waves as well as optimized routeing and efficiency of main engine. According to MUNIN (Maritime Unmanned Navigation through Intelligence in Networks), dependent on the ship type it is possible to save up to $7m over a 25-year period in fuel consumption, crew supplies and salaries [13].

The main challenges for autonomous vessel operations are regulatory issues (see subsection 2.4) which have to be defined by policy measures and by the involved stakeholders. Another challenge are the large capital costs in initially investing due to the new applied technology in an early development stage [10]. Further investments are expected besides the vessel for setting up and operate an onshore centre for monitoring fleet movements [10]. In addition, current infrastructure and unmanned vessels need to communicate and therefore use compatible systems which is a high risk for cyber security. Currently, vendors use their own system, like Kalmar with KalmarOne, which needs to be able to communicate with several other systems on vessels probably designed by different contractors. A lot of work needs to be done create common standards for autonomous vessels.

4. Developed vessel designs

In this section, the developed vessel designs for each use case regarding the conclusions from subsections 2.1 to 2.3 will be presented.

The descriptions of the vessel designs include general main dimensions, like length over all (L_{OA}), breadth (B), and draught by design (T_{Design}) as well as information about the propulsion system, fuel concepts, and on-board cargo handling. Further, the implemented autonomy concept is described.

First the developed vessel designs for use case A are presented in subsection 3.1, where the mother concepts are described in subsection 3.1.1 and the daughter concepts in 3.1.2. Second, in subsection 3.2 the developed inland waterway RoRo vessel designs for use case B are presented. Third, subsection 3.3 depicts developed vessel concepts for use case C.

4.1. Mother and daughter concepts for Use-case A

As mentioned above, this subsection presents the current state of the vessel development for use case A. Note, that these designs are in concept state and not fully developed or detailed.

4.1.1 Mother vessel designs. According to 2.1, different scenarios are defined within the use case, thus requiring more than one vessel design for the mother vessel.

New Design of 1000 TEU vessel

This vessel design is developed to cover the transshipment from Rotterdam to the Trondheim region. Therefore, a container vessel with on-board handling systems and a green propulsion system is developed and shown in Figure 10 and the main dimensions are summed up in Table .

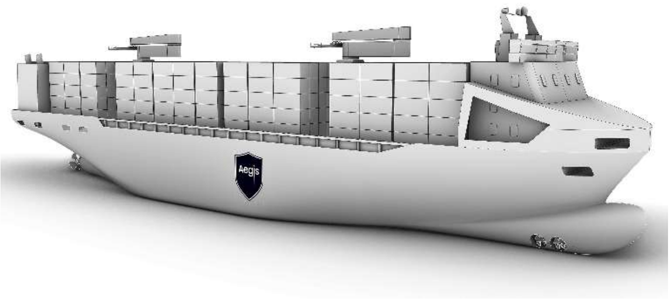


Figure 10 New design of mother vessel.

Table 1 Main dimensions for new design.

L_{OA}[m]	B[m]	T_{Design}[m]
143.8	25.5	8.2

This vessel is designed as an open top concept with a total capacity of 1046 TEU, however cargo places for 40’, 45’ and reefer containers are considered in the design.

The propulsion system is designed for the route between Rotterdam and the Trondheim region, and for the harsh and windy conditions at the North Sea. Therefore, a methanol combustion engine is chosen (in the first state “methanol ready” to be switched to full methanol operation when the infrastructure is existing) which is expected to reach an average speed of 15 kn. The vessel is driven by a controllable pitch propeller (CPP) which is built with separated blades which move “simultaneously through an arc to change the pitch angle and therefore the pitch” [14]. This system results in optimized propeller efficiency for different loading and weather conditions which leads to a reduced fuel consumption. Two electrically driven bow thrusters enable a high manoeuvring capability. In further developing steps, a hybrid solution with battery support will be considered, which might be needed in highly restricted fjord and near coastal areas. Furthermore, wind-assisted propulsion systems, such as Wing sails or Flettner Rotors [15] might be possible options due to the windy conditions along the Norwegian west coast.

