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Evaluation of an autonomous, short sea shipping feeder-loop service through advanced simulations

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Abstract. Traditionally, container-freight being shipped from central Europe to the coast of Norway has been transported either by road, or by larger containerships to central ports. For the past 3 years the AEGIS consortium has worked to develop a new, disruptive short sea shipping feeder-loop service based on mother and daughter ships [1]. The hypothesis is that introducing smaller, autonomous, battery-powered vessels into the fjords of Norway would open new business areas, provide access to remote regions, and allow shipping companies to take on cargo that could not previously be transported by water. Such a transport system has the potential of reducing cost, GHG emissions and external costs, while increasing frequency of service and the waterborne cargo volume in Europe. One of the main challenges of the mother-daughter logistic system is how transshipment affects defined key performance indicators (KPIs), especially in terms of cost. For this purpose, the SIMPACT tool [2] was developed in the H2020 projects AEGIS and AUTOSHIP. The tool allows for rapid iterations of maritime logistic systems through discrete event scheduling, and estimation of energy, fuel, emission, and cost.
This paper will present results from a case-study on two different daughter ship concepts. The concepts are evaluated through cost and environmental KPIs presented in [1], in addition to external costs based on the European handbook on the external costs of transport [3].
Results from the case-studies indicate that transport systems including green daughter-vessels have the potential of being cost competitive and would lower externalities compared to the baseline truck transportation system.

1 Introduction

Mother-daughter concepts for shortsea shipping has been studied previously by several authors. A shortsea liner network with transhipment at sea is studied in [4]. The concept involves mother and daughter ships where cargo is transferred at sea by using cargo handling equipment on board the mother ship. The study in [4] addresses liner shipping network design and determines optimal routes and daughter vessel sizes. An extension of the problem introduced in [4] is found in [5], where uncertain sailing times is taken into consideration in the synchronisation between routes such that mother and daughter ships (see AEGIS [1] ships in Figure 1) meet at the same location at the same time for transhipments. They introduce the combination of optimisation and discrete event simulation to find optimal routes and evaluate them in terms of robustness under uncertain weather conditions.

Figure 1 The AEGIS example on a mother – daughter fleet of ships, 1110 TEU mother ship in the upper part and the two daughter concepts below (60 TEU and 110 TEU)

A liner network design study where different network structures are compared, including mother-daughter concepts where transhipments are done at ports, is found in [6]. They find that including daughter ships and split pickups can lead to a significant cost decrease. The economic impact of introducing autonomous ships in a shortsea liner shipping network is studied in the related studies [6], [7]. The concept is based on conventional mother ships and autonomous daughter ships where transhipments are synchronized at different ports. The results show that autonomy may contribute to considerable cost savings. The focus of the studies is on the network design and comparing the performance of conventional and autonomous ships operating the network. The cost models are rather simple, where fuel consumption is defined by tonnes/hour and weekly time charter cost as a lump sum estimate.

The estimated performance of ship concepts in their intended operational environment is studied in [8]. Hydrodynamic models of ship concepts are developed and used in discrete event simulations, including realistic routes, sailing patterns, and weather conditions, to estimate energy and fuel consumption for operations spanning years. The approach to energy and fuel estimation in [8] provides more insight into how a specific ship concept performs in its intended operations than that of [6], [7].

The cost and benefits of introducing autonomy in shipping has also been studied previously. However, in the literature review in [9] it is found that valid financial models are lacking and that there is significant uncertainty in the cost estimates. This leaves only reliable evaluations of specific case studies. The AUTOSHIP roadmap [10] investigates gaps related to autonomous ship development, including economy and emissions, and finds that it is still uncertain when and where autonomous ships are applicable. Hence, more studies are needed to build the knowledge base.

The study in [11] provides a detailed evaluation of important cost impacts of introducing autonomy, such as the Remote Control Centre (RCC), maintenance by boarding teams, and removal of superstructure and additional equipment and redundance. A proposed method for quantification of competitiveness and societal impact is also available in [12].

1.1 Problem definition
Previous studies on mother-daughter concepts focus on network design and optimisation. Two studies investigate the economic impact of autonomous daughter ships; however, the studies compare the relative performance of conventional and autonomous daughters, and neglects to evaluate the competitiveness towards road transport. Furthermore, the cost model seems to be a best guess where cost elements are not shared, fuel-consumption models are based on rough assumptions (fuel/hour), and emission impact is neglected. More detailed analysis of specific ship concept performance, such as in [8], for autonomous daughter concepts is therefore needed to evaluate the question: *Assuming that autonomy reduces transportation cost, can autonomous daughter ships compete with truck transportation?*

The contribution of this paper is a simulation-based evaluation of a feeder-loop network operated by autonomous daughter ships, developed through the AEGIS project [13]. The evaluation is done by quantification of logistical, cost, and external cost performance of the shortsea daughter network compared to a truck transport network. This provides new insight into the performance of autonomous daughter concepts, and their impact on waterborne transport competitiveness towards road transport. Furthermore, energy estimation is done based on the same methodology as in [8], while cost estimation is a combination of estimates from existing literature such as [11] and [12], and data provided by the AEGIS project partners, while logistics analysis and KPI estimation is done as described in [2]. The contribution is thus also a detailed quantification of the performance of autonomous daughter ships, as well as a detailed cost breakdown where the CAPEX estimate is specific for the autonomous ship concept and includes component cost estimates that are rarely found in literature (e.g., auto-mooring and autonomy package).

The following key assumptions are made:

- A1: Mother ships operate on the same schedule and transport the same container volume for all case studies. Costs and other KPI impacts related to mother ships are therefore omitted.
- A2: Mother ships call upon a main hub at Sandstad (SAN) twice a week. Daughter schedules are constructed to distribute and consolidate cargo for the mother ship port calls. Daughter ship cargo capacity (single ship or fleet of daughter ships) is adjusted to handle one mother port call. Hence, the sailing frequency will be twice a week for each daughter ship.
- A3: All cargo delivered or loaded at SAN by the mother ships are transported to or from SAN by either a) Daughter ships, or b) trucks. Daughter ships are compared against trucks for the transportation of the same container volume between the same locations.
- A4: Autonomous daughter ships have a lower cost and emission per transported ton-kilometer than conventional daughter ships. Conventional daughter ships are therefore not considered.
- A5: Truck cost and emission analysis does not model transportation for getting to/from the transport job. Truck cost and emission estimates are hence conservative.
- A6: Last-mile transport is assumed identical for all cases and therefore omitted from the analysis. Even when the transportation between the locations is done by trucks it will be necessary to do cross-docking to last mile trucking (stripping and re-stuffing). The exception is VDL where there is a factory who produces full containers and receives empty containers to the factory port, hence no last mile transport is needed.

