Autonomous ship concept evaluation – Quantification of competitiveness and societal impact

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Abstract. The prospect of large-scale international adoption of autonomous ships has led to expectations of reduced costs and emissions for waterborne transport of goods. This is commonly attributed to the possibility of removing manning from the ship, which enables more efficient ship designs and reduced operational costs. So why have we not seen a multitude of autonomous ship building projects? There are several reasons for this, including immature technology and regulations. However, there is another reason which has received less attention; the lack of quantifiable evidence for the benefits arising from investing in autonomous ships. There are some case studies on the impact of autonomy on transport cost, but there is no established method for evaluating the effects of an investment in autonomous ships. This paper will present Key Performance Indicators (KPIs) developed to enable such quantification. Furthermore, the developed KPIs are chosen not only to enable quantification of benefits but also to be calculable based on data which it is reasonable to assume that are available or obtainable at a concept stage.

1. Introduction

The EU has had a long-standing goal of shifting transportation of cargo from road to rail and water [1]. This is a result of the high societal costs caused by road transportation through accidents, congestion, pollution, health impact and other negative side effects, estimated to 820 billion Euro for the EU28 countries in 2016 [2]. The total external cost of transportation was estimated to be 987 billion Euro in 2016, where 31% of these costs are caused by freight transportation [2]. Unfortunately, to date, no development towards a shift of cargo flows from road to waterborne or rail transport is observed [3], [4].

We believe that a key reason for this failure is that investments needed to set up an alternative to road transport are too high. This when considering that the alternative must meet the customers' key demands to the transportation service (e.g., lead time and shipment frequency), at an equal or lower cost, to be competitive. There is hence a need for increasing the competitiveness of alternative transport modes, such as waterborne transport.

New concepts such as autonomy are expected to increase waterborne transport competitiveness by opening for new ship- and transport system concepts [5], [6], [7]. Still, the impact of such novel concepts on competitiveness needs more studies [8], [9], [10]. Such studies need methods for quantifying the impact of new ship and transport system concepts on competitiveness. Furthermore, some concepts may prove to yield insufficient in terms of competitiveness, but still give significant societal benefits. In such cases it is conceivable that the would-be investors could obtain subsidies from public financing programs, provided that the societal benefits can be quantified. An example is the construction of the Yara Birkeland, which will remove 40,000 truckloads annually. The construction cost for the ship is estimated to 250 million NOK and the Yara Birkeland project was supported by the Norwegian Government agency ENOVA by a 133.6 million NOK grant [11]. The grant was given due to an estimated reduction of 772 ton CO_2 equivalent emissions annually [12]. It should be noted that the reduction in CO_2 equivalent emissions is mainly a result of the ship being fully electric. It should also be noted that the estimated construction cost is for the construction contract with the yard VARD. This means that other investments, such as infrastructure for charging, cargo handling, etc., is not included in the estimated 250 million NOK.

Much is written about definitions of MASS and levels of autonomy; this is not a debate that we will visit in this paper. However, for the purpose of discussions in this paper we consider a MASS to be a ship without crew and which is supported by a Remote Control Center (RCC) and automatic facilities services as shown in Figure 1. Automatic facilities services are the services that are required to support the operations of a MASS and examples are connectivity, auto-mooring and automated cargo handling. A formal definition of automatic facilities services is given in [13].

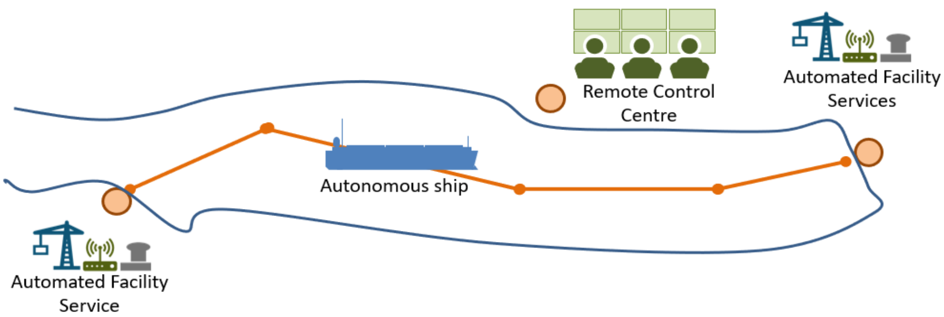

Figure 1. The autonomous ship, RCC, and Automatic Facilities Services. The figure is taken from [14].

