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A novel method for evaluating ship concept performance in transport systems

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Abstract: Transport carries significant external costs such as climate change, accidents, pollution, and road congestion, driving national and international strategies for the development of new transport concepts. This includes shifting larger cargo volumes away from roads to more sustainable transport modes such as waterborne. The SEAMLESS project was launched in 2023 to answer to these needs by developing technology for autonomous waterborne zero-emission feeder-loop services. The realisation of such services depends on their modal competitiveness. Autonomous ships are expected to reduce transport costs and emissions, and ultimately improve logistical performance. There are, however, few published studies that quantify these impacts of autonomy. Furthermore, commercial waterborne autonomous transport services do not exist yet, limiting the possibilities for empirical analysis. Hence, research is needed to address exactly how and to what extent, autonomy improves competitiveness in different applications. This paper addresses the need for more empirical analyses of innovative waterborne transport performance, by presenting a novel method for evaluating ship concept performance in transport systems. The impacts of design choices are captured through hydrodynamic and logistical simulations. The method can be applied to transport systems consisting of both conventional and novel ship designs, operating on one or more routes including transhipments. It is implemented in the software SIMPACT and applied to a case study which establishes a shortsea feeder-loop service in the Bergen area in Norway. The Bergen municipality has decided that the container terminal is to be moved out of the city centre to reduce local traffic and emissions. However, in the absence of a competitive waterborne transport service in this region, the relocation will have the unfortunate consequence of an estimated annual net increase in regional truck traffic of 40,000 additional truck trips over 25km. By means of the proposed methodology, this paper investigates the feeder-loop concept and compare its quantified performance to truck transport and finds that competition is feasible.

1 Introduction and background

Autonomous ships[1] are expected to bring several benefits, ranging from reduced costs [3] and increased earnings [4], to improved working conditions and safety [5]. A consequence of this is

[1] In this paper the autonomous ship is understood as ***Constrained autonomous*** and ***unmanned*** as defined in [1]: ***Constrained autonomous*** *(CA): Uncrewed operation with constrained autonomy onboard but with operators in RCC that can handle more complex situations,* and in [2]: ***Unmanned:*** *ship with no humans onboard.*

that ships may become more competitive to trucks, and that autonomy may be the key to achieving the long-standing goal of moving more transport from road to water [6]. This has led to the emergence of the first commercial projects in shortsea shipping, with Yara International [7] and ASKO Maritime [8] leading the way. Their motivation for investing in autonomous ships is to reduce the external effects of truck transport such as GHG, air and noise pollution, as well as accidents and congestion. Both have put battery-electric ships in operation that in time will become autonomous. While details on their business cases are not published, these commercially-driven initiatives have contributed to accelerating the necessary research and development. However, much work remains before the emerging technologies enabling autonomous ships are widespread and available options to prospective buyers [9]: while commercial initiatives aim for automatic operations with remote control and continuous supervision to enable the first commercial operations with unmanned cargo ships, the long term development goal is to achieve constrained autonomous ships requiring low operator attention and several ships per Remote Operations Centre (ROC) operator. Required developments towards this long-term goal are within technology, physical and digital infrastructure, technical standardisation, legislation, logistics integration and new business models supported by impact evaluations [9]. The SEAMLESS[2] project was launched in 2023 to address the required technical developments, the logistics integration, and the business models.

The AUTOSHIP roadmap provides a discussion on six reasons why autonomous ships are beneficial [9]. Two of these reasons are improved competitiveness and environmental performance, where reduced cost and fuel consumption per performed work are the enabling factors. The roadmap also investigates previous literature reviews and identifies gaps in the economy, emission, and business case of autonomous ships, and finds that it is necessary to investigate what mechanisms are most important and how they relate to market segments. The roadmap concludes that the investigated reviews [6], [10], [11], [12], [13], [14] "*…find that the application of autonomous ships must be studied in more detail as cost and impact on emissions, in quantitative terms, are unclear due to few available studies…*".

So, what are the impacts that need to be quantified to provide proof of the economic and environmental benefits of autonomy in a specific shipping application? To create an overview of the main factors impacting cost and emissions for autonomous ships, this paper investigates previous studies that includes some form of quantification of cost and/or emissions for autonomous ships.

1.1 Previous research

A conventional bulk carrier is compared to an autonomous bulk carrier in [15]. Detailed estimates are given by breaking down the cost categories: capital, operating, and voyage costs, to the main cost elements and making a cost model for both the conventional bulker, and an autonomous bulker by analysing cost changes. A detailed study of the required operational organisation for the ROC is given in [16], which is used in [15] to estimate the ROC cost. The yearly costs and scheme for maintenance of autonomous ships is also proposed. Fuel estimation for the autonomous ship is based on typical fuel consumption rate for a reference conventional bulker and adjusting it for reduced light weight and wind resistance, due to removal of the superstructure. Increased cargo capacity, or reducing the size of the autonomous ship, is not considered.

The study of the economic feasibility of an autonomous container ship in [17] solves the problem of estimating the autonomous ship new build cost by instead estimating how much more the autonomous ship could cost than the conventional ship, when other cost impacts such as operational cost changes and ROC costs are accounted for, and when the ships operate on the same route and transport demand.

[2] https://www.seamless-project.eu/

An analysis of a network of small container ships, intended to replace truck transport, is given in [18]. The study solves an optimisation problem to find an optimal distribution network design. It is not considered whether the ships are conventional or autonomous, however, one of the scenarios considers reduced variable sailing costs of 20%, where the reduction is said to be relevant in the case of autonomous ships. A continuation of the study is found in [19], where vessel sizes and routes are adjusted. The vessel concept is still unclear, and the focus is on investment decision support for establishing the network.