2 Evaluation method

The case studies presented in the later sections compare the effects of moving containerized cargo from road to sea. This is done through two different simulation methods developed at SINTEF. A Base Case (BC) using road transport is described later in section 4.1. This road transport is simulated in a road transport energy estimation module created by SINTEF Community [14] presented in section 2.2. Concept cases (C#) that transport containers on small autonomous daughters are presented in sections 4.2 and 4.3. These are simulated in a toolbox called SIMPACT [2], developed in the H2020 EU projects AUTOSHIP and AEGIS, and is presented in section 2.1.

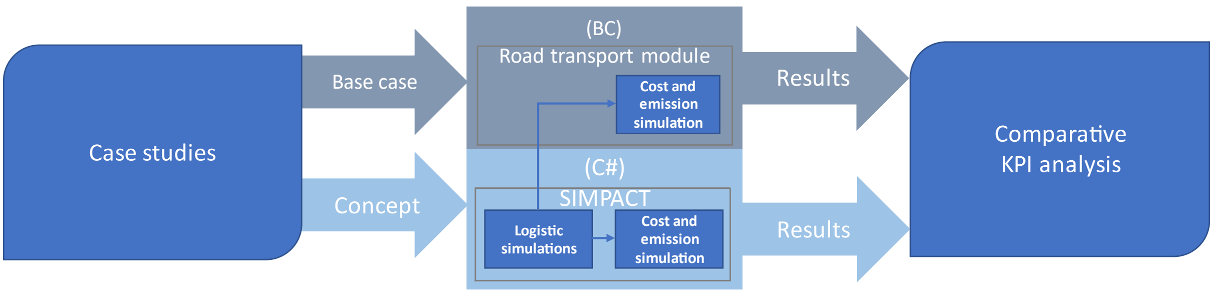

Figure 2 Case study evaluation workflow

2.1 SIMPACT
The evaluation method is based on a simulation toolkit developed by SINTEF called SIMPACT, which is described in detail in [2]. The toolkit consists of two applications: 1) the logistics analysis tool (LA-tool), 2) the MASS analysis tool for cost and emission estimation (MA-tool). The toolkit can be used for validating a case by first doing a logistics analysis to evaluate that the basic logistical requirements can be met, and second, by estimating resulting transportation costs and emissions. The case study evaluation workflow is illustrated in Figure 2, and the toolkit is labelled SIMPACT in the figure. The case study evaluation is done by comparing concepts to a base case, see section 4 for details on the base case and the concepts.

The LA tool is based on simple models for locations, routes, ships, sailing schedules, and cargo production. These models are used in discrete event simulations of, e.g., a year, to evaluate KPIs measuring schedule keeping, capacity utilization, lead time, etc. Parameters such as number of ships, ship size, sailing speed, routes or sailing schedules, can be adjusted until satisfactory logistical performance is achieved.

Once the transport system is dimensioned, the cost and emission analysis are done in the MA tool by extracting the routes, shipments, sailing speeds, etc., found in the logistical analysis. The MA tool needs additional configurations such as a hydrodynamic model of the ship modelled in ShipX [15], [16] and cost parameters. Energy estimation is done based on the discrete event method in [8], while cost estimation is based on [12].

2.2 Road transport energy module
The road transport energy module developed by SINTEF Community simulates a single trip between two locations [14]. The input to perform a single trip is the start and stop location, as well as several parameters describing the truck performing the trip. The main input parameters are vehicle type, accelerating power, braking power, vehicle weight, payload weight, front area, and accessory load. The method behind the tool is described in more detail in [14]. The input for cargo transported per trip is the same as the input for the MA-tool. This ensures that when comparing KPIs, all studied cases have transported the same number of containers between the same sources and destinations.

3 Green and advanced daughter ships
Several green daughter ships have been developed in the AEGIS project. Two of these are evaluated in the simulation studies in this paper. The design is based on use case A from AEGIS [1] and cargo volumes studied in the project. It has been concluded that two different sizes can be applied to the transport system of this study, where one has the container cargo capacity of 56 TEUs, shown in Figure 3 and the other 106 TEUs, shown in Figure 4. Both ships are based on zero emission propulsion systems with 4 swappable battery containers with a total capacity of 11.200 kWh, and on-board cargo handling equipment. This gives a total TEU capacity of 60 and 110 TEU, respectively. Further, both daughter ships are moored utilizing robotic mooring arms from MacGregor, as installed on Yara Birkeland [17]. For containerships, the standard design tonnage capacity is 14t/container. The two daughter ships, however, are designed to carry 25t/container due to the expected high weight cargo.

3.1 60 TEU daughter ship
The 60 TEU daughter ship has a length of 65.0 m and breadth 11.5 m, and a service speed of 6 kn. The 60 TEU ship is based on a concept where an autonomous reach stacker (ARS), see Figure 3, is brought onboard, to handle the containers in any terminal, completely independent from other equipment quayside. The ARS is designed, together with Kalmar, to be lightweight at approx. 11 t, with two counterweights stored at each port. The counterweights are needed to handle containers during un/loading and at horizontal movements at the port. A 30t counterweight is connected to the ARS via a coupling system at its backside, a second block of 10 t connects at the front end. During sailing the ARS is parked on a lift platform at the lower deck in the foreship. Once moored, the shear lift can raise the light-weight ARS to the needed height and the ARS can drive on the quay via the foldable ramp.