The structure of this paper is: First, we present our method in section 2, followed by the results in section 3. The results are organized as KPIs and calculation methods for competitiveness evaluation in subsection 3.1, and for societal impact evaluation in subsection 3.2. An example of how two of the most central KPIs can be calculated is given in section 4. Finally, we discuss the results and conclude the paper in section 5.

2. Method

This article is mainly based on the work conducted within the AUTOSHIP project [15]. The AUTOSHIP project has two demonstration cases, one covering inland water ways shipping and one covering short sea shipping. Both demonstration cases are based on ships that are in operation today, and the project will upgrade these ships and demonstrate autonomous operations with them. The project has mapped the supply chains of both use-cases and identified the involved stakeholders [16]. Moreover, we have performed an analysis of the stakeholders that are involved in investments in autonomous ships, and their main objectives for- and rationale behind such investments [17]. The identified objectives may hold a somewhat different meaning for the different stakeholders. As a result, the different stakeholders may also evaluate whether their objectives are met, differently. We have approached this problem by dividing the main questions "is my objective met/is this a rational decision" into more precise sub-questions capturing what each stakeholder wants to verify when assessing the investment at hand. We then created KPIs to represent quantitative answers to said questions.

As an example of this approach consider the objective *Reliability* and which questions must be answered to demonstrate a concept's achievement of this objective. The following are some examples:

- How does a specific investment or set of investments impact the ability to keep slot times, delivery times and pick-up times?
- How much of the time is the solution operational?

These sub-questions can be answered quantitatively by defining KPIs. The necessary calculation formulas for evaluating the KPIs were also derived. This enabled us to define input parameters for the KPI calculation and evaluate if the KPI could be calculated at a concept stage or not, by applying the following criteria:

- The KPI must be possible to calculate based on data that is likely available at a concept study stage or,
- The KPI must be possible to estimate based on data that is generated by some model, where the input data to the model must be available at a concept stage or,
- The KPI must be possible to estimate based on data that is produced by some simulation tool, and the simulation tool can only depend on input data that is available at a concept stage.

3. Results

The evaluation of an investment in a MASS should first and foremost evaluate the competitiveness of the considered transportation service. In addition, it should be evaluated if the considered investment will give significant societal benefits as this could result in obtaining subsides, potentially balancing the cost-benefit assessment result. In the following we will give KPIs for evaluating competitiveness and societal impacts.

3.1. KPIs for competitiveness

Competitiveness is about meeting the customers' demands to the service, and about cost. If we consider the view of a transportation service customer, it is not that important how the transportation provider implements the service if it meets certain demands and is cost competitive. Therefore, it might not be important for the customer whether the transport is by road, sea, rail, or a combination, if the alternatives perform equally in terms of the customer criteria for the service. It is therefore important to be able to evaluate the transportation service performance for typical customer criteria, and a business case for investing in MASS should quantify the impacts of the investment on the customer demands to the service, including costs.

So, what do we know about customer demands to transportation services? In [17] we studied the customer objectives, and suggested the following customer demands as being most important: Reliability, flexibility, and cost. In the following we will give our definitions of KPIs and show how they can be estimated.

3.1.1. Reliability. Reliability, in short, is about on time deliveries and pickup. We have defined KPIs that can express these factors and a common denominator for these KPIs is that their estimation requires supply chain analysis. In the following we will give the KPI definitions, and briefly discuss how they can be estimated.

The estimation of on time delivery or pick-up can be done by estimating delays. If the number of delays, and duration of delays during a given time are estimated, delays can be measured by two KPIs; the average duration of delays ($\overline{t_{\mathrm{d}}}$), and the percentage of deliveries (or pick-ups) that are delayed P_{d}:

$$\overline{t_{\mathrm{d}}} = \frac{\sum t_{\mathrm{d}}}{n_{\mathrm{d}}} \tag{1}$$

$$P_{\mathrm{d}} = \frac{n_{\mathrm{d}}}{n} 100\% \tag{2}$$

where t_{d} is the duration of each delay, n_{d} is the total number of delays, and *n* is the total number of either deliveries or pick-ups.

To estimate the duration and number of delays, it is necessary to analyze the supply chain. This can be done through simulations where the transportation need is modelled along with the terminals, cargo handling, transporters, and factors disrupting the transporters. In [18] we presented a simulation method and models intended for this purpose. When such simulations are conducted, it is possible to detect delays, measure their durations and frequency. The simulations will be based on a schedule, and on scenarios for weather or other environmental or stochastic conditions influencing operations and causing delays. It will be necessary to simulate over a considerable time to get good estimates.