As shown in Figure 10, the new designed mother vessel is equipped with two triple-joint cranes – a development of the AEGIS partner Cargotec/MacGregor (CT/MCG). Each crane has an outreach of 32 m and a safe working load (SWL) of 45 t. The benefit of the triple-joint crane is its high internal stability, space saving design, smooth operation with anti-sway system, and precise movements. It will be operated highly autonomous. CT/MCG offers special autonomy solutions for their cranes, such as anti-collision systems and automated cargo grabbing. Although, in international hubs such as Rotterdam the use of their port-side cranes is obligatory, however an on-board cargo handling system enables a high flexibility at the Norwegian ports. The vessel is not restricted to the availability of port equipment and can use its own green energy for the transhipment process. Also, the option of using green electricity provided by the port will be considered.

The first developed design of the mother vessel is considered to operate on an autonomy level of one to two. There will be crew on board and the captain’s bridge and accommodation are part of the vessel concept. During operation an increase of autonomy is expected (due to learning effects and adopted regulations). Therefore, the superstructure has a modular design and can be removed partly as needed. Additionally, automated mooring [16] and automated cargo handling will save time and will allow for transshipments independent of the port operation hours. A digital twin enables customers and shipowners to observe and compare the vessel status and to predict the arrival time.

Design of a coastal feeder vessel

Investigations on cargo volumes in the area of use case A yield to the idea of a coastal feeder vessel design to call ports along the Norwegian west coast before small, autonomous daughter vessels cover the last mile transport within the fjord. Figure 11 depicts the initial design and Table lists the developed main dimensions.

Figure 11 Coastal feeder vessel.

Table 2 Main dimensions for coastal feeder vessel.

L_{OA}[m]	B[m]	T_{Design}[m]
103.5	13.4	2.7

As shown in Figure 11,different container sizes will be transported. The vessel is designed for each 32 TEU, FEU and 45 ft containers, respectively. This results in an overall capacity of 160 TEU. Further developments will consider storage space for high cube and refrigerated container, according to the required data from subsection 2.1.

The coastal feeder vessel travels short to medium distances along the Norwegian west coast with multiple stops along the route which offers multiple opportunities to refuel or recharge. Therefore, propulsion systems like batteries can be used. Hence, no funnel or exhaust system need to be designed. In general, the use of batteries requires more storage place and the loss of payload since the weight of batteries is higher than other fuels by the same covered operating distance. By calling many ports along the route, the operating distances are reduced and batteries could be recharged during the process of loading and unloading the cargo. The required energy to recharge those batteries should be provided by green energy, e.g. hydroelectric power or wind power, to reach the main AEGIS goals. This green energy is used to drive electric engines within two azimuth thrusters at the stern of the vessel. Further, two bow thrusters are used to gain high manoeuvrability and flexibility.

The coastal feeder vessel is equipped with two on-board cranes. Each of them with 35 t SWL, one with 18 m beam and the other with 25 m beam. This ensures the accessibility of each cargo container on the ship. These on-board cranes are designed highly autonomous and are located on portside of the vessel. This ensures the possibility to use terminal cranes in bigger ports. By locating the cranes on portside of the vessel it is assured that these on-board cranes do not interfere with the terminal cranes during loading and unloading.

This concept is developed with an autonomy level of two to three which requires a bridge and crew accommodation. However, the bridge is designed to be modular and therefore, could be dismantled by increasing the autonomy level in the future. Additionally, automated mooring and automated cargo handling as well as the implementation of a digital twin is considered for this developed design.

4.1.2. Daughter vessel designs. This subsection describes two different approached for daughter vessel designs for cargo distribution within the Trondheim region.

Self-propelled Shuttle

The self-propelled shuttle is conceived as a fully autonomous vessel with green propulsion for transporting container only and depicted in Figure 12. In addition, the vessel is equipped with an on-board handling system. With respect to the expected cargo volume along the scenario described in subsection 2.1, the main dimensions were calculated and are listed in Table 3Table .