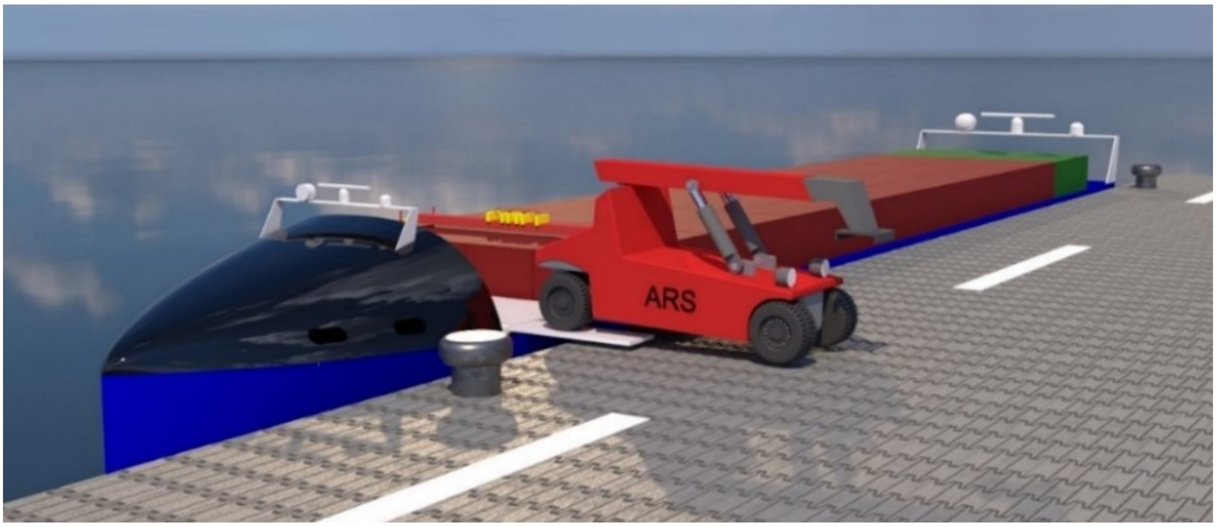

Figure 3 The 60 TEU daughter ship, source: ISE

3.2 110 TEU daughter ship

The 110 TEU daughter ship has a length of 80.0 m and a breadth of 12.5 m, and a service speed of 8 kn. The ship has an on-board gantry crane inspired by a design from a German project called Watertruck [18], which also makes it versatile, enabling port calls to any terminal in the area. The crane can be seen in Figure 4, along with the ship itself.

Figure 4 The 110 TEU daughter ship, source: ISE

4 Case studies

This chapter gives specifics to each case study and how they are modelled. These cases are inspired by use case A in the AEGIS project [1]. All case studies are evaluated over a full year of operation. The first section covers the Base Case, denoted BC which is the benchmark case study where all goods travel by road on trucks. The second section covers the first concept case, denoted C1 that evaluates two 60 TEU daughters and the last section covers the second concept case denoted C2 that employes on 110 TEU daughter.

Figure 5 Route SAN - ORK - TRD - VDL – SAN

The locations and cargo flow are identical for cases. Figure 5 shows a screenshot from the SIMPACT frontend with the different locations, and the route between them. The locations for the case studies are Hitra Kysthavn Sandstad (SAN), Orkanger (ORK), Trondheim (TRD), and Verdal (VDL). SAN is a new transshipment terminal. It acts as a hub between short sea ships travelling along the coast of Norway, to locations outside of Norway. VDL is a factory location that consumes empty containers and produces full containers. Container production at this location roughly equals the consumption rate of empty containers. ORK and TRD are on-demand terminals where goods can either go within the fjord, or to SAN for transshipment. Today, cargo travels mainly by road. The case studies challenge this traditional mode of transport by introducing autonomous daughter ships serving these smaller terminals in the fjord. SIMPACT models cargo flow between locations as shipments of orders transported from producers to different consumers, where producers can also consume orders. The locations presented in Figure 5 are locations that produce and consume orders.

Based on analyses together with NCL, it has been found that the cargo-volume in Trondheimsfjorden consists of a combination of heavy 20′ and 40'/45' containers. From this cooperation, a cargo flow design was made where containers are either full, or empty. If they are full, they are assumed to weigh 25t, if they are empty, they weigh 2.2t, which is the weight of an empty 20′ container [19]. For simplicity, it was decided to only include 20' containers in the study. The relative impact between the studies will not be largely affected by this choice since all transport modes would need to account for the different sized containers. In fact, since 20' containers can be loaded heavier than 40' containers, the energy consumption due to lower draught for the ships will be higher than if there was a mix of 20 and 40'/45' containers, ensuring the results do not favor the proposed solutions.

Table 1 Weekly order production

Producer	Consumer	Order size (containers)	Initial order (Simulation day)	Frequency (days)
SAN	**ORK**	38	0	7
SAN	**ORK**	38	3.5	7
SAN	**TRD**	18	0	7
SAN	**TRD**	18	3.5	7
SAN	**VDL**	17[a]	0	7
SAN	**VDL**	17[a]	3.5	7
VDL	**SAN**	15	0	1
ORK	**SAN**	10	0	1
ORK	**VDL**	5[a]	0	1
TRD	**VDL**	5[a]	0	1

[a] Empty

Table 1 shows the order production designed to evaluate the different case studies. The Initial order is a SIMPACT specific parameter that describes which simulation day the order first appears in the logistic simulations. It is followed by the frequency which describes the frequency at which the order appears in the simulation after the initial order day.

The production design aims to capture a large volume of containers travelling from SAN into the different locations in the fjord and a smaller volume from each of the smaller locations out to SAN to be transported out of the region. The production from SAN represents orders with destination TRD, ORK, and VDL, and which arrives at SAN with NCL mother ships twice a week, once at the start of the week, and once mid-week.

4.1 Base Case

The base case (BC) transports all containers on road with trucks. The base case considers energy and cost KPIs through simulating one truck voyage in the road transport energy module described in section 2.2. Therefore, the weekly order production from Table 1 can be simplified for the BC to a set of truck voyages going between locations with either full or empty containers. Figure 6 shows a node graph for how orders travel between locations on trucks.

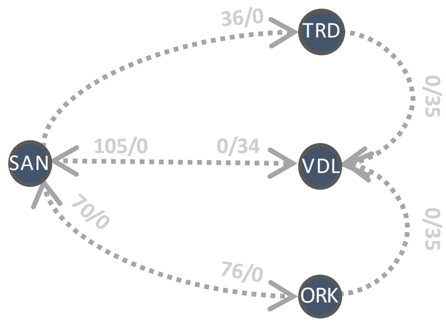

Figure 6 BC weekly cargo flow (full/empty)

4.2 Concept 1: Two 60 TEU daughters

The first concept case (C1) investigates the effects of using two of the 60 TEU capacity autonomous daughters from Figure 3 serving the locations in the fjord from SAN. The daughters' route is shown in Figure 5. Both daughters travel the same route, but with an offset in time of 1.75 days, to carry the different shipments described in Table 1. This ensures a low average lead time for all orders in the transport system. The notation C1D# (Concept 1 Daughter #) is used to differentiate between them when discussing the parameters and performance of each daughter separately.

Table 2 C1 - Simulation parameters

Ship	Capacity	Cargo handling	Approach / Depart time	Initial location	Scheduled start	Scheduled stop	Epoch size	Scheduled downtime	Sailing speed
	TEU t	Containers/h	h		day	day	days	days	knots
C1D1	56 1400	10	0.25 / 0.25	SAN	0	3.5	3.5	0	5
C1D2	56 1400	10	0.25 / 0.25	SAN	1.75	5.25	3.5	0	5

Table 2 specifies sailing parameters for the two 60 TEU daughter ships necessary to create a sailing schedule withing SIMPACT. The daughters are modelled with a 56TEU capacity because there is always four battery-containers occupying four cargo-locations. The schedules for the two daughters are displaced by a quarter week to align with the initial order arriving at SAN the first simulation day. This allows C1D1 to carry the initial shipments from SAN, while C1D2 carries the remainder within 2 days of the shipments arriving at SAN. The daughters are expected to complete their respective voyages within 3.5 days, before starting over. There is no planned downtime between sailings for any of the vessels and the daughters sail at 5 knots. The approach and depart time for all daughters are set to 15 minutes. This is time spent on approaching and departing on top of the time spent sailing between locations at service speed.