3.1.2. Flexibility. Possibly the main competitive edge of trucks is flexibility. They can transport small quantities on one truck, and large quantities by several trucks. They have relatively short lead time, high frequency of delivery, and can reach almost any destination which are connected through land or ferry. To evaluate competitiveness in terms of flexibility, we therefore define the KPIs frequency, lead time, and ship capacity utilization. These KPIs can be estimated through the same type of supply chain simulations as discussed for the reliability KPIs and given in [18]. Lead time can be estimated by measuring the duration from when a cargo unit enters the supply chain until it exits the supply chain, frequency by measuring the number of shipments over a time period, capacity utilization by measuring the ship capacity utilization for each simulated voyage.

3.1.3. Transportation cost. Probably the most important factor for determining the competitiveness of a service is the cost of the service. For transportation, the customer is interested in comparing the total cost of transporting their goods between certain origin and destination points. With the lack of new business models related to the introduction of autonomous shipping [19], we have decided to exclude the profit element from our cost definitions, thus focusing on the actual cost of transporting a certain cargo unit between a start and end point. Such transportation can be done either by one transport mode only or by an intermodal transportation chain. If the customer compares two transport services, where one service provider transports the goods by truck between the two points and the other transports the goods by a combination of MASS and truck between the same two points, both the MASS and truck transportation costs must be included in the latter case. However, as we have identified a need for extending the knowledge on the impact of MASS on competitiveness, transportation by MASS will be the focus of the more detailed discussions of cost estimation in this paper.

The transportation cost KPI is therefore taken to be the cost of transporting one cargo unit between an origin and a destination. This is similar to the *Unit Cost* as given by [20], which is the sum of costs (including repositioning costs) divided by the parcel size. The *Unit Cost* is an estimate of the cost of transporting one unit of a certain cargo type for a certain ship. As we are interested in estimating the cost per transported unit between certain points, including all transportation legs (for example truck or MASS transportation legs), we adapt the *Unit Cost* and define the transportation cost KPI *cost per unit* C_{pu}:

$$C_{\mathrm{pu}} = \sum_{i=1}^{n} \frac{C_{\mathrm{leg},i}}{n_{\mathrm{units},i}} \tag{3}$$

where $n_{\mathrm{units},i}$ is the number of units at leg i, and $C_{\mathrm{leg},i}$ is the sum of costs for transportation leg i, including the costs associated with the transfer of cargo between transportation legs.

To estimate $C_{\mathrm{leg},i}$ it is necessary to include all costs related to owning and operating the transportation service. For ships, we find a well-established cost categorization in [20]: Operating costs, periodic maintenance, voyage costs, capital costs, and cargo handling costs. For MASS, we suggest a slight adaptation of some of the cost categories to account for the differences between MASS and conventional ships. The following definitions are taken from [20] and our changes are highlighted by using *italic* font for changed text and […] for omitted text which can be found in the source for interested readers:

- Operating costs, which constitute the expenses involved in the day-to-day running of the ship – essentially those costs such as *remote-control center, insurance, and maintenance by boarding crews*, that will be incurred whatever trade the ship is engaged in.
- Periodic maintenance costs are incurred when the ship is dry-docked for major repairs, usually at the time of its special survey. […]
- Voyage costs are variable costs associated with a specific voyage and include such items as *Automated Facility Services (AFS)*, fuel, port charges and canal dues.
- Capital costs depend on the way the ship has been financed. They may take the form of dividends to equity which are discretionary, or interest and capital payments on debt finance, which are not.
- Cargo-handling costs represent the expense of loading, stowing, and discharging cargo. They are particularly important in linear trades.

These cost categories can be sorted into two higher level categories; costs which are incurred because of performing the freight work (voyage costs and cargo-handling costs), and costs which are incurred independently of performing freight work (operating costs, periodic maintenance, and capital costs). While the former can be calculated per transportation leg performed by a ship or a MASS, the latter is more conveniently estimated as annual costs and divided amongst performed transportation legs during a year, based on the relative duration of performing each transportation leg. This gives the following definition of C_{leg} for conventional ships and MASS:

$$C_{\mathrm{leg},i} = C_{\mathrm{VOYEX},i} + C_{\mathrm{CH},i} + \frac{(C_{\mathrm{CAPEXyear}} + C_{\mathrm{PM}} + C_{\mathrm{OPEX}})t_{\mathrm{leg},i}}{t} \tag{4}$$

where $C_{\mathrm{VOYEX},i}$ is the voyage cost of leg i, $C_{\mathrm{CH},i}$ is the cargo-handling costs of leg i, $C_{\mathrm{CAPEXyear}}$ is the annual capital costs, C_{PM} is the annual periodic maintenance costs, C_{OPEX} is the annual operational costs, t is the duration of all performed transportation legs in a year, $t_{\mathrm{leg},i}$ is the duration of the transportation leg i.

