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Design and application of a key performance indicator (KPI) framework for autonomous shipping in Europe

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ABSTRACT

The European Union (EU) transport policy recognizes the importance of the waterborne transport systems as key elements for sustainable growth in Europe. By 2030, 30% of total road freight over 300 km should shift to rail or waterborne transport, and more than 50% by 2050. Thus far, this ambition has failed but there have been several project initiatives within the EU to address these issues. In one of these projects, we consider a new waterborne transport system for Europe that is green, robust, flexible, more automated and autonomous, and able to connect both rural and urban terminals. The purpose of this paper is to describe work and preliminary results from this project. To that effect, and in order to assess any solutions contemplated, a comprehensive set of Key Performance Indicators (KPIs) has been defined, and three specific use cases within Europe are examined and evaluated according to these KPIs. KPIs represent the criteria under which the set of solutions developed are evaluated, and also compared to non-autonomous solutions. They are grouped under economic, environmental and social KPIs. KPIs have been selected after a consultation process involving project partners and external Advisory Group members. Links to EU transport and other regulatory action are also discussed.

1. Introduction

In recent years, the shipping industry is rapidly adapting to regulatory pressure and seeks to improve its operations in a quest to decarbonize. The development of innovative technologies is vital in improving shipping operations. In recent years, autonomy and automation are some of the most highly-sought technological developments that promise to significantly reduce operating costs and bring also environmental benefits. In fact, autonomy has been a key research and development field across other transportation modes (Duarte and Ratti, 2018).

In the context of waterborne transportation, autonomous ships and terminals offer several significant advantages over conventional ships. Reductions in personnel costs, increased efficiency, resilience of operations, flexibility on speed and frequency are among the characteristics that can further increase the competitiveness of shipping versus other modes (Rødseth et al., 2020). Moreover, there are further synergies with technologies available for conventional shipping. For instance, the use of green propulsion systems, improved hull designs, and optimized routing can further enhance these benefits. Data from the EU MUNIN project predict potential savings of USD 7 Million over a 25-year period for an autonomous merchant ship, due to improved fuel consumption and reduced crew supplies

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and salaries (MUNIN, 2016). Autonomous shipping solutions can also offer alternative transport options inline with the overall ambition of the European Union to shift cargo away from road options towards rail or maritime alternatives (Zis and Psaraftis, 2019). This ambition has been clearly set out in the EU White paper on transport policy (EC, 2011). These modes are traditionally perceived as more environmentally friendly due to economies of scale, and also result in lower external costs when considering reductions in accidents and exposure of population to harmful pollutants (Zis et al., 2019). More recent European Union (EU) policies, in the context of the "European Green Deal" introduced in 2019 by the new European Commission President and further implemented in the form of specific EU legislative actions, are designed to encourage and promote a shift to greener modes of transport and to the use of greener fuels (more on this in Section 5 of the paper).

In terms of capital expenses (CAPEX), there might be savings from the design of autonomous shipping, due to the reduced need for crew accommodation or bridge, also allowing an increase in carrying capacity of the ship. The fact that an autonomous ship can travel without seafarers can also play a role in its sailing speed, as it could be sailing at far lower speeds without concerns for an overly time-lengthy voyage with unpleasant effects on crew. This can also lead to significant cost savings due to the lower fuel consumption at slower speeds. At the same time, CAPEX can be higher given the more advanced technology onboard for ships of similar size.

Solutions contemplated within autonomous shipping consider the use of smaller ships, which may facilitate a more flexible and customer friendly transportation system. A higher number of ships also has positive effects on the resilience of the fleet, as in case of a break down or malfunction of one ship, the remaining fleet is still operational. In addition, less cargo is affected by delay, damage, or loss compared to a larger vessel malfunctioning. In the same fashion, safety of operations is higher in an autonomous ship, and exposure of crew to potential life-threatening injuries is eliminated. A study by insurance company Allianz shows that between 75 and 96% of maritime accidents are caused by human error (Allianz, 2020). From a societal perspective, labour is affected through the reduced need for crew, but there are also employment opportunities on highly qualified personnel that will manage and monitor the autonomous fleet from the shore, as well other types of jobs that will be created (for example, experts in software development, cybersecurity, procurement, as well as employment for the operation of the building housing the control tower).

In parallel with autonomous shipping, research and development on automation in ports and terminals has been a staple in maritime logistics. For example, attempts at automated berthing and mooring operations will be easier if operations are unmanned on both the port and ship side. Automation can also relieve the administrative burdens and bureaucracy dealing with imports and exports of cargo on seaports, that are a source of significant costs and delays.

This paper presents some initial results and research directions stemming from the first two years of an EU-funded project focusing on autonomous ships and terminals. The main focus of the paper is on the design of Key Performance Indicators (KPIs) that will be used to benchmark business as usual transport systems with an autonomous solution. After setting the scene in Section 1, Section 2 presents a brief literature review of academic work in KPIs in the context of logistics, as well as latent research on autonomous shipping. Section 3 presents the methodology and breakdown in our selection of KPIs, categorized into economic, environmental, and social indicators. Section 4 presents three Use Cases selected to highlight the potential of autonomous shipping and conducts a preliminary analysis on the examined routes. Section 5 finishes with some initial conclusions and remarks on potential future research questions in this theme.

2. Literature review

The use of KPIs is very important in benchmarking any type of operations. Only by measuring the performance of operations it is possible to manage and improve. Hamel et al. (1994) note that the basis of performance management theories is that "if you cannot measure it, you cannot improve it". Defining and selecting appropriate KPIs is vital for measuring and monitoring performance (Meng and Minogue, 2011), although there is a degree of subjectivity in what kind of KPIs are relevant for each problem. In this section, we identify relevant research themes where KPIs were used, and justify the approach we used for the selection of KPIs to benchmark and monitor the performance of the autonomous solutions.

2.1. Research on key performance indicators in shipping

In the highly competitive shipping industry, acknowledging one common set of KPIs which could be implemented systematically and methodologically has always been vital (Konsta et al., 2012). Following this need, in 2008, a group of 18 ship management and ship owning companies decided to launch the Shipping KPI (2008) project aiming at an international standard defining, measuring and reporting information on operational performance in shipping. The Shipping KPI Standard is based on internal improvement and external communication, and classified three levels of indicators: Performance Indicators (PIs), Key Performance Indicators (KPIs) and Shipping Performance Indexes (SPIs). The Shipping KPI model defined over 100 PIs, 33 KPIs, and 7 SPIs. The Shipping KPI standard was revised and updated in 2020 (BIMCO Shipping KPIs, 2020).

Academic papers in the field of maritime transport and logistics, frequently define custom KPIs to compare the performance of a transport system before and after a certain intervention. In economic evaluation of different solutions, there