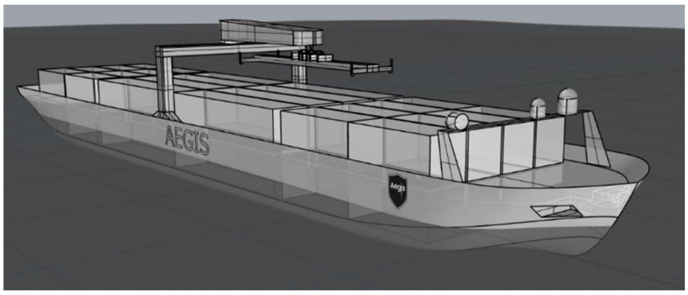


Figure 12 Self-propelled shuttle.

Table 3 Main dimensions for self-propelled shuttle.

L_{OA}[m]	B[m]	T_{Design}[m]
61.0	12.4	3.3

Required input data are assumed with a capacity of maximum 60 TEU stored longitudinal in four rows and two levels and an operation speed of 10 kn.

The main routes cover short distances for this vessel concept and provide opportunities to stop and recharge or refuel along the route. Therefore, a fully electric propulsion system powered by batteries is considered. As mentioned before, batteries have less range and higher weight than current liquid fuels. This needs to be considered by investigating storage places, stability issues, and safety aspects like fire protection. Another approach for the shuttle concept is the use of fuel cell technology driven by green hydrogen. As for the batteries, hydrogen requires large storage solutions and because of its properties it is suitable for shorter distances and refuelling regularly. This technology uses hydrogen, stored in cooled and/or high-pressure tanks, which is converted in fuel cells to generate electrical power. The biggest challenge in using hydrogen as a fuel is the wide flammability range and the easy ignition. Regardless of which fuel is used, they have to be produced or generated from renewable energy sources like wind, solar, or waterpower. These requirements meet the conditions for green transport systems where zero CO_2 emission is aspired.

This shuttle vessel is equipped with a fully automated, lightweight built gantry crane with telescopic legs. The crane ranges from starboard to portside and can move on guide rails from stern to bow to ensure each container can be reached and long crane booms can be avoided, which otherwise would cause stability problems. The usage of such a mobile crane is beneficial for smaller ships as storage loss can be avoided. During sailing the crane will be secured at the stern. Furthermore, a telescopic spreader for 20 to 45 ft container is used to load and unload cargo.

The shuttle vessel is designed to be highly autonomous. As shown in Figure 12, the vessel has no superstructure since no crew is on board. Dependent on the level of autonomy the vessel could be operated by a remote-control centre on shore (level 3) or sail fully autonomous (level 4). Additionally, automated mooring and automated cargo handling as well as the implementation of a digital twin is considered for this developed design.

Barge convoy

The second vessel concept contains small, autonomous, and self-propelled barges which will be pushed by a green, advanced, and highly automated push boat. As found in the analysis of use case A, the main cargo types are containerized cargo and bulk cargo. Therefore, universal barges are developed with a capacity of 36 TEU stored longitudinal in three rows and in three layers. It is also possible to load bulk or a combination of bulk and containerized cargo as seen in Figure 13. These barges are designed as additional storage space off-shore or as an expansion of port-side storage space for possible customers. Resultant from these assumptions the main dimensions are listed in Table .

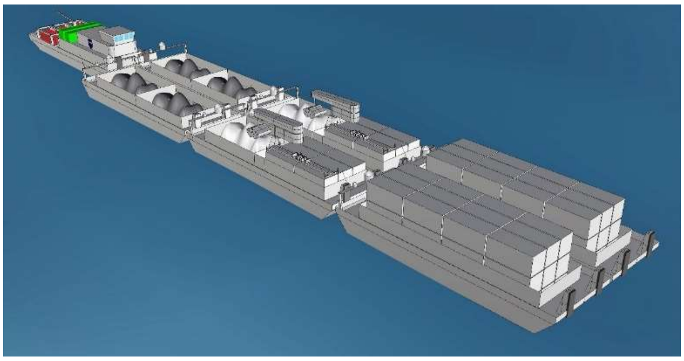


Figure 13 Push convoy with three different barge concepts.