At a concept stage, some of these costs are not immediately available, and some of the required data must be generated. We will discuss the cost items C_{CAPEX}, C_{OPEX} and $C_{\mathrm{VOYEX},i}$ in some detail, while the estimation of $C_{\mathrm{CH},i}$ and C_{PM} can be found in [20].

Estimating the cost of acquiring a ship is not straightforward. Historically, the newbuild and second-hand market are both highly volatile due to immense variations in supply and demand [20]. It is possible to create regression models for estimating new-building costs of conventional ships within different market segments, however, it should be noted that one must take great care and consider the current and projected market situation and adjust such estimation results accordingly. Estimating the new build cost for a MASS is even more challenging as the only MASS built to date for commercial trade, is the Yara Birkeland [21]. It is built for operating manned initially, and then to gradually transition into autonomous operations. Though the estimated construction cost of the Yara Birkeland is published [11], it is as much a research and development project as a commercial project, and hence, the Yara Birkeland estimate is hardly representative for the cost of future MASS construction.

Some studies have suggested that construction costs will be comparable to that of conventional ships [5], so an option is to assume a certain percentage of the cost of a corresponding conventional ship. Another option is to use what we know and develop a cost model. Both options imply significant uncertainty, and it remains to see which will give the best estimates. We have chosen to develop a cost model based on a regression model of conventional ship newbuild costs. Based on 474 general cargo and container ships, the SATS project [22] have developed the following cost estimation formula (in million Euro) for new builds of conventional ships:

$$C_{\mathrm{CAPEX}} = (0.0053 - 0.0000001DPL)(0.8LDT + 0.2PWR) \tag{5}$$

where DPL is the displacement of the ship in ton, LDT is the ship lightweight in ton, and PWR is the installed power in kW. Equation (5) for estimating C_{CAPEX} will capture some of the cost differences between MASS and conventional ships. Namely reduced steel weight and reduced energy consumption. However, other differences such as technology for MASS, increased redundancy in systems, and costly machinery requiring low maintenance, are not captured. One would therefore need to adjust the estimate by adding these factors:

$$C_{CAPEX} = (0.0053 - 0.0000001DPL)(0.8LDT + 0.2PWR) + C_{\mathrm{tech}} + C_{\mathrm{M}\delta} \tag{6}$$

where C_{tech} is the total additional technology and redundancy cost, and $C_{M\delta}$ is the additional cost for non-conventional machinery. The additional machinery cost can be estimated by:

$$C_{\mathrm{M}\delta} = PWR(k_{\mathrm{M}} - k_{\mathrm{convM}}) \tag{7}$$

where k_{M} and k_{convM} are factors converting installed power to Euro, respectively for the installed machinery and a conventional machinery. One source for these factors is found in table 1 of [23]. Note that this source provides the factors in USD. Also note that C_{CAPEX} in equations (5) and (6) is the estimated investment cost and must be converted to an estimated yearly cost of the investment $C_{\mathrm{CAPEXyear}}$ before $C_{\mathrm{leg},i}$ is estimated in equation (4).

Automated facility services (AFS) will give rise to additional costs for MASS compared to conventional ships. Depending on the situation for each case that is under evaluation, they may be part of the MASS investment, or considered to be available services at a charge, for example per usage or per year. Most AFS are resources that could be used by several autonomous ships, in some cases even conventional ships. Considering that the conventional versions of some AFS (like cargo handling) often is a per usage cost, we include AFS in the estimation of voyage costs. The estimation of voyage costs is given in [20] as:

$$C_{\mathrm{VOYEX}} = C_{\mathrm{fuel}} + C_{\mathrm{PD}} + C_{\mathrm{TP}} + C_{\mathrm{CD}} \tag{8}$$

where C_{fuel} is the fuel cost, C_{PD} are the port costs and light dues, C_{TP} are the costs related to tugs and pilotage, C_{CD} are canal dues. For MASS, we add the cost from the AFS that are utilized during the voyage C_{AFS}. The VOYEX cost estimated in [20] can therefore be updated to:

$$C_{\mathrm{VOYEX}} = C_{\mathrm{fuel}} + C_{\mathrm{PD}} + C_{\mathrm{TP}} + C_{\mathrm{CD}} + C_{\mathrm{AFS}} \tag{9}$$