4.3 Concept 2: One 110 TEU daughter
The second concept case (C2) investigates the possibility to serve the fjord with a single 110 TEU daughter ship from Figure 4. Such a solution could be a cheaper alternative to the double 60 TEU daughter concept if it is able to perform the same amount of work as the two daughters in C1. The 110 TEU daughter has a higher design-speed and can therefore cover more locations in a week than a single 60 TEU daughter. The 110 TEU daughter travels the same route as the C1 daughters shown in Figure 5.

Table 3 C2 – Sailing parameters

Ship	Capacity	Cargo handling	Approach / Depart time	Initial location	Scheduled start	Scheduled stop	Epoch size	Scheduled downtime	Sailing speed
	TEU t	Containers/h	h		day	day	days	days	knots
C2D1	106 2650	15	0.25 / 0.25	SAN	0	3.5	3.5	0	8

Table 3 specifies sailing parameters for the 110 TEU daughter ship. Just like C1 daughters, it is assumed that the 110 TEU daughter spends 15 minutes on approach and depart.

5 Input data for the case studies
The simulation study is based on a lot of underlying detailed data like cost, operational data for different equipment, weather conditions, road transport costs etc. This chapter presents this data in the following subsections, starting with costs, which are mainly divided into CAPEX and OPEX, as well as external costs.

5.1 Costs
This section covers cost inputs to SIMPACT and the road transport energy module. All costs are adjusted for inflation to $€_{2021}$. If a cost element is subscripted with the currency year, it means that for simulation it was adjusted for inflation.

5.1.1 Ship costs
CAPEX estimation for daughter ships has been based on modern commercial vessels of similar type and size, that are currently in operation or being developed. This information was obtained from numerous sources like the Significant Ships and Hansa magazines [20],[21]. In general, the CAPEX estimation depends on various factors, including costs for the materials used in constructing the vessel, such as the structure (mild steel, high tensile steel, aluminium), outfit (related to structure, cargo, accommodation, deck machinery), machinery (propulsion, auxiliary machinery, structure-related components), and special equipment (cranes, cell guides, etc.). Estimating labour costs involves considering the number of man-hours required for constructing the vessel. This includes hours spent on tasks like hull construction, machinery installation, outfitting, and related activities. Labour costs can vary based on factors like location, labour rates, and productivity. Overheads are additional expenses beyond direct material and labour costs. They include expenses like bank loans, rates and taxes, insurance, electricity, and salaries of managers and office staff involved in the project. Overheads contribute significantly to the overall CAPEX. General for both daughters are the autonomous systems. They will both need to be equipped with situational awareness, intelligent machinery systems, connectivity-equipment, and autonomous navigation systems, which are estimated to cost 600k€. The two robotic arms for auto mooring are estimated to 450k€.

The new build cost for the 110 TEU daughter vessel is modelled after the modern coastal trader "RHAS 5" from the Hanse Eco-Series [22]. The new building cost for "RHAS 5" is approximately €9 million. Propulsion is supported by an electric motor. For the estimation of the CAPEX of 110

TEU daughter vessel with fully electric propulsion, Investment in structure & outfit is estimated to €7 million. Investment in Energy Storage System (ESS) to €6.7 million. This estimate is based on the cost range of €500-700 per kW [23]. The ESS is a crucial component of the vessel's fully electric propulsion system. Investment in two azimuth thrusters: Approximately 600-750k€

The CAPEX of the 60 TEU daughter ship, is estimated from the cost of inland navigation vessels of the Johann Welker type. Based on current information, the new building costs for a Johann Welker vessel are approximately €2.75 million, with an estimated €1.75 million attributed to the hull costs [24], [25]. By adding to the hull costs, the costs of the propulsion system (approximately €650,000), and the ARS with ramp (approximately €2.5 million), the total costs would amount to approximately €4.9 million. Table 4 shows the rough CAPEX estimates for the vessel concepts. The CAPEX accounts for two sets of 4 containerized batteries for the ESS. This allows for one swapping location to always have a spare set for each ship.

Table 4 CAPEX elements for ships

Ship	Cost of new build	Cost of ESS with spares	Cost of key enabling technologies	CAPEX years of depreciation	CAPEX interest rate	CAPEX yearly according to (1)
	m€					
Daughter 60 TEU	4.9	13.4	1.05	25	5	1.37
Daughter 110 TEU	9.8	13.4	1.05	25	5	1.72

The investments are assumed to be linearly depreciated according to

$$CAPEX_{yearly} = i * \frac{CAPEX}{1-(1+i)^{-n}} \tag{1}$$

Where i is the interest rate and $CAPEX$ denotes the sum of all investments for a given ship. n represents the number of years of depreciation. The downpayment assumes zero residual value.

Both ships are subject to the same OPEX costs. Firstly, a general cost of 300k€ is assumed. AUTOSHIP deliverable 7.3 [26] evaluates changes in autonomous ship concepts OPEX and concludes that these are reduced crew costs, increased maintenance cost from boarding teams and Remote Operation Centre (ROC) costs. The costs related to boarding team is estimated to 155k€ per ship per year.

5.1.2 ROC costs

Costs related to ROC for monitoring and controlling autonomous daughter-vessels will be assumed as a 3rd-party service that imposes a yearly OPEX on the ship owner. J. G. V. Küchle et.al [27] identifies OPEX costs imposed on the ship-owner renting a ROC service. Assuming their cost model for a large-scale ROC service, the price per ship is estimated to 152.000$/year. For the case studies where autonomous ships are used, this cost is appended per ship in the transport-system.

5.1.3 Port costs

SIMPACT applies relevant port costs to ships when visiting locations. For this study, all locations are in Norway. The port call costs for all locations are therefore assumed to be the same. The port costs are based on a report by DNV GL from 2018 [28]. In the report, port costs from several different port jurisdictions of Norway are collected to form a national average for the different cost elements. The report states that shipping companies that frequently visit a port or operate within a certain jurisdiction may have agreements with the port operators for discounts on these different costs.