Two similar studies in [20] and [21] both consider a shortsea container shipping network serviced by a mother-daughter concept, and investigate the cost impact of autonomous ships. In both studies, the economic effect is investigated by differentiating the Twenty foot Equivalent Unit (TEU) capacity, fuel consumption rate, and time charter cost of the various ship concepts. While the studies provide the estimates of these items, the underlying calculations are not given.

Partially autonomous ship concepts are studied in [22], [23], and [24]. In [22] and [23] the NOVIMAR platooning concept for inland waterways is studied. Cost estimates are done by detailed cost models, however, the cost elements differ slightly in the two studies. Furthermore, while [22] provides estimates for most of the cost elements, [23] gives aggregated estimates per vessel.

Impact of autonomy on shortsea container transport cost in slender ship designs is investigated in [24]. It is assumed that technology enables a reduced crew, removal of the superstructure, and increased cargo capacity. The study compares hydrodynamic performance but does not provide details of the estimation method of energy or cost.

An autonomous wind powered vessel with hybrid propulsion is studied in [25] and compared to a conventional ship. Both ships have the same main dimensions, however the hybrid autonomous ship has a slightly larger cargo capacity and smaller installed propulsion power. The cost estimation is done by a detailed cost category breakdown, however, the estimates per cost category are not given for most categories. Energy estimates are based on scale model testing.

The AUTOSHIP shortsea use case was studied in [26]. The study is based on actual data for a conventional ship, exploring the impacts of redesigning it as autonomous. An important assumption is made in that the reduction in lightweight is not exploited for increased cargo capacity, but rather for reduced draught. The study in [26] also considers the impact of voyage modifications due to removal of crew by analysing AIS data to find the non-operational time. Furthermore, it is estimated how much of this time is spent on loading, maintenance and waiting for weather, such that the non-productive time that could be utilised for sailing is identified. The study then evaluates the impact of different steps of reduction of non-productive time, where the additional time for sailing is used to reduce the sailing speed. Energy estimation is based on sea-trial speed-power data from the conventional ship, which is adjusted for the autonomous ship by estimating reduced resistance due to reduced draft and wind area (similar approach as in [15]).

1.2 Problem definition

The investigation of previous literature on autonomous ship cost and emission impact shows that quantification is based on different methods, and that all details of the estimated cost elements or fuel/energy consumption is often missing. Some important shortcomings are also observed for these studies: Firstly, they are typically not based on modelling the autonomous nor the conventional vessel. Instead, statistical data from ships within the segment are used to represent the typical ship, e.g. average ton fuel/nautical mile. This limits the extent to which design choices are sufficiently captured in the evaluations. Furthermore, using the average fuel consumption of an existing ship and adjusting it for reduced lightweight and wind resistance, limits the possibility to explore performance differences of novel ship designs of different size and cargo capacity.

Secondly, the impact on fuel consumption from wind resistance and weight reduction due to super structure removal is often considered rather than investigating if increased cargo capacity or a smaller ship would result in a higher impact on cost and emissions. This is likely related to the choice of basing fuel consumption estimates on typical consumption for the baseline ship.

Lastly, the increased freedom in designing the ship (due to removal of equipment and super structure) is not sufficiently explored. Design choices related to the hull shape and size (and propulsion) have a significant impact on power consumption. It is therefore important to consider the hydrodynamic performance of the design in its intended operational conditions to capture design choice impact on power consumption. Methods such as agent-based hydrodynamic simulations [27] enables such design evaluations and could be used to explore how the increased design freedom of autonomous ships can be fully exploited. Such evaluations are missing in the existing literature on autonomous ships.

1.3 The contribution of our work
Our contribution is a simulation-based method for evaluating ship concept performance in transport systems. The method adds logistics flow simulation and cost estimation on top of hydrodynamic ship simulation methods, such as in [27]. This enables quantification of cost and emission performance for ship concepts applied in the transport systems and areas in which they are designed to operate in.

Hydrodynamic simulations make it possible to include the impact that wind, waves and current have on resistance, by evaluating the hydrodynamic model for every change in conditions, heading, or speed, along the route. Furthermore, by including the cargo flow in the simulations, the loading condition and resulting draft during each leg of a voyage is accounted for in the hydrodynamic model, improving the energy estimation. The resulting method captures design choice impacts from variations in the hull and propulsion, energy and machinery system, cargo hold capacity, operational profile (sailing speed and frequency, operational area, weather, route, and transport demand), and draft due to carried weight per sailing leg within a voyage. The method is valid for evaluating both conventional and novel ship concepts, dedicated liner services, and several ships operating in a network including transhipments. Different ship designs of different sizes can be compared, as well as different fleet compositions.

To illustrate its use, the method is applied in a case study that compares the performance of two ship designs to truck transport. This is a contribution towards advancing the understanding of how autonomy can be used to reduce costs and emissions. One study applying the method is found in [28], where the focus was on a case study while the method was not elaborated.

2 Method
The method presented in this paper is implemented in a toolbox called SIMPACT. SIMPACT consists of two main tools. The first is a simulation tool for performing logistics analysis to support the design of a transport system network. The second is a tool for evaluating the cost and emission performance of a given ship concept executing the logistic operations derived by the logistics analysis. This paper will focus on the latter: a method for evaluating ship concept performance in transport systems. At a high-level, the performance evaluation can be split into two main processes: simulation and post-processing, see Figure 1. This chapter will describe each element that make up the cost and emission simulator. First the model components are discussed (for more details refer to the SIMPACT user manual [29]). Then, in the following sections, the simulator and post-processor is described.