If we consult the estimation of operational costs in [20], we find that for a conventional ship it can be estimated as:

$$C_{\mathrm{OPEX}} = C_{\mathrm{M}} + C_{\mathrm{ST}} + C_{\mathrm{MN}} + C_{\mathrm{I}} + C_{\mathrm{AD}} \tag{10}$$

where C_{M} is the crew cost, C_{ST} is the cost of stores and consumables such as lubricants, C_{MN} is the cost of maintenance and repairs, C_{I} is the cost of insurance, C_{AD} is the cost of administration and general costs. For MASS we can adjust this to:

$$C_{\mathrm{OPEX}} = C_{\mathrm{RCC}} + C_{\mathrm{MN}} + C_{\mathrm{I}} + C_{\mathrm{AD}} \tag{11}$$

where C_{RCC} is the annual cost of the RCC and replaces the cost of crew (C_{M}), C_{ST} is removed as stores are related to the presence of crew, and as it is expected that MASS will depend on less maintenance intensive machinery and as such consume considerably less consumables such as lubricants. For MASS C_{MN} should also include an estimated cost for required technology upgrades and maintenance. There are some available sources for estimating the cost items of C_{OPEX}, [20] being one such source. However, the cost items C_{RCC} and C_{MN} for autonomous ships are less discussed in existing literature, though one source for estimating these is [5].

3.2. KPIs for societal impact

Some investments in transportation services may have considerable impacts on the society by bringing down external costs. The main categories for external costs of transportation in Europe are accidents (29%), congestion (27%), air pollution (14%), climate (14%), noise (7%), well to tank (5%) and habitat damage (4%), [2]. If we compare road transportation to waterborne transport, we find that accidents, congestion, noise, and habitat damage related costs would be more or less eliminated if a waterborne transportation service option is chosen over road transport (though inland water ways do cause some minor costs related to accidents and habitat damage). We can also see that the main external costs of waterborne transportation are from air pollution, climate (GHG emission), and well-to-tank (the external costs related to supplying the ships with fuel).

Based on this we define the KPI EC_{δ} for evaluating the annual impact on external costs from an investment in MASS that would reduce truck transport:

$$EC_{\delta} = Lk_{\mathrm{ship}} + L_{\delta}k_{\mathrm{truck}} \tag{12}$$

where L is the yearly ship transport in ton-km, L_{δ} is a negative value representing the yearly reduction in truck transport resulting from the introduction of the ship and is given in ton-km for HGV (heavy goods vehicle), and vkm (vehicle kilometer) for LCV (light commercial vehicle), k_{truck} is the factor converting ton-km or vkm to external costs in Euro, k_{ship} is the factor converting ton-km to external costs of ship transport in Euro. Notice that L_{δ} is a negative value because it represents the reduction of truck transport, and that a negative value of EC_{δ} means that the shift of transportation from road to sea gives a reduction in external costs, corresponding to the negative value of EC_{δ}. The factors k_{ship} and k_{truck} are found in [2]. The way of estimating EC_{δ} in equation (12) would give the difference between average external costs of truck transport and waterborne transport. If we instead want to investigate the difference between average external costs of truck transportation and the external costs of a specific MASS transportation service concept, we can estimate EC_{δ} as:

$$EC_{\delta} = L_{\delta}k_{\mathrm{truck}} + CO_{2\mathrm{eq,TTW}}k_{\mathrm{CO_2}} + \sum_{i=1}^{n} P_i k_i + Lk_{\mathrm{w2t}} \tag{13}$$

where $CO_{2\text{eq,TTW}}$ is the tank-to-wake emitted CO_2 equivalents in ton per year for the ship concept, k_{CO_2} is a factor converting ton CO_2 to external costs in Euro, which is set to 100 in [2], P_i is air pollutant i in kg per year for the ship concept, and k_i is a factor converting pollutant i to external costs in Euro. Values for k_i can be found in table 14 of [2]. L is the yearly MASS concept transport in ton-km, and k_{w2t} is a factor converting ton-km to the cost of well-to-tank in Euro. In [2] k_{w2t} is set to 0,001 for average IWW vessels, and 0,0006 for average maritime freight ships.