Table 4 Main dimensions for universal push barge.

L_{OA}[m]	B[m]	T_{Design}[m]
33.0	9.8	2.0

The barges can be un-propelled for pure push operation or equipped with a short-range propulsion system. The self-propelled barges are designed to be able to operate small distances. They are equipped with a centred foldable rudder propeller which folds into a hull niche while the barges are part of the pushed convoy. It is also possible to operate this rudder propeller as a sail drive, which works as a hydro generator to generate power while being pushed in the convoy. These barges are designed to sail the “last mile” fully electrically to and from the end destination by itself powered by battery packs which are not easily exchangeable and permanently installed, but they are still accessible and can be removed or exchanged if repairs are needed. The battery packs are placed midships above the rudder propeller dependent on the barges purpose, either below the crane or in the first layer of containers which involves capacity loss of about two TEU, or between the cargo rooms on the bulk barge (see Figure 14). Further, integration of solar panels on deck of the barges supports the power supply on board ([17], [18], [19]), although the space is very limited and exposed to a high risk of damage.

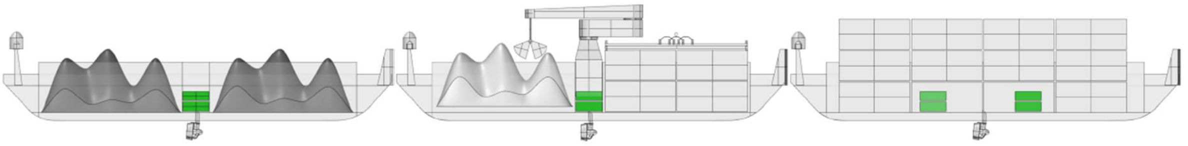


Figure 14 Possible battery (green) storage inside the different barge concepts.

The cargo handling equipment for the modular designed barges depend on the transported cargo. In case of mixed cargo, it is required to handle different cargo with the same crane. Thus, equipment for handling both cargo units is needed and should be easily and preferably autonomously exchangeable. All cargo handling equipment will be carried on the barge, easily accessible for the installed crane.

The barges are designed to be fully autonomous (level 4). Equipment for positioning, navigation, and communication is installed on board. Furthermore, automated mooring and automated coupling in and out of the convoy is supported by the on-board equipment.

Push boat

This vessel (see Figure 15) is developed to be able to push a maximum of nine barges (described above) at an operational speed of 8 kn. Resultant from these assumptions the main dimensions are listed in Table .

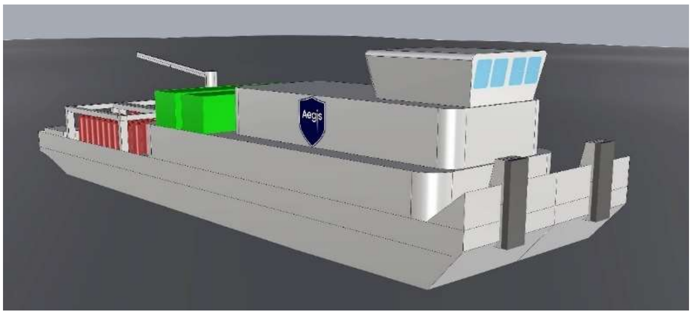


Figure 15 Push boat for convoy concept.

Table 5 Main dimensions for push boat.

L_{OA}[m]	B[m]	T_{Design}[m]
33.4	10.8	2.0

The coupling system at the bow of the vessel is similar to the one designed for the barge concepts. Such coupling system allows the coupled units movements in vertical direction while it suppresses any movements in horizontal direction. Furthermore, no payload is stored on the push boat but only on the barges.

However, some storage areas on the push boat are considered for fuels. The vessel is designed as hybrid solution with fuel cells driven by hydrogen, and battery packs. As machinery two Azimuth thruster are considered to ensure high manoeuvrability of the vessel. At the very end of the vessel the hydrogen (red colour) is stored in pressure bottles at 200–250 bar which are combined to three packs, each in the size of a 20 ft container. This storage solution is designed to be standardized, and therefore easy to exchange which saves time for loading and refuelling. Furthermore, permanently installed battery packs inside the vessel ensure a homogeneous power supply.