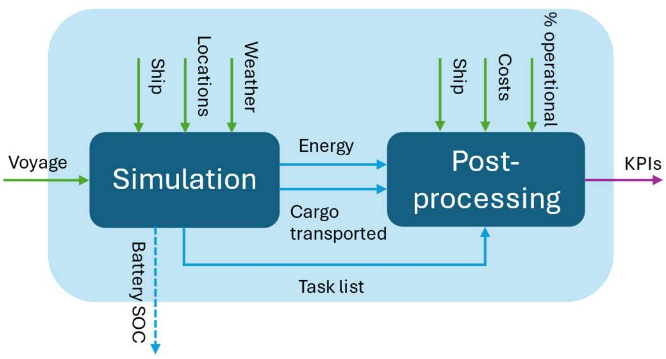

Figure 1. Cost and emission tool

Ship model: consists of a hydrodynamic model that gives the required power to maintain a given speed for different draft and weather conditions [27], a cargo hold model defining the weight and volume capacity for cargo, an auxiliary power model to capture all other energy usage than that of the propulsion, and a machinery model to convert the used energy to fuel and emission components. The machinery model considers power train efficiency, and in case of battery systems the charging efficiency is included. The ship model also includes a cargo handling model, which defines the energy usage and cargo handling rate, in case the ship has its own cargo handling equipment.

Cost model: includes all investment cost items and a depreciation model to estimate yearly capital costs, all yearly operational cost items, a port cost scheme including all time and activity based cost items for a port call, including cargo handling costs, a parametrized ROC cost model for autonomous ships based on [15], and energy costs as euro/ton or kwh.

Voyage model: includes the shipments, route, sequence of locations to visit on the voyage, and the average sailing speed. Shipments are defined as the complete set of cargo to be loaded at a location and contain a list of orders. An order is the subset of the shipment that is to be delivered to a given location. The route is given as a set of waypoints between the locations. Locations include a cargo handling and charging model defining the handling and charging rate, respectively.

Weather model: contains a set of weather profiles consisting of the parameters significant wave height, wave direction, peak wave period, wind speed and direction, and current speed and direction. A weather profile can be defined for as many points on the route as needed, and for each point several weather profiles can be configured along with the percentage of time that the profile is valid for. Energy is then estimated by adding the results from each profile, weighted by the time it is valid for. Historical weather data can be retrieved from public sources to create weather profiles using the tool Gymir [27].

2.1 Simulations

A ship's voyage is simulated by deriving a sequence of simulation tasks and executing them sequentially. There are two main categories of tasks [30]: location tasks and sailing tasks. Locations have tasks such as *load cargo* and *charge batteries*, where time is calculated from the number of tasks to perform and the duration of one activity (e.g., load one container or charge one kWh). Energy consumption is calculated based on the estimated time and the power rating in kW. Sailing tasks can be divided into *depart location, transit* and *approach location*. Simulation of these tasks are based on the method in [27] where a simulation step is inserted every time there is a change in weather conditions, or the relative heading between the ship and the weather (i.e., wave or wind direction). As an extension to the method in [27], SIMPACT always re-evaluates the draft based on the cargo load condition upon leaving a location and adjusts the hydrodynamic model

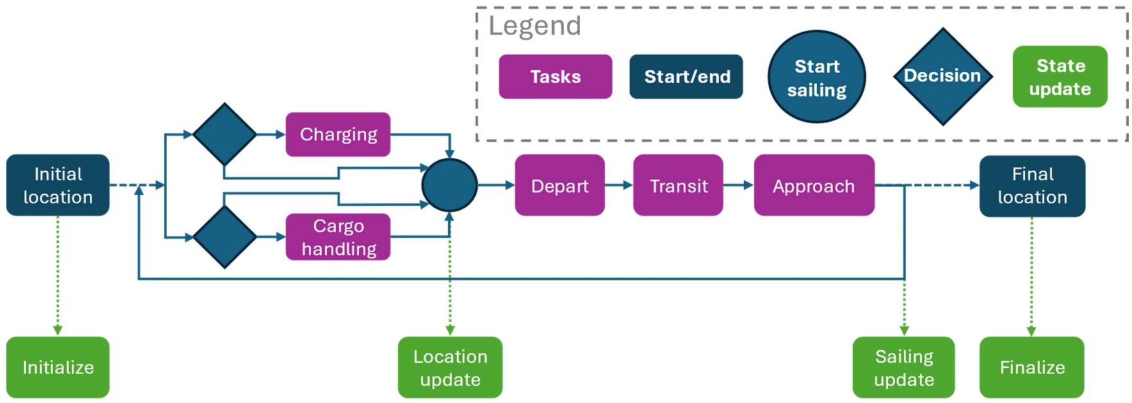

Figure 2. The simulation steps

accordingly. A record of energy, duration and shipments are registered through states that are updated during the simulation.

The sequential execution of the simulation is given in Figure 2. Any simulation starts with the ship being at an initial location. If the voyage includes transporting a shipment from the initial location, the first step is to run the load cargo task. Depending on the initial state of the battery charge, a charge battery task may be run. If there are no location tasks at the initial location, the simulation moves to the first sailing task. If there are both charging and cargo handling tasks, these are run in parallel. The sailing task involves three stages; depart, transit and approach, all of which are executed sequentially when sailing between locations. At the next location, the first task is to deliver any orders destined to that location, before loading any shipments going from the current location, while charging if necessary. If there are more locations in the task list, this process repeats itself until the final location is reached. The bottom half of Figure 2 shows where in the process the relevant states are updated.