It should be noted that the estimated average societal cost of well-to-tank emissions for ships in [2] is given as a function of ton-km. Which means that the estimates are independent of the fuel type and amount of consumed fuel. Which makes the estimate rough, and independent of the specific ship concept. It is however stated that GHG emissions contributes to 60-65% of the well—to-tank external costs. As can be found in [23], the well-to-tank GHG emissions varies considerably for various fuel types. In fact, new fuel types that are currently being researched as means to reduce global warming are estimated to produce well-to-tank GHG emissions ranging from 0 to 30 times as much as for more traditional maritime fuels. EC_δ can therefore be adapted to better capture the change in external costs for the specific ship concept as follows:

$$EC_\delta = L_\delta k_{\text{truck}} + (CO_{2\text{eq,TTW}} + CO_{2\text{eq,WTT}})k_{\text{CO}_2} + \sum_{i=1}^{n} P_i k_i + 0.4 L k_{\text{w2t}} \quad (14)$$

where 40% of the estimated well-to-tank cost from [2] is included to account for the well-to-tank costs that are not related to GHG emissions, and the cost from well-to-tank GHG emissions is included by adding $CO_{2\text{eq,WTT}}$.

For IWW, EC_δ should be extended to include costs related to accidents and habitat damage, such that EC_δ becomes:

$$EC_\delta = L_\delta k_{\text{truck}} + (CO_{2\text{eq,TTW}} + CO_{2\text{eq,WTT}})k_{\text{CO}_2} + \sum_{i=1}^{n} P_i k_i + L(0.4 k_{\text{w2t}} + k_{\text{accident}} + k_{\text{habitat}}) \quad (15)$$

where k_{accident} is a factor converting ton-km to the external cost of accidents in Euro and k_{habitat} is a factor converting ton-km to the external cost of habitat damage in Euro. The factors are found in [2]. Note that some of the factors in [2] are given in Eurocent.

In some cases, the investment might not be in a transport solution that competes with truck transportation. For rail, the expression $L_\delta k_{\text{truck}}$ in equations (14) and (15) can be changed by replacing k_{truck} with k_{rail} and calculating L_δ as the yearly reduction in ton-km by rail, as [2] also provides values for k_{rail}. For comparing maritime shipping alternatives, the expression $L_\delta k_{\text{truck}}$ can be replaced with $-(CO_{2\text{eq,TTW}} + CO_{2\text{eq,WTT}})k_{CO_2} - \sum_{i=1}^{n} P_i k_i - 0.4 L k_{\text{w2t}}$ for the base case ship(s). Furthermore, for IWW, $-0.4 L k_{\text{w2t}}$ can be replaced with $-L(0.4 k_{\text{w2t}} + k_{\text{accident}} + k_{\text{habitat}})$.

Some of the data needed for the estimation of EC_δ at a concept level for a MASS, can be produced by simulations that estimates the required energy consumption for propulsion (and other loads). Energy consumption can be converted to emitted CO_2equivalents and pollutants P_i, by using conversion factors. Conversion factors for converting energy to CO_2, to CH_4 in CO_2 equivalents, and to N_2O in CO_2 equivalents, for a range of machinery types, are found in [23]. One source for conversion factors that converts energy consumption to pollutants P_i is found in [24]. Energy consumption estimation by simulations, for propulsion of ships, is discussed in [25] and [18].

4. Example calculation of investment and societal costs

To give some example calculations of C_{CAPEX} and EC_{δ} in a case study of autonomous ship concepts, we will use the study of the impacts from replacing truck transportation with autonomous ship concepts in [26]. The study in [26] was done as part of the SATS project [22] where autonomous ship concepts were developed and compared to a real conventional ship, and to truck transportation, for container transportation between two short sea ports. The purpose was to study the impact on cost and emissions from design changes made possible by autonomy, and to study if autonomy made shipping more competitive to trucks. The autonomous ship concepts were developed by a naval architect and included GA drawings, hydrodynamic models (speed-power curves), and dimensioning of machinery. Thus, the study is an excellent source for realistic weight, resistance (water and waves), installed power, and cargo capacity impact from design changes made possible by autonomy. And this is what is needed to show the impact of autonomy on C_{CAPEX} and EC_{δ} for a specific case.

The study in [26] does not consider differences in machinery type. Since our proposed KPIs C_{CAPEX} and EC_{δ} captures differences in machinery choices, we have made a change to the case studied in [26] before using it in our example. The change is that the autonomous ship concept has hydrogen fuel cells as energy source instead of diesel, while the conventional ship machinery is unchanged. The data required for estimating the impact on C_{CAPEX} and EC_{δ} from replacing the diesel machinery with hydrogen fuel cells are taken from the study of alternative fuels and engine technologies in [23].