Table 5 Port costs for autonomous daughters in Trondheimsfjord

Country	Terminal costs	Cargo dues[b]	mooring and cast-off cost		Port dues[a]		Fairway dues[a]	
	(€/Container)		GT	€	GT	€	GT	€
Norway	53	17	2800	75	<=2000	140	<=2000	80
					3000	195	3000	120
			11500	380	4000	255	4000	165
					>=5000	300	>=5000	195

[a] Paid once every 24 hours
[b] Paid once within port jurisdiction

Table 5 shows the port costs as applied to all locations for the case studies involving the autonomous daughters. GT denotes the gross tonnage. Terminal costs are paid per container handled at location while cargo dues are paid once within a given port jurisdiction. The other cost elements are paid per port visit.

5.1.4 Charging costs
The swappable battery containers are charged on SAN. The base electricity price is based on Statistics Norway table *09364 Electricity prices in the end-user market* [29] for the year 2021. The average electricity price for the service segment is approximately 0.7NOK = 0.069€ which is used for simulation in the SIMPACT tool.

5.1.5 External costs
External costs are costs indirectly imposed on a third party because of transporting goods in the market. These costs include road congestion, accidents, air pollution and climate change to name a few. The market does currently not provide any incentive to account for external costs when choosing a transport mode. The 2019 handbook of external costs [3] argues the potential future external cost accountability as follows *"By internalizing these costs, externalities are made part of the decision making process of transport users. This can be done through regulation (i.e. command and control measures) or by providing the right incentives to transport users, namely with market based instruments (e.g. taxes, charges, emission trading, etc.)"*. New transport modes, such as the ones proposed in the AEGIS and AUTOSHIP projects could greatly decrease the external costs associated with transporting a piece of cargo. To assess and compare external costs, this analysis relies on the handbook of external costs [3] for data. Method for calculating externalities is taken from [12]. Since the Tank-To-Wake (TTW) GHG and pollutant emissions from battery-powered ships are negligible, the expressions are simplified. The total external cost difference is the difference between the external cost associated with shipping and the one associated with truck transportation. The handbook of external costs describes external cost coefficient $K_{ECtruck} = 0.028\ (€_{2016}/tkm)$ for Norway, while the Wake-To-Tank (WTT) coefficient for shipping $K_{WTT} = 0.0006\ (€_{2016}/tkm)$.

5.1.6 Road transport costs
The Norwegian public road administration has a series of handbooks it publishes regarding different aspects of national road transportation. Handbook V712 [30] presents an impact analysis of road transport.

Table 6 Road transport cost elements

Cost element	As listed NOK	Adjusted $€_{2021}$	Source
Cost per km	7.97	0.77	[30] Tabell 5-4
Cost per hour	791	76	[30] Tabell 5-17

In this handbook, both private and public costs of transportation is presented. Table 6 shows the cost elements for road transport. The cost per km used is the cost to a private actor operating a freight-trailer. The cost includes cost of fuel, oil, tires, and reparations. Similarly, the cost per hour is the privately incurred cost due to salaries, administration cost, garage cost and other time dependent charges.

A 2021 report from the institute of transport economics in Norway (TØI) estimates a terminal cost of 179 NOK/tonne pluss 171NOK/container for a transferred container including costs related to the time spent in the terminal for the truck. The cost per container includes costs related to stuffing and stripping of the containers, which is not relevant when transferring containers. This cost is estimated to 170 NOK/tonne. The terminal transfer cost is therefore calculated at 9 NOK/tonne pluss 171 NOK/container [31].

5.2 Machinery and equipment

The ARS on the 60TEU daughter is a conceptual RS. Therefore, the exact cargo handling rate from ship to quay is uncertain. Based on feedback from Kalmar on traditional equipment, it is assumed that it handles 10 containers per hour. The 110 TEU daughter is equipped with a gantry crane that can do 15 containers per hour, which is slightly slower than a traditionally operated gantry.

The battery containers need to be swapped when they are low on energy, and the swapping station is located at SAN.

5.3 Weather

The weather distribution used in C1 and C2 is produced from the MyWaveWam800m [32] data set from the Norwegian Metrological Institute. This set has 800m geographical and 1-hour temporal resolution, making it suitable for relatively sheltered waters as found in the Trondheimsfjord. A software to simulate ship operations [8] along the routes shown in Figure 5 has been used to aggregate encountered weather data for the year 2021. The resulting weather applied in C1 and C2 are shown in Table 7. When running energy-estimation for a ship sailing a voyage in SIMPACT, the % time spent parameter aggregates the results of the energy-consumption of the different weather profiles into one energy-consumption for the ship. This is described in more detail in [2].

Table 7 Wind profile for simulation

% time spent	hs (m)	Wave direction (°)	Peak wave period (s)	Wind speed (m/s)	Wind direction (°)
25	0.23	-135	2.78	4.53	-135
25	0.23	-135	2.78	4.53	135
25	0.23	135	2.78	4.53	-135
25	0.23	135	2.78	4.53	135

5.4 Road transportation

For the base case, all transport work is performed by trucks. As described in section 2.2, there are several input parameters necessary to simulate a truck voyage. There are several different trucks that could potentially pick up a container at port. This study considers a single truck of the type Volvo FH-500 D13K500 [33]. It is a Euro 6 truck with a diesel engine managing 368kW (500hp). It has a 375kW engine braking power. The globetrotter type cabin has a front area of around 8.3m^2 [34], furthermore, it is assumed a 2kW AUX load to accommodate for all consumption not related to the powertrain such as AC, lights and other driver comfort systems.

A single truck can haul two 20' containers each. Considering the simplified cargo flow presented in section 4 specifying that full containers weigh 25t each, the maximum haul weight on a single trip for a single truck is 50t, while the minimum haul weight is 4.4t.

6 Results and discussion

The results in this section is the output of running the case studies from section 4 through the method presented in section 2, given the ships from section 3, and the input data from section 5. The results are split into two categories: logistical and cost. Logistical KPIs compare results between the concept studies and the respective ships. Cost KPIs also include results from simulations in the road transport module.

6.1 Logistical KPIs

Figure 7 to Figure 9 shows the tonnage and TEU capacity utilization for the different concept daughter ships for every leg of a voyage. Each datapoint in the boxplot is the utilized capacity for that respective ship on a single voyage. One box represents the yearly performance for that ship. The X marks the average utilization. The results for the C1 daughters show that C1D1 travel full from SAN at the start of each voyage, while C1D2 travels with lighter containers at 30% capacity. These results indicate that C1D1 picks most of the shipments from SAN, while C1D2 is better utilized later in the route, due to having more available capacity to pick up shipments at later locations. The 100TEU ship will always transport all pending orders from all locations. C1D1 and C1D2 have an average capacity utilization across all legs of respectively 88% and 59% in terms of TEU, and 75% and 31% in terms of tonnage. C2D1 has an average utilization of 78% in terms of TEU, and 57% in terms of tonnage. In all, C1D1 is well utilized, while C1D2 has some more residual capacity, that could be used in picking up larger order size variations without having an impact on the lead time. C2D1 has a very high TEU utilization throughout each voyage, leaving less room for order size variations. All in all, C2 is better utilized than C1.