The states are shown in Table 1. The states are initialized at the initial location before the first task, and then updated before departing, to capture the activity at the location. It's then again captured after sailing to store sailing energies and durations. This process repeats with as many locations and legs as there are in the voyage.

Table 1. States recorded during simulation

Task	Energy [kWh]	Duration [h]	Battery SOC [kWh]	Shipments
Initialize	0	0	SOC_0	N/A
Cargo Handling	E_{ch}^{loc}	d_{ch}^{loc}	$SOC_1 = SOC_0 - E_{ch}^{loc}$	s^{loc}
Charging	E_c^{loc}	d_c^{loc}	$SOC_2 = E_c^{loc}$	N/A
Sailing	E_s^{leg}	d_s^{leg}	$SOC_3 = SOC_2 - E_s^{leg}$	N/A
Finalize	N/A	N/A	$SOC_f = SOC_3$	N/A

Table 1 shows how the different states are updated throughout the simulation for each of the different available tasks. It describes a record of energies E^{loc} and durations d^{loc} at location loc. It also records the state of charge (SOC) for a battery-system. The state s^{loc} describes the state of the shipments onboard the ship. This state changes when orders are loaded or offloaded at location loc. For a sailing task, the energy E_s^{leg} and duration d_s^{leg} states are recorded per leg sailed. This relationship between tasks and states allows for post-simulation association of states to their respective tasks to create totals. The aggregated voyage duration d_v for voyage v is described by:

$$d_v = \sum_{legs} d_s^{leg} + \sum_{locs} \max\,(d_{ch}^{loc}, d_c^{loc}) \tag{1}$$

where the two sums represent the total aggregated durations from all sailing legs and locations respectively. The total energy consumed for the ship for a given voyage E_v is given by the sum of all recorded energy states E_t in the simulation for each of the tasks performed:

$$E_v = \sum_{tasks} E_t \tag{2}$$

These states can be associated with shipments transported to calculate tonne kilometres (tkm) or per unit KPIs during post-processing. Whereas the SOC states can be used to associate the battery-state to the different tasks when analysing the voyage, e.g., to sufficiently dimension the battery package.

2.2 Post-processing

One of SIMPACT's strengths is the ability to re-iterate on cost KPIs without re-running a full simulation. The following describes how the post-processor transforms tasks, energy-, duration-, and shipment-states to create voyage and yearly KPIs for the transport system. There are two main KPI categories that SIMPACT outputs: emissions and costs. The extrapolation done in the post-processor extends the simulator outputs to a full year by injecting port stays between voyages, while assuming that the ship consumes auxiliary power during this time. This is done through an input-parameter describing the operational percentage for the vessel. The operational percent input is used to calculate the time spent on voyages throughout a year (d_{uptime}) and the downtime between voyages spent at harbour ($d_{downtime}$). With this relation, the voyage duration d_v as described in equation (1) can be used to calculate the number of voyages N

$$N = \frac{d_{uptime}}{d_v}, N \in \mathbb{R}^+ \tag{3}$$

Since N may contain decimal-place voyages that cannot be carried out, there is residual yearly time r_N

$$r_N = (N - \lfloor N \rfloor) d_v \tag{4}$$

Where $\lfloor N \rfloor$ is the integer floor for N. In combination with the yearly downtime this can describe the port stay duration between voyages d_p in the following way:

$$d_p = \frac{d_{downtime} + r_N}{\lfloor N \rfloor} \tag{5}$$

With this, the total duration $\hat{d}$ of a voyage can be expressed as

$$\hat{d} = d_v + d_p \tag{6}$$

2.3 Cost and emissions

The output of the cost KPI calculator includes: cost breakdown (capital, operational, energy, and port costs), operational cost breakdown (Crew, ROC, Other), voyage cost per transported unit according to [31], Voyage cost per tkm according to [32], and location to location costs per unit. The cost calculation consolidates the ship-model inputs and other costs with the states from the simulation to calculate the cost of port stays between voyages C_p, as:

$$C_p = C^{dues} + \left(P_{AUX} C_E + \frac{C_{CAPEXyear} + C_{OPEX}}{d_{year}} \right) d_p \tag{7}$$

Where P_{AUX} is the auxiliary power consumption of the ship, C_E is the cost of fuel or charging, and C^{dues} are port stay dues. The total voyage cost $\hat{C}$ is then given by

$$\hat{C} = C_p + C_v \tag{8}$$

Where C_v is the voyage cost as described in [31]. The total yearly cost for the ship is then $\lfloor N \rfloor * \hat{C}$.

The different machinery models available in SIMPACT describe the relationship between consumed energy and fuel, and tank-to-wake (TTW) emission intensity through conversion factors. This includes factors for CO_2, CO, HC, PM_{10}, $PM_{2.5}$ and SO_X. The output of the emission KPI calculator is (for details see [31], [32]): ship energy efficiency operating indicator (EEOI), voyage TTW emissions, emissions per transported unit, emissions per transported tkm, location to location emissions per unit and tkm. The method for calculating the port stay emissions for a given engine is given by its specific emission factor and the port stay duration. This in turn is extrapolated to yearly results, e.g., with $\lfloor N \rfloor * \widehat{CO}_2$, where $\widehat{CO}_2$ is the voyage emission including port stay for CO_2.