Not all required data points for the KPI estimations are given in [26], however, this data is available to the authors of the present paper as they contributed to the study and co-authored [26]. We will highlight the data that this applies to in the discussion throughout the example. This means that the example calculations in this section are an extension of the previous study in [26], and that some previously unpublished data from the study in [26] are made available in this paper.

4.1. CAPEX estimation

The study in [26] compares a conventional ship with 4 autonomous ship concepts, and a truck, for the transportation of cargo between two points. In the example CAPEX estimation, we will use the conventional ship and the *concept 100%* ship from [26]. This means that we are comparing ships with the same main dimensions.

The ship particulars are given in Table 1 of [26], however the ship light weight (LDT) is missing as well as the displacement (DPL). These are available to the authors of the present paper. The additional cost for autonomy related technology is also not given in [26], but is available to the authors of the present paper. The machinery for the conventional ship is kept the same as in [26], a diesel engine running on MGO, and for the *concept 100%* ship we have changed the machinery to fuel cells running on liquid hydrogen. This is different from [26] and is done to include the impact of non-conventional fuel and engine types in the CAPEX estimate.

The impact of choosing liquid hydrogen over MGO, $C_{\mathrm{M}\delta}$, can be estimated by inserting the installed power for the ship and the factors k_{M} and k_{convM} from [23] in equation (7) for $C_{\mathrm{M}\delta}$. For the conventional ship this is not needed, as $C_{\mathrm{M}\delta}$ will be zero. For the concept ship with fuel cells, we estimate $C_{\mathrm{M}\delta}$ as:

$$C_{\mathrm{M}\delta} = PWR(k_{\mathrm{M}} - k_{\mathrm{convM}}) = 1700(2700 - 400)USD = 3\ 910\ 000\ USD \tag{16}$$

Assuming an exchange rate of 0.9 Euro per USD, this gives a $C_{\mathrm{M}\delta}$ of 3.5 million Euro. The data for estimating C_{CAPEX} is summarized in Table 1.

Table 1. Input data to CAPEX estimation, based on [26] and [23].

Parameter	Conventional	*Concept 100%*
L_{pp} (m)	85.0	85
Breadth (m)	15.8	15.8
Design draft (m)	5.4	5,4
C_b	0.825	0,7
DPL	6133	5220
LDT (ton)	1970	1670
PWR (kW)	2400	1700
C_{tech} (Million Euro)	0	0,925
$C_{M\delta}$ (Million Euro)	0	3.5

The CAPEX for the conventional ship can then be estimated by inserting the respective data from Table 1 into equation (6):

$$C_{\mathrm{CAPEX,conv}} = (0.0053 - 0.0000001 * 6133)(0.8 * 1970 + 0.2 * 2400) = 9.6\mathrm{MEuro} \tag{17}$$

While the CAPEX for the *concept 100%* ship can be estimated by inserting the respective data from Table 1 into equation (6):

$$C_{CAPEX,con} = (0.0053 - 0.0000001 * 5220)(0.8 * 1670 + 0.2 * 1700) + 0{,}925\mathrm{MEuro} + 3.5\mathrm{MEuro} = 12.4\mathrm{MEuro} \tag{18}$$

Which means that in this example the concept ship with hydrogen fuel cells has a 2.8 million Euro higher investment cost than the conventional ship. It is worth noting that the investment cost would be slightly lower for the autonomous ship than the conventional if the machinery was identical.

4.2. External cost reduction estimation

The estimation of the KPI EC_δ for quantifying the societal impact of investing in the ship concept in [26], requires that we know the distance that the concept ship sails, and that the truck drives, the number of transported containers, and the weight of the containers. It also requires the conversion factor for estimating GHG emissions for the energy consumed by the ship (or tank-to-wake) and for well-to-tank for the ship, and the factors for converting the truck travel distance to euro, CO_2 equivalents to euro, and ship travel distance to euro. These values are given in Table 2 and are taken from the case study of the ship *concept 100%* in [26]. The estimated energy is not given in [26], but is available to the authors of the present paper. The conversion factor for energy to well-to-tank (WTT) and tank-to-wake (TTW) emissions is taken from [23]. The conversion factors k_{truck}, $\mathrm{k}_{\mathrm{CO_2}}$ and $\mathrm{k}_{\mathrm{w2t}}$ are taken from [2].

Table 2. Parameters for EC_{δ} estimation based on scenario B in [26] where the ship concept 100% carries 50% of its TEU capacity.