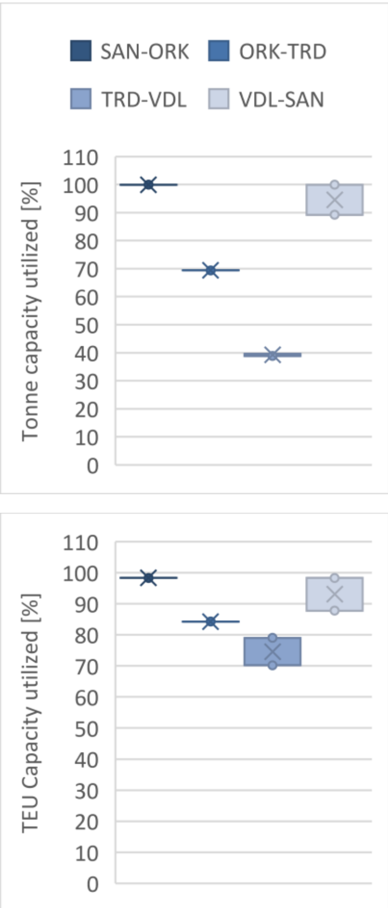

Figure 7 Utilization C1D1

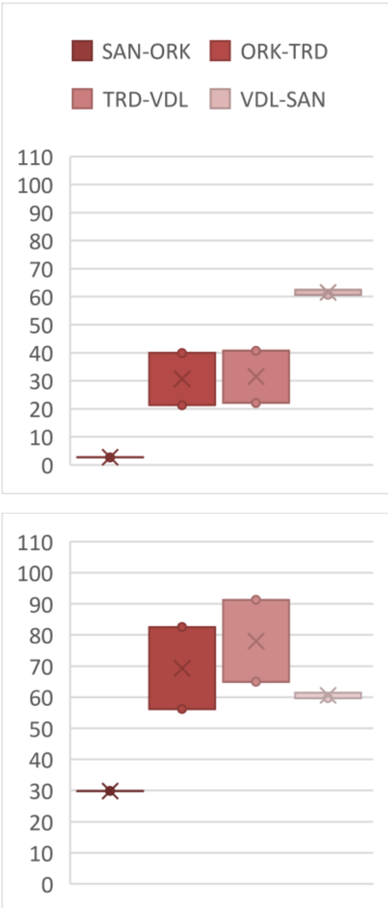

Figure 8 Utilization C1D2

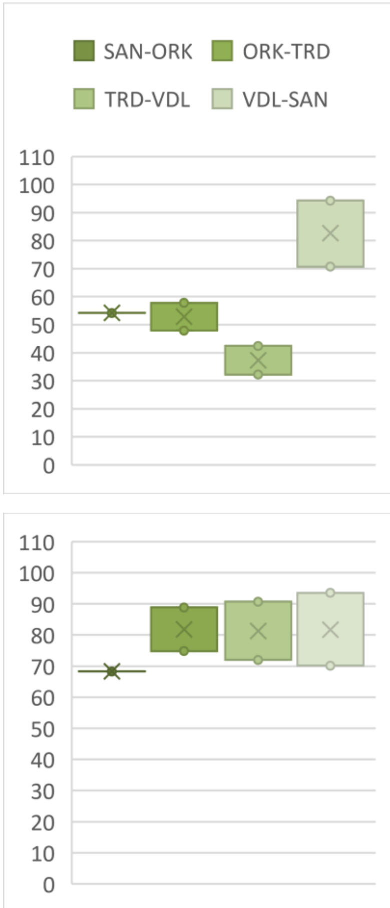

Figure 9 Utilization C2D1

Figure 10 shows the timeliness of each ship from the LA tool simulation. It shows that all ships are well ahead of their respective schedules, with all ships having an average timeliness of around 30 hours. This rather large downtime ensures robustness of the results, as there are uncertainties connected to the exact performance of the cargo handling systems, and as unplanned downtime is not modelled in the simulations. Another perspective on high timeliness is the possibility of taking on ad-hoc cargo and making additional port calls along the route, and the possibility to add a weekly roundtrip for handling growth in transportation demand, though the latter might imply increasing the sailing speed somewhat. By having this spare time, we therefore also ensure that cost estimates are conservative.

SAN, being a transshipment terminal between Trondheimsfjorden and short sea ships along the coast is a central location for the study. Lead times for the containers from this location to the other ports in the fjord are shown in Figure 11. C2 is able to transfer all shipments within a day of arrival at SAN. This is comparable to what would be expected with truck transportation. The lead times, however, increase significantly with the C1 concept as the capacity of the ships is smaller than for C2. For the case of SAN-VDL the difference becomes over three days. This is because some of the containers that arrive with the mothership on the first day of the week must wait until the second daughter picks them up. Figure 12 shows the lead time for all cargo going with the daughters to SAN. In contrast to the lead time for orders coming through SAN and into the fjord, C1 performs better in terms of lead time for orders leaving the fjord. This is due to the two daughters serving the locations at a higher frequency than the single daughter in C2.