3 Case study: autonomous feeder loop vs trucks

The proposed methodology to evaluate autonomous ship concepts will be showcased in a waterborne transport scenario which is being analysed within the SEAMLESS project [33]. As part of its political agenda, the Bergen municipality has outlined a path to improve the quality of urban life and health while significantly reducing emissions in the city. This includes minimizing the environmental and spatial footprint of port-related activities which are currently located at the "Dokken" area in the inner-city of Bergen [34], [35]. The Bergen Port Authority is therefore investigating options to relocate freight transport activities to areas outside the city centre. One location which is under consideration to become the new maritime gateway for the region is the village Ågotnes in the Øygarden municipality, located approximately 11 nautical miles west of the current container port in Bergen [35]. However, since a major share of maritime transport demand originates from the metropolitan districts within the region [36], relocating the port to Ågotnes may significantly increase the volume of road transport.

A potential solution which is currently investigated within the SEAMLESS project, is the introduction of autonomous ships in a zero-emission waterborne logistics network. The network links the maritime gateway in Ågotnes with small minimally equipped terminals in the region by means of an autonomous feeder loop [33]. Besides technical specifications pending clarification, this concept poses several questions to be investigated from a logistics perspective, such as optimal network design, required terminal characteristics as well as the integration of first and last mile transports. The study in [19] showed the feasibility of such a zero-emission network. However, from a cost perspective, the multimodal option could only compete for a rather small share of the transport volume. The study did not develop the vessel concepts and only made some rough cost assumptions to consider autonomy.

This case study will do a more detailed evaluation of potential vessel concepts for the new logistics system, by using the SIMPACT methodology presented herein. Specifically, the use case will compare the performance of a low frequency service which utilizes a 110 TEU vessel design (scenario 1) with a higher frequency loop running on a smaller 60 TEU vessel (scenario 2). Pre-haulage and last mile are carried out by trucks in both scenarios S1 and S2. Furthermore, average sailing speed is assumed to be 8 knots. In a third scenario, the transport demand will be met by road transport only to provide a benchmark for the waterborne scenarios. In all scenarios, it is assumed that trucks drive a round trip with cargo in one direction, and empty in the other. This is based on input from Port of Bergen. In order to reduce the complexity of the scenario and to mitigate the influence of external factors, the scope of the analysis is limited to a containerized connection between Ågotnes as the new maritime gateway, and a city terminal at the current container port in Bergen, dedicated to serve the metropolitan area (see Figure 3). To further limit the scope, external costs are also not considered but assumed to be lower for S1 and S2 than S3.

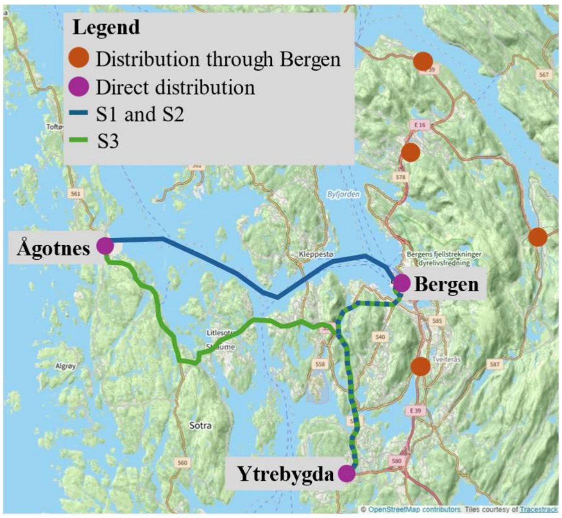

Figure 3. Network scope for this study

3.1 The vessel and port concept

This work represents an early stage of the case study within the SEAMLESS project, and at the current stage, the project's proposed vessel concept for the Bergen use case is not finalized yet. As a substitute, and input to the design process for the project going forward, this use case will employ zero-emission vessel concepts with swappable battery containers that have been developed within the AEGIS project and presented in detail in [28]. For S1, the 110 TEU vessel with an onboard-gantry crane for loading and unloading at the terminal is used. The crane is designed to allow an average handling-rate of 15 moves/hour. In S2, the 60 TEU vessel will be used. Cargo handling for the 60 TEU vessel will be carried out using an (autonomous) reach stacker which handles 10 moves/hour. The 60 TEU vessel hence includes a roro ramp. Design differences between the two vessels are included in the cost and hydrodynamic models [28]. Both vessels are assumed to operate in a constrained autonomous and unmanned mode as defined in [1]. With regards to the terminal operations, internal moves as well as the landside interface of the terminals are assumed to be carried out by reach stackers. While the S2 vessel concept includes a reach stacker transported onboard, the S1 vessel does not. This means that in S1 the addition of a reach stacker for the small terminal in Bergen will be required. It is also assumed that Ågotnes will offer land power to supply the vessel during terminal operations, while the Bergen terminal will not. Furthermore, battery container swapping is done at Ågotnes only. Thus, the battery containers must have capacity for handling the power demand during the terminal operations in Bergen, as well as for sailing the roundtrip between Bergen and Ågotnes. Finally, the non-propulsive loads, i.e., equipment, reefer containers, etc., are estimated to an average continuous load of 100kW for both S1 and S2.