As mentioned above, no cargo capacity is considered on the vessel and therefore no cargo-handling equipment per se is needed. Nevertheless, the vessel is equipped with a small, stationary, and automated crane to load and unload the hydrogen packs when exchanging empty by fuelled ones.

The autonomy level of this vessel is considered to grow from 2 up to the level 4, hence, a bridge and crew accommodations are needed at the beginning. The sensors for positioning, navigation, and communication as well as supporting software and systems are also on board installed. Route and fuel consumption optimization are currently available and required for this push boat concept. Step by step, the vessel could be operated by a reduced crew with many supporting systems (level 2). Later the operation via a remote-control centre (level 3) on shore with no crew on board is possible. The last step is a fully autonomous operation (level 4) monitored in a control centre.

4.2. IWW vessel designs for Use-case B

In this subsection, the current status of the developed vessel designs for use-case B is described. Note, that these designs are in concept state and not fully developed or detailed.

As mentioned in subsection 2.2, these RoRo vessels are required to sail on inland water ways (IWW) in the region of Netherland and Belgium to reduce congestion of the roads. Therefore, the vessel design is strictly limited to the available waterway dimensions along the expected route. These dimensions are classified within the CEMT and provide basis for the development of green and advanced vessel designs.

In Figure 16, three different sizes of RoRo vessels are shown. The two upper designs are suitable for CEMT class II (top left) and CEMT class IV (top right) where the bottom design is a new combination of the CEMT classes IV with an adapted breadth according to CEMT class VIb.