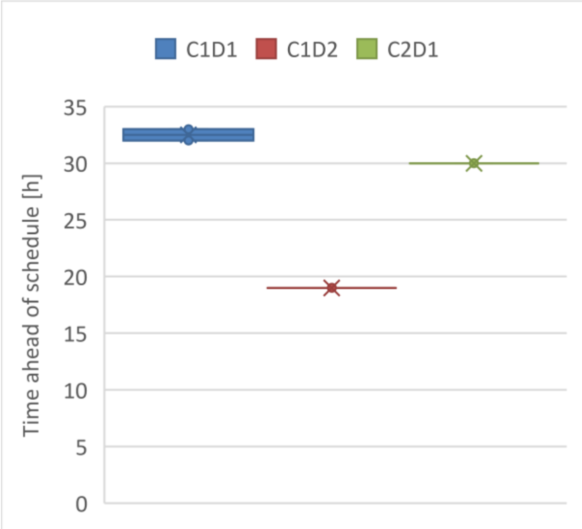

Figure 10 Daughter timeliness

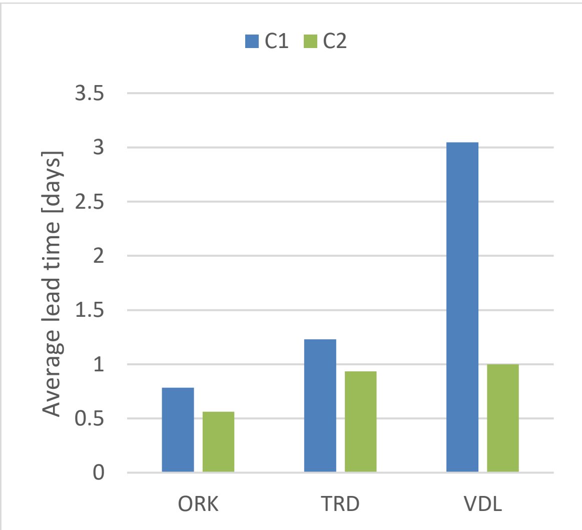

Figure 11 Lead time comparison from SAN

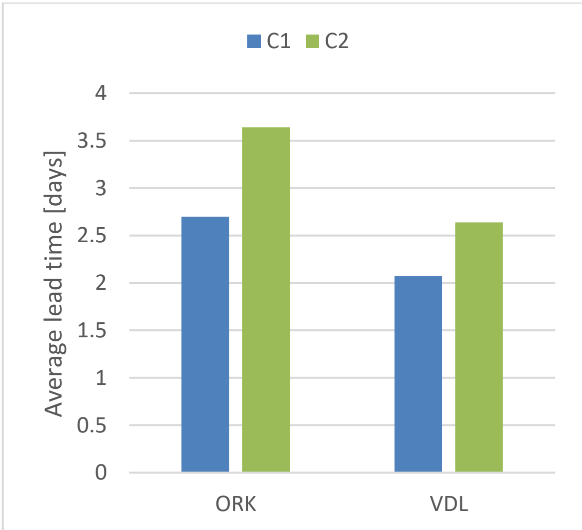

Figure 12 Lead time comparison to SAN

Since the results show averages throughout a year of operation, and the lead time for C1 for goods going to SAN is below the half week frequency of the motherships, it is expected that the C1 daughters will be able to serve the motherships in time for departure, meaning it would be inconsequential in terms of lead time if the daughters were used, or the goods travelled on truck. For C2 there will be some cargo through a year that will arrive at SAN after the motherships depart, and therefore must wait half a week for the next departure.

SIMPACT also outputs the battery energy consumption for each ship in the simulation. This output is for a single voyage. All battery-charging is performed in SAN, which is the first and last location on the ship's voyages. Figure 13 shows the discharge-curve for C1 and C2. C1 is represented through C1D1 since it has the heaviest average cargo load in terms of tonnage on its route, leading to a deeper draught and higher energy consumption. SIMPACT allows the ships to enter negative battery-charge. C2 is discharged outside of its battery capacity on the last leg of the voyage. It is also observed that C1 daughter uses most of its battery charge on its voyage. Since batteries typically should not be fully depleted of its charge, there is a need to either charge the batteries at e.g. TRD where there are plans to install charging facilities [35]. This implies that the port stay at TRD would increase by some hours, but according to Figure 10 there is available time in the schedule of all ships for this.

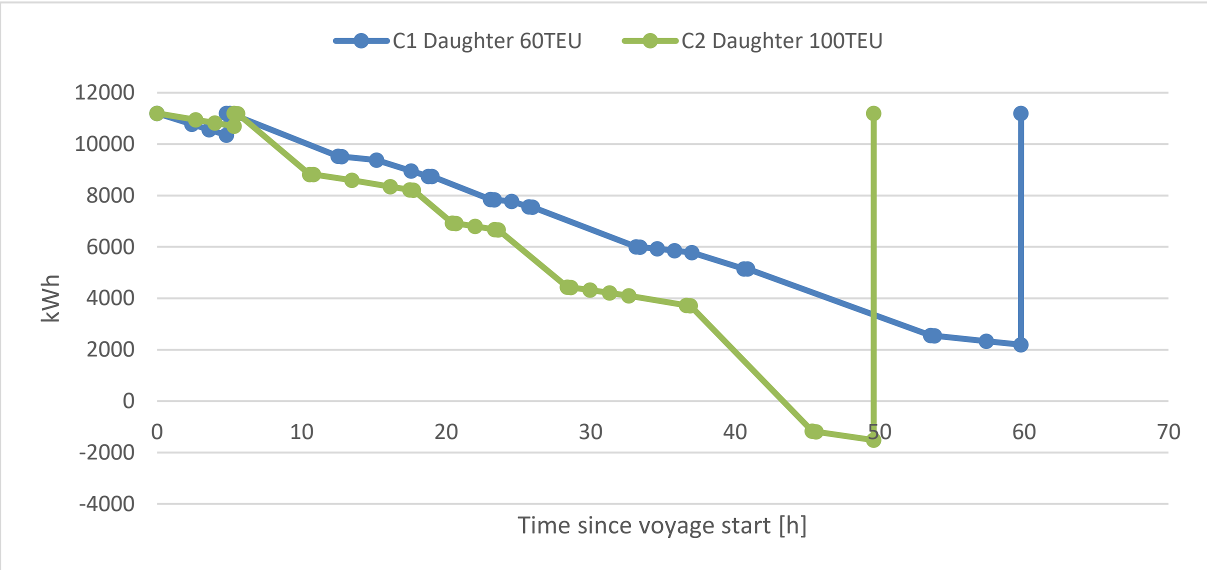

Figure 13 Battery energy consumption

6.2 Cost KPIs

When analysing the simulation results for the case studies, the focus has been on comparing the costs between the cases, C1, C2 and BC. Figure 14 compares the yearly cost outputs from SIMPACT for the concept cases, to the output of the road transport energy estimation module for the BC. Cargo dues and terminal costs from the port cost scheme in Table 5 have been separated from the rest of the yearly port cost elements since they are dependent on the amount of cargo transported, and typically forwarded to the end customer. Naturally, the CAPEX and OPEX cost elements are higher for C1 since it includes two ships. Both C1, C2 and BC are performing the same transport volume in terms of containers carried per year. Here we observe higher port costs for performing the same transport volume with the smaller C1 daughters. Port cost elements directly imposed on the visiting ships like fairway dues are higher when performing the transport work with the smaller ships.