3.2 Network flows

Since the case study transport system is not yet realized, the analysis is based on various assumptions. As indicated above, the case study is based on a simplified network model which consists of two terminals as well as several origins and destinations within the different districts of the Bergenhus municipality. As the scope is limited to maritime cargo, the Ågotnes terminal serves as either source or destination for every transport order in the system. For the waterborne scenarios (S1/S2), it is assumed that all flows between Bergen and Ågotnes are moved by the autonomous shuttle, while first and last mile transport is carried out by road transport. In the benchmark scenario (S3), every order is directly transported by road transport.

It can be deduced from the map representation in Figure 3 that road transport connecting Ågotnes and destinations east and north of Bergen will have to pass the port area due to the existing road network structure. Therefore, the case study assumes that all scenarios differ only in terms of the distance to be covered between Ågotnes and Bergen. An exception is made for cargo flows going to the Ytrebygda region south of Bergen which can be accessed in shorter distance from Ågotnes directly through county road 557. For these orders, the case study will use the combined transport within S1/2 and compare the results with the benchmark S3.

3.3 Transport demand

For the total transport demand in the system, the case study adopts the import and export volumes of full and empty containers handled by the Port of Bergen in 2023 as described in [37], which amounts to 37,502 TEU and will be moved to the terminal of Ågotnes. As the analysis is restricted to 20ft and 40ft containers, all volumes for larger containers have been labelled as 40ft. To determine the transport volumes to and from the Ytrebygda region, a share of 18% is assumed, which corresponds to the geographical distribution of inbound and outbound cargo in the region, based on [36] and the districts included in [19]. Table 2 shows the assumed annual transport volumes in containers for the three scenarios to be analysed.

Table 2. Yearly demand

Scenario	From	To	Distance (road) [km]	Duration (road) [min]	40ft	20ft	40ft empty	20ft empty
S1/S2	Ågotnes	Bergen	-	-	6168	3860	1054	995
S1/S2	Bergen	Ågotnes	-	-	2669	1947	4353	2212
S1/S2	Bergen	Ytrebygda	21.5	28	1110	695	190	179
S1/S2	Ytrebygda	Bergen	21.5	28	480	350	784	398
S3	Ågotnes	Bergen	28.2	31	5058	3165	864	816
S3	Bergen	Ågotnes	28.2	31	2189	1597	3569	1814
S3	Ågotnes	Ytrebygda	36.7	43	1110	695	190	179
S3	Ytrebygda	Ågotnes	36.7	43	480	350	784	398

As simulations are carried out per voyage, the average shipment size per voyage is derived from vessel cargo capacity and Table 2, by assuming the transport system operates 50 weeks per year, which also accounts for public holidays. Even though expert inquiry indicates variations of transport demand during the week, this has not been accounted for in this demand model. This resulted in 200 yearly voyages for S1, and 344 for S2. Furthermore, it is assumed that the average weight for full 20ft and 40ft is 26 tonnes, empty 20ft is 2.1 tonnes and empty 40ft is 3.8 tonnes.

3.4 Costs
This study adopts most of the cost assumptions made in [28] with the following adjustments:

- Vessels: In contrast to [28], it is assumed that one battery container (instead of four) onboard the vessel, is sufficient, and that the cost of batteries is reduced from 13.4 million Euro to 3.35 million Euro. All other cost figures for the vessels are as given in [28].
- Energy: Adjusted to twice the kWh price in [28] to account for uncertainty.
- Port: The analysis considers the waterborne shuttle transports to have the function of "household" moves from the perspective of the port. Therefore, dues that would normally be paid by external port users, such as port and fairway dues, will not be included in S1 and S2. Instead, port costs are included by the additional operational cost for having the small terminal in Bergen as 150,000 Euro added to the annual operational cost in S1 and S2. For S1, an additional 1 million Euro investment is added to account for a reach stacker in the Bergen city centre terminal. These costs are supplied by port of Bergen. While the vessel cost in S2 already includes the cost of an autonomous reach stacker. For Ågotnes, terminal cost differences for scenarios 1, 2 and 3, are considered negligible.
- Road transport: same cost model as [28], however, cargo handling costs are not included as they are assumed identical for all three scenarios; all pre-carriage and last mile is done by trucks. Thus, the same number of loading and unloading operations applies to all scenarios.

3.5 Weather
The weather distribution used for S1 and S2 is based on the same method presented in [28]. The statistics for the region show that throughout the year, the average weather is calm in the region. Table 3 describes two weather profiles gathered from statistical data of the region from 2022, where h_s describes the significant wave height. The average profile comprises the weather that is expected for about 50% of the yearly operation. This profile is used for cost and energy comparison for S1 and S2. In contrast, the worst weather profile occurred no more than 1% of the year. Additionally, this profile has been modified with an intentionally unfavourable wind and wave direction on the route that it is impacting. This profile is used to determine if the battery containers on S2 have sufficient charge to operate in this worst-case scenario.

Table 3. Wind profiles for waterborne simulations

Profile	% time spent	h_s (m)	Wave direction (°)	Peak wave period (s)	Wind speed (m/s)	Wind direction (°)
Average	33	0.1	135	1	3.1	135
	33	0.2	135	3.8	5	135
	34	0.25	135	6.6	6.8	135
Worst	100	1	0	15	16	0

3.6 Results
Scenarios S1 and S2 were modelled in SIMPACT and simulated according to the collected data and assumptions discussed in the previous sections. The results show that the capacity utilization of the transport systems is low with 47% operational time at 86% cargo capacity utilisation for S1, and 69% operational time at 92% cargo capacity utilisation for S2. Having sufficient capacity utilization is critical for good cost performance, which means that a smaller design would most likely perform better and should be investigated in the SEAMLESS project's further work.

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As the battery containers make up a significant part of the investment cost, it is important to verify that the assumption of 2 units per vessel (1 onboard and 1 for swapping) holds. For S1, the result is given in Figure 4. Cargo handling at Ågotnes is carried out while connected to shore power, hence the vessel leaves with full charge. As the vessel transits to Bergen, perform the cargo handling activities at Bergen and return to Ågotnes, the battery charge continues to reduce until the vessel is connected to shore power at Ågotnes. Before leaving Ågotnes on the next round trip, the battery container is replaced. As can be seen from the dotted line in Figure 4, the S1 vessel SOC goes to 0% just before returning to Ågotnes. The average sailing speed was therefore adjusted to 6 knots, seen as the solid line in Figure 4. This resulted in an SOC of 10%, which can still be considered too low. The solution would be to either add one battery container, i.e., purchase two battery containers, or to invest in shore power at Bergen since a significant part of the consumption is from the terminal activities at Bergen. The results for S2 are given in Figure 5 where it can be seen from the solid line that the vessel in S2 can complete the roundtrip with 33% remaining charge. For the worst-case weather scenario, given by the dotted line, the SOC reduces to 28%. This confirms that one battery container is sufficient in S2.

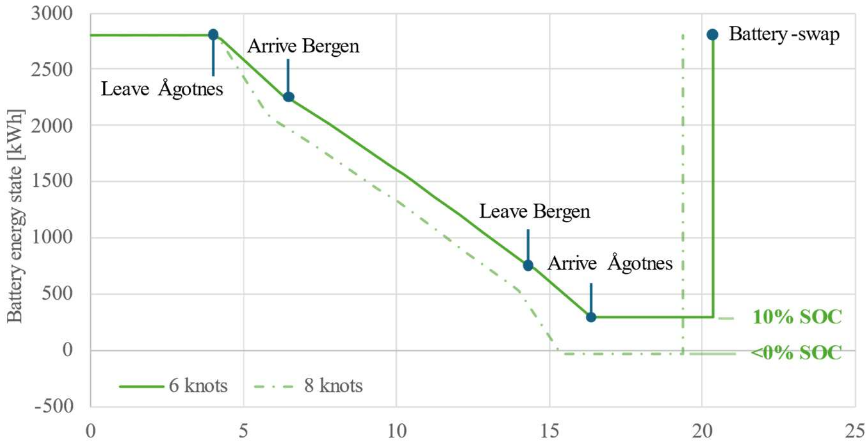

Figure 4. S1 state of charge

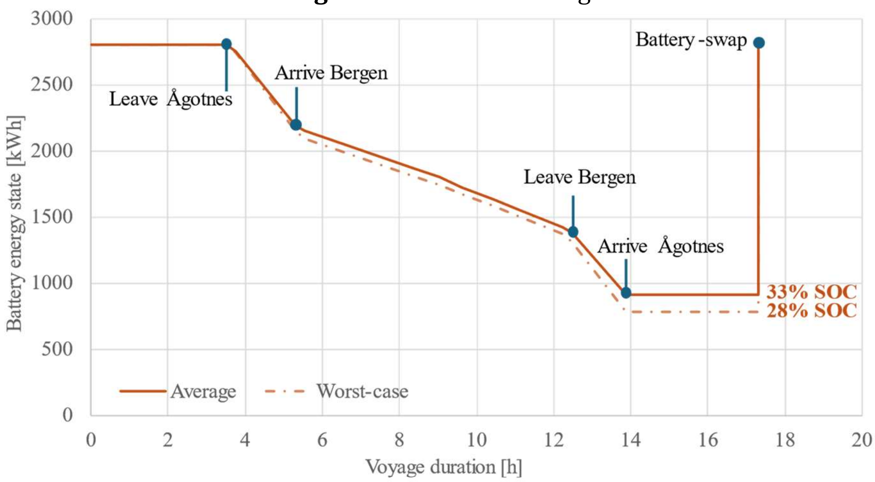

Figure 5. S2 state of charge

Investigating the resulting transport costs in Figure 6, shows that the total costs of yearly operations for the three scenarios favour S2, with S1 coming in second and S3 last. This contrasts with the results in [28] where the road alternative led to the lowest cost. The reason why S1 and S2 perform better than S3 (road) in this case study is mainly due to the shorter distance allowing for a significant reduction in investment cost related to the battery containers. However, as was observed in Figure 4, S1 would require another battery container or shore power at Bergen. This cost increase is not further investigated as S2 already has a lower cost. The short distance also results in low energy consumption. Furthermore, as this case is evaluated from the port perspective, port and terminal costs are somewhat lower (in this analysis they are included in the OPEX and CAPEX estimates, hence not separate costs in Figure 6). Another observation is that with the lower transport demand in our case study, relative to [28], the 60TEU vessel of S2 performs better than the 110TEU vessel of S1 due to a better capacity utilization. In [28], two 60TEU vessels were needed to serve the demand whereas one 110TEU vessel was needed, which resulted in the 110 TEU vessel having a better cost performance. This is not surprising and aligns with [19] which compares 15, 30 and 45 TEU vessels on the present problem.

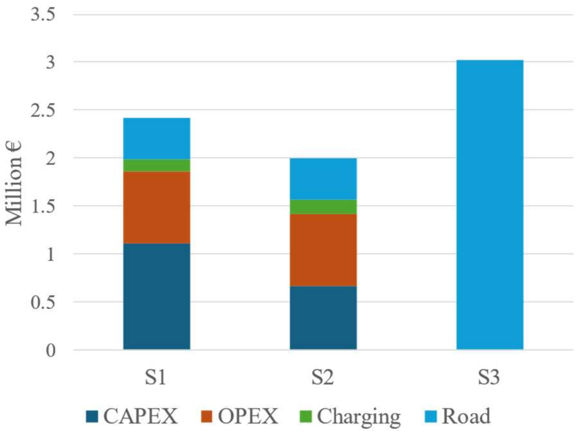

Figure 6. Yearly cost of operation

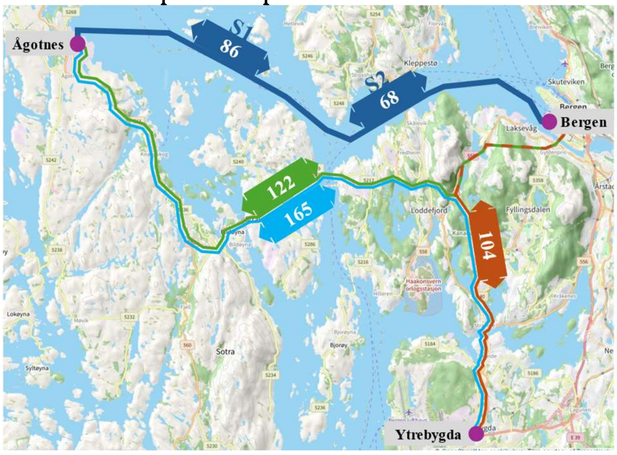

Figure 7. Cost per container (€ per container)

The cost per transported container presented in Figure 7 shows that for transport between Ågotnes and Bergen, S2 has the lowest cost at 68 Euro, and S3 has the highest cost at 122 Euro. However, for Ågotnes – Ytrebygda, S3 has the lowest cost per container at 165 Euro and S2 comes in second at 172 Euro (68+104 Euro). While the difference between S3 and S2 is quite low, the result indicates that it could be better to extend the network with a small terminal at Ytrebygda.

4 Conclusion and outlook

In this paper, a novel method for evaluating ship concept performance in transport systems was presented and applied to a case study being investigated in the SEAMLESS project: Can an autonomous feeder-loop connecting a new container terminal at Ågotnes to a small terminal in Bergen compete with trucks and thereby reduce external cost impacts? Some assumptions were made to set the focus on SIMPACT and demonstrate the proposed method, and to provide some insights for further work in SEAMLESS. All aspects of the proposed method cannot be addressed by one case study, however, the case study demonstrated that SIMPACT enabled the evaluation of the vessel concepts by simulating the operational phases of the vessels and estimating time, cost, and energy consumption. This was used to investigate if the transport demand was served, how well the capacity was utilized, if the battery package was sufficient, and to compare costs.

While the transport demand was served in both S1 and S2, both scenarios had significant spare capacity for transport. More so in S1 than in S2. It was found that in S1 the battery package was too small, while in S2 it was sufficient. Furthermore, the cost performance of S2 was found to be better than S1, more so if the investment in another battery package or land power at Bergen is added to the S1 investment cost. This shows the importance of considering the energy consumption of the evaluated vessel concept as it may have a significant impact on total cost.

Interestingly, our results indicate that the autonomy-driven ship designs allow for competitive transport costs. Compared to the results in [18], [19], where it was not considered if the vessel was autonomous or not, the multimodal alternative has a better performance in terms of transport cost when the ships are autonomous. It should be noted that the networks in [18], [19] include more nodes than in our case study, which should be addressed in future SEAMLESS project work.

While the results show that the investigated vessel concepts in both S1 and S2 are competitive to trucks (S3) in terms of cost performance, it was also found that their capacity utilization was low and that their designs are not optimal for the case they were applied to. Economies of scale as a dominant paradigm in shipping does not work in case of low capacity utilisation. An aspect to note here is that the growth scenarios indicated by Port of Bergen could be an argument for investing in a system with some spare capacity, especially if it is cost-competitive with current cargo volumes. Nevertheless, the SEAMLESS project will continue the study of the Bergen region case. Important outcomes of the present study that will be further addressed are:

- The SEAMLESS concept vessel design will be developed and needs to be of a suitable size relative to current and future demand. Fixed installation batteries should be compared to battery containers since battery container cost is high and is a concept that is probably more beneficial in cases with several vessels sharing the same pool of battery containers.
- The case study should be expanded to include more locations to further reduce truck traffic. Specifically, the presented cases S1 and S2 do not significantly reduce the inner-city traffic as all containers would still be shipped via the smaller Bergen terminal. Furthermore, the cost per container in Figure 7 already indicates that there might be a case for sailing at least to Ytrebygda, but more locations should be evaluated. These evaluations should trade-off transport cost versus external cost.
- Government funding and subsidies are not accounted for in the case study. At present, there are programs that would be applicable to the studied concept. This could have an influence on what network nodes can be included while keeping overall transport costs sufficiently low.
- SIMPACT has functionality for logistics analysis, which was not discussed in the present paper. This functionality should be used in the design phase for a logistic network including additional locations to Ågotnes and Bergen. It can handle variations in demand during the week, more advanced scheduling, and provide insight into shipment sizes. This can be used to determine the number and size(s) of vessels, which in turn is an important input for the design of the SEAMLESS concept vessel. SIMPACT logistics analysis can also evaluate how the inventory at terminals develops over time, which is crucial for the planned small terminal in Bergen.

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