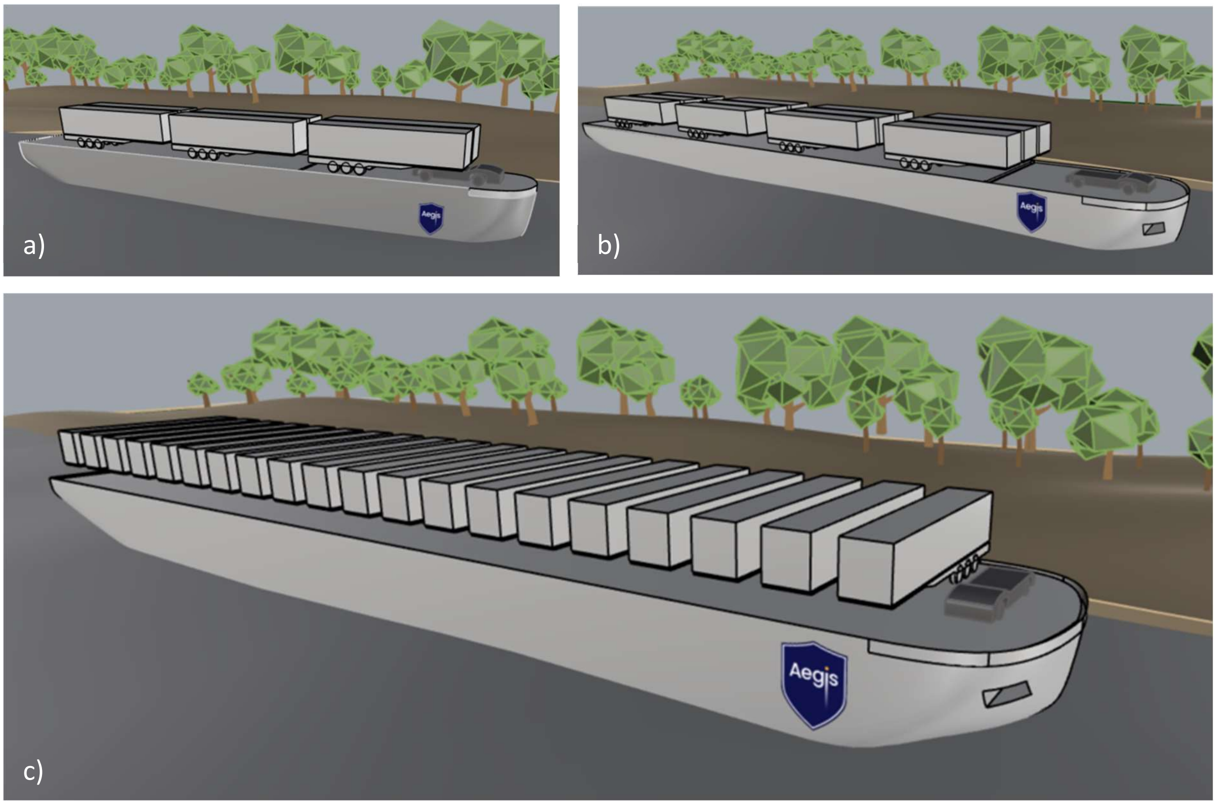


Figure 16 IWW RoRo vessel designs; suitable for CEMT II (a), CEMT IV (b) and CEMT IV+ (c).

These approaches yield to main dimensions, which are listed in Table . In general, the propulsion and cargo handling systems are the same for each vessel, however they are adopted to the vessel size. The capacity of the vessels are 12 trailers for CEMT II, 21 trailers for CEMT IV and 38 trailers for CEMT IV+.

Table 6 Main dimensions for IWW vessels.

Vessel	L_{OA}[m]	B[m]	T_{Design}[m]
CEMT II (a)	55.0	6.6	2.3
CEMT IV (b)	85.0	9.5	2.5
CEMT IV+ (c)	85.0	15.0	2.5

The developed vessels are designed to drive fully electrically powered by batteries. These battery packs are located at the end of the vessels and due to fire protection and on-board safety [20], it is required to surround the batteries with transverse bulkheads. Further, the vessel is equipped with two azimuth thrusters at the stern, and on rotatable bow thruster [21] to maximise the manoeuvrability and flexibility of the developed vessel designs.

For loading and unloading, it is required for the vessels to have a ramp build into it (not shown in Figure 16) which is located at the bow, automated and connected with an automated mooring system. Furthermore, two layers of cargo are planned which requires a lift system for the trucks or trailers where the distribution into the two layers is possible. In addition, the vessels will also have an own AGV (automated guided vehicle) on board for loading and unloading the trailers in smaller ports along the route. The AGV will be stored on deck when the vessel is sailing. All loading systems are developed to be fed by the vessels power supply or by green shore power, if available.

Loading the trailers transversal to the sailing direction requires a different type of cargo handling. Every pair of trailers stored on top of each other uses its own lift combined with a moveable side ramp to load and unload over portside. Therefore, an automated stability system for loading and unloading is required. This system is considered to continuously pump water in and out the ballast water tanks.

Not depending on the loading direction of the trailers, the vessels are designed to be highly autonomous. Regarding the level of autonomy, it is either fully autonomous (level 4) or remotely controlled from a remote-control centre on shore without crew on board (level 3), leading research projects are FernBin [22] and AutoBin [23]. Furthermore, autonomous mooring systems are used and digital twins will be implemented in operating the vessels.

4.3. Combined concepts for Use-case C

This subsection describes development approaches for use case C. The developed vessel designs are deducted from the two other use cases. As mentioned in subsection 2.3, LoLo as well as RoRo vessels are required to cover the possibilities of the defined regions in Denmark.

First approaches are shown in Figure 17 and Figure 18. In the top picture, a combined SSS and IWW container vessel with a capacity of about 128 TEU is depicted. The lower picture shows also a combined SSS and IWW vessel but for mixed cargo transportation.

Figure 17 Container vessel design.

Table 7 Main dimensions for container vessel.

L_{OA}[m]	B[m]	T_{Design}[m]
71.0	10.9	2.8

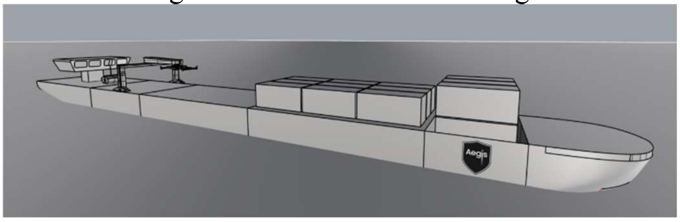


Figure 18 Mixed cargo vessel design.