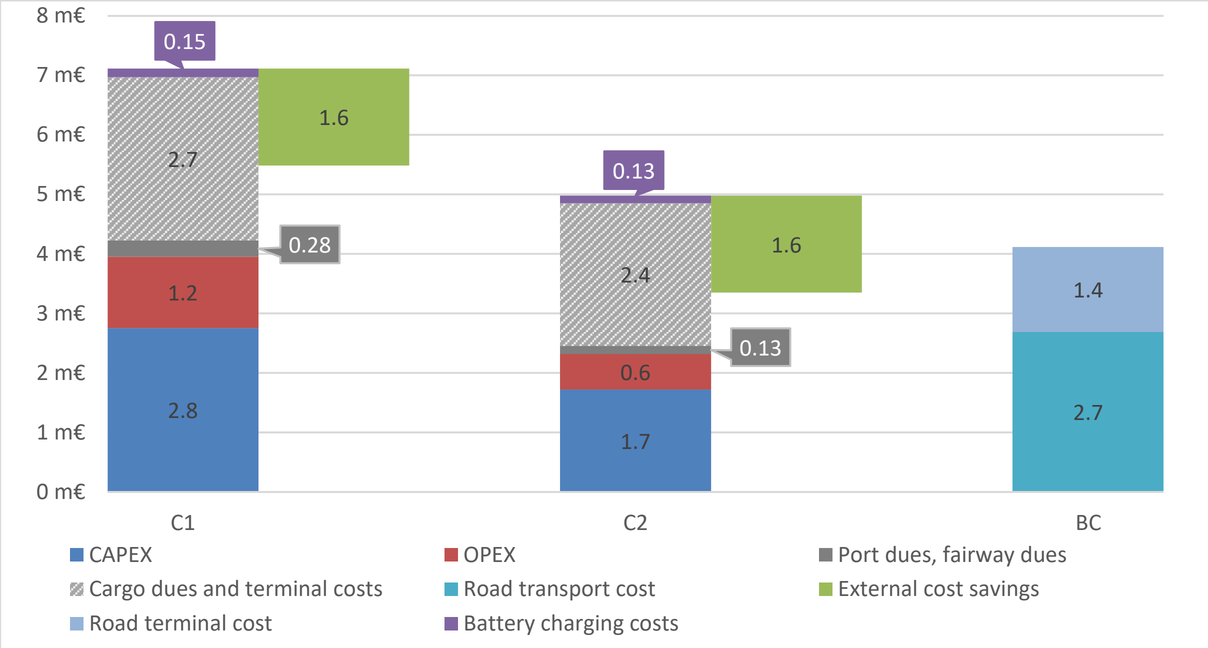

Figure 14 Yearly costs

Both concepts replace the same amount of road transport work while not adding a lot of external costs themselves, leading to the same external cost benefits for both solutions. Charging costs for the battery containers are higher for the C1 daughters, but neglectable. Each daughter is equipped with the same number of battery containers, but C1 spends more energy per year on operating the two ships. Overall, there is a business case for both concepts. The results indicate that C2 is the most competitive solution, and if external costs are internalized through subsidies, even able to compete economically with trucks. Such subsidies are feasible, considering that the studied case is comparable to the ASKO ferries and the Yara Birkeland who received funding by ENOVA of respectively 112 mNOK and 134 mNOK for realizing zero-emission transportation [36], [37].

There is also a strong case to be made in that the new transport modes could be cheaper with new port cost models. Truck transportation pays no cargo dues and has low terminal costs per container compared to ships today. Since the autonomous daughters are equipped with their own handling systems, there is room for reduced terminal costs through new cooperative models between the ship owners and the port owners. Furthermore, any reduction in ship terminal cost could be balanced by introducing a gate fee for trucks.

7 Conclusion

This paper analyzes logistics and cost KPIs for two new transport system concepts based on autonomous daughter ships in Trondheimsfjorden and compares them to conventional truck transportation. First a presentation of the tools used as a method for simulating the transport systems is presented. Next, the innovative new autonomous daughter ships are presented to provide the details needed for modelling the ships in the simulation tools. The three case studies are then presented. The base case (BC) uses trucks to perform the transport work. The first concept case (C1) uses 2 smaller autonomous daughter ships to perform the transport work, while the second concept case (C2) uses one bigger autonomous daughter. Then, the detailed simulation input data for cost, machinery and environment is presented. Finally, results are presented with a discussion on how the different case studies perform in terms of the defined KPIs.

The results show that the case study C2 (one large autonomous daughter) is the preferable option. It results in a significantly lower transportation cost than C1 and has a comparable performance in terms of lead time as C1. It should be noted that though C2 has lower lead times on cargo outbound from Sandstad than C1, it is a higher lead time for cargo inbound to Sandstad causing some occasions of cargo having to wait for the next mother ship. The results also find that the realization of both C1 and C2 depends on the establishment of a charging service in Trondheim, which is considered feasible given ongoing initiatives.

Comparing C1 and C2 to the BC truck transportation, we find that 1) although trucks have a lower lead time, the impact is low as the mother ships only calls to Sandstad twice a week. 2) only C2 is competitive with trucks in terms of cost. Although the analysis find that C2 has a slightly higher total cost than the trucks in BC, it was shown that the external cost impact is significant, and that if internalized, C2 would be the preferable option. Furthermore, internalization of external cost reduction by launching zero-emission transport options have been observed in recent years in Norway, exemplified by the ASKO ferries who received 112 million NOK and the Yara Birkeland that received 134 million NOK, for reducing emissions.

It is also observed that the terminal costs made up a significant portion of the daughter ship costs, and that current terminal cost policies should be revised to reduce the competitive disadvantage that this poses for ships. Reduction of terminal costs for ships and the introduction of port fees for trucks could be a way forward for supporting policies targeting transportation mode shifts from road to water.

A limitation of the study is that it did not consider the full transport system including the motherships. This means that the lead time end-to-end, which would capture issues such as containers having to wait for the next mothership, was not quantified. Instead, an evaluation of the lead time from Orkanger and Verdalen to Sandstad was done, and it was found that C1 mainly deliver containers to Sandstad in time to make the same mother ship as for the case of transport with trucks, while it is probable that for C2 there will be some occasions where some containers reach Sandstad too late to make the same mother ship as for truck transport.

Another limitation is that the study assumed that all containers moved between the locations of the study were either moved by ships or by trucks. It would be interesting to investigate the performance of a transport system that includes both daughter ships and trucks. This would allow for a higher average utilization of the ships, without severe lead time impacts.

8 Future work

Although the first initiatives for realizing small autonomous battery powered ships are already found in Norway, and their commercial viability has been established, the potential for such transport systems are possibly even higher in areas such as the inland waterways of central European countries. This is because the cargo volume as well as the potential external cost savings are higher [3]. The need to decongest the roads is also imminent, providing a strong incentive. The impact on emissions and other external costs of realizing a large-scale inland waterways network, operated by small autonomous zero-emission vessels, would be significant. Studies on larger transportation systems operated by smaller autonomous inland vessels, potentially like the AEGIS daughter ship designs, should therefore be conducted to provide quantitative estimations of the potential impact of realization.

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