Parameter	Truck	*Concept 100%*
Travel distance (km)	236	194
TEU weight (ton)	14	14
Transported TEU	104	104
Energy (MJ)	-	144 121
$k_{e2GHG_{WTT}}$ ton $CO_{2\mathrm{eq}}$/MJ	-	0.0001508
$k_{e2GHG_{TTW}}$ ton $CO_{2\mathrm{eq}}$/MJ	-	0
k_{truck} (Euro/ton)	0.04	-
$k_{\mathrm{CO_2}}$ (Euro/ton $CO_{2\mathrm{eq}}$)	-	100
K_{w2t} (Euro/ton km)	-	0.0006

If we insert all these parameters to the equation for EC_{δ} (equation 14), we find that the ship *concept 100%* would reduce external costs by an estimated 12 190 Euro for each trip that it sails, when this results in moving the transport from road to sea. The calculations are as follows:

First, we calculate the reduction in truck ton km:

$$L_{\delta} = -236 * 14 * 104 = -343\ 616 \text{ ton km} \tag{19}$$

The additional shipping ton kilometer:

$$L = 194 * 14 * 104 = 282\ 464 \text{ ton km} \tag{20}$$

And the emitted $CO_{2\mathrm{eq}}$ by the ship:

$$CO_{2eq} = energy * \left(k_{\mathrm{e2GHG_{WTT}}} + k_{\mathrm{e2GHG_{TTW}}}\right) = 144121 * (0 + 0{,}0001508) = 21.73 \text{ ton } \mathrm{CO_{2eq}} \tag{21}$$

Before the reduction in external cost is estimated by inserting all values into equation (14):

$$EC_{\delta} = -343616 * 0{,}042 + 21.73 * 100 + 0{,}4 * 282464 * 0{,}0006 \ = -12\ 190 \text{ Euro} \tag{22}$$

Note that P_i from equation 14 was set to zero in this example since the concept was assumed to be using hydrogen fuel cells for energy generation, which results in emitting zero pollutants P_i.

5. Discussion and conclusion

Deciding to invest in a transportation service requires that one is confident that the service will be competitive and attract customers. Therefore, we took on the transportation service customer perspective when we developed KPIs for evaluating the competitiveness of autonomous ship-based transportation service concepts. Additionally, there are expectations for autonomous ships having a positive impact on the society and external costs. If autonomous ships could be shown to have such impacts, it might give rise to subsidy programs. Such as ENOVA which subsidies investments with positive environmental impacts, Yara Birkeland being an example [12].

There are methods for comparing alternatives based on multiple criteria, such as grey relational analysis (GRA) where criteria scores are weighed and aggregated into one score which is used for comparison of alternatives. GRA is applied in [27] to investigate "…*beneficial (competitive) impact of* *the Northern Sea Route…*". Another well-known method is to monetize benefits and costs and perform a cost benefit analysis. It is also possible to compare criteria by criteria, and simply do a qualitative assessment. Whichever approach is chosen, the KPIs proposed in this paper can be applied.

External costs generated from well-to-tank for new fuels, such as hydrogen, are missing in [2]. Some alternative sources exist, such as [23], however, therein, the only well-to-tank impact on society that is considered is the emitted CO_2 equivalents. More research is therefore needed on external costs related to well-to-tank for modern fuels.

Remote control center costs, autonomous technology costs, Automatic Facilities Services costs, and maintenance costs for autonomous ships are also cost items that there are few published sources for estimating. Further studies on these topics are therefore needed.

There are some shortcomings in our proposal for KPIs related to life-cycle evaluations. What is missing is the end-of-life, or decommissioning costs (both economic and environmental). Studies on how these costs are influenced by different novel ship concepts are therefore needed.

Regarding access to reliable, high-quality data in the estimation of KPIs in the design phase, we are relying on simulation tools utilizing available calculation parameters. This is particularly relevant for KPIs related to emissions. Several initiatives are currently underway, such as in the projects AUTOSHIP [15] for ship designs and AEGIS [28] for logistics chains. Such tools will be a vital part of producing reliable KPIs, especially in early phases such as the design phase. One will never be able to make true calculations (such as Annual Energy Ratio or Energy Efficiency Operational Indicator) before the MASS is in actual operations but the closer the estimates derived from such tools; the better decision support can be provided. The KPI formulas will be the same, but the quality of the estimates will increase in correlation with the development of accurate simulation tools.

Positive cost benefit assessments are key to large scale uptake of MASS. In this regard, societal KPIs, expressing the actual positive societal impact of MASS will be ever more important in terms of providing decision support to assessment of public support and subsidies. A clear and internationally accepted set of societal KPIs is an important contributor in that regard.

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