Table 8 Main dimensions for mixed cargo vessel.

L_{OA}[m]	B[m]	T_{Design}[m]
85.0	9.5	2.5

For both vessel designs, a hybrid propulsion solution is considered. Batteries are required to support the power supply during peak performance and when entering and mooring in ports. For the container vessel, the main propulsion system is considered to be fuel cell technology driven by hydrogen which requires high pressure tanks and extra space for bunkering. On the other hand, the mixed cargo vessel is considered to use methanol or ammonia as the main power source for the vessel. The concept design with the arrangement of cargo, fuel tank (pink), and battery packs (orange) is shown schematically in Figure 19.

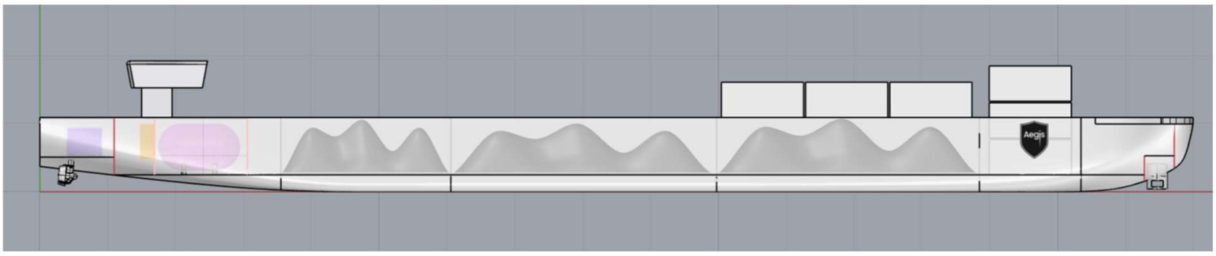


Figure 19 Mixed cargo vessel schematically; fuel tank (pink), battery packs (orange).

This hybrid solution is selected due to the sailing distances expected for the vessel and due to the future infrastructure of methanol built by Maersk ([24], [25]). Ammonia might also be available due to its usage in fertilizer production. The infrastructure for handling of ammonia is established but not yet enough extended to cover the consumption needs for worldwide shipping.

The applied cargo handling equipment on the developed vessel designs are deduced from use case A vessel designs. One design on the container vessel design is a triple joint crane from project Partner MacGregor. These kinds of cranes are self-stabilising and therefore very suitable for the concept seen in Figure 17. Due to the location of the crane on the vessel, all cargo can easily be reached and loaded/unloaded without requiring any further equipment from the portside. The other design is a moveable gantry crane similar to the one described in subsection 4.2. For the concept seen in Figure 18, the width of the crane is adapted to the vessel breadth and exchangeable equipment for different cargo units are required. When the ship is sailing the crane is secured in front of the bridge as close to the deck as possible.

These first approaches tend to align only one part of use case C. Therefore, further concepts need to be developed to fit all requirements. Especially a RoRo vessel serving along the south of Scandinavia will be designed. For this purpose, the CEMT class IV+ RoRo design from subsection 4.2 will be adopted to the requirements and conditions of this use case.

These vessels are designed to be operated medium to highly autonomous. During operation, the autonomy level will increase from level 2 up to level 4. Therefore, planned captain’s bridges and crew accommodation will be modal and easy to deconstruct. Additionally, automated mooring and automated cargo handling as well as the implementation of a digital twin is considered for this developed design.

5. Conclusions and future steps

The central objective of AEGIS is to develop a new waterborne transport system for Europe that leverages the benefits of ships and barges while overcoming the conventional problems like dependence on large terminals, high transhipment costs, low speed and frequency and low automation in information processing.

To reach this goal, new advanced, efficient, green and smaller vessel designs are developed besides other factors like terminal automation and digital connectivity, especially the communication between all the participants of the future transport chain. These vessel designs, as well as the whole transport chain including all transport modes and terminal activities are developed regarding three different real life use cases in Europe with respect to the environmental and regional conditions.

One main part of the vessel development is the implementation of new technology for autonomous vessel operations and transhipments. Therefore, new technology approaches from the project partners MacGregor and Kalmar for autonomous transhipment are investigated, simulated and built in terms of a demonstrator.

Investigations within the use cases leads to the development of a logistics analysis tool. This tool is required to be able to simulate and compare costs of shipping routes with a current vessel design or a comparable autonomous vessel design. This is going to be just one aspect of the logistics analysis tool.

Acknowledgements

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Appendix A

Table A 1 Summary Table KPIs for AEGIS.

KPI Level	KPI Sublevel	KPI Name	KPI Measurement	KPI Description
Economic	Cost	CAPEX	€	Capital expense
Economic	Cost	OPEX	€	Operating expense
Economic	Cost	Maintenance costs	€	All expenses to ensure the correct operation of an asset and keep reliability high
Economic	Cost	Port charges	€	Fees paid to port authorities for the use of its facilities and services
Economic	Cost	Fuel cost	€/NM	Total amount of money spent in fuel
Economic	Cost	Wages	€	Total amount of money spent on salaries
Economic	Cost	Cargo unit cost	OPEX/TEUs	OPEX divided by the number of cargo units
Economic	Time	Loading time	h	Duration of the loading process
Economic	Time	Unloading time	h	Duration of the discharging process
Economic	Time	Sailing time	h	Duration of the vessel voyage
Economic	Time	Waiting time	h	Time during which cargo is idle or delayed
Economic	Time	Drive time	h	Duration of the trip of the cargo from to its final inland destination, and vice versa
Economic	Time	Punctuality rate	% of port calls	Mean deviation from expected arrival/departing time.
Economic	Time	Recovery time	h	Time from the detection of a disruption to when full level of performance is restored
Economic	Time	Cargo handling time	TEUs/h	Time to move goods on and off ships plus the terminal handling time
Economic	Others	Energy consumption	KWh	Total energy needed
Economic	Others	Cargo carried	TEUs/ship	Cargo carried from loading to discharging
Economic	Others	Percentage of load	Cargo car/max cap.	Actual cargo carried compared to vessel maximum loading capacity
Economic	Others	Cargo lost	% total cargo	Cargo unable to be found
Economic	Others	Number of Cyber-attacks	#	Quantity of cyber-attacks suffered
Economic	Others	Restored level of	%	How fully performance is

		performance		restored after a disruption occurs
Economic	Others	Autonomy level	levels	Degree of autonomy
Economic	Others	Frequency of service	Shipments/week	Number of available sailings per week
Economic	Others	Energy efficiency	%	Energy-expenditure required to achieve a target
Economic	Others	Number of container moves	#TEU/route	Amount of goods shipped per route
Environmental	Emissions	CO_2	Kg of CO_2/tkm	CO_2 emissions
Environmental	Emissions	NO_x	Kg of NO_x/tkm	NO_x emissions
Environmental	Emissions	SO_x	Kg of SO_x/tkm	SO_x emissions
Environmental	Emissions	Particulate matter	Kg of PM_{10}/tkm	PM_{10} emissions
Environmental	Emissions	Acoustic emissions - Noise	dB	Noise emitted
Environmental	Others	Use of renewable energy sources	%	Percentage of energy consumed that comes from environmental-friendly energy sources
Social	Security /Safety	Accident rate	#	Amount of unfortunate incidents resulting in damage or injury
Social	Security /Safety	Fatality rate	#	Amount of occurrences of death by accident
Social	Security /Safety	Fire incidents	#	Amount of incidents involving smoke, heat and flames causing damage
Social	Work-life	Labor conditions	Work-life-balance	Quality of working environment
Social	Work-life	Employment	% of change	Influence on the occupational rate
Social	Work-life	Income	% of change	Influence on earnings
Social	Work-life	Training	Time/worker	Time invested in teaching an employee a particular working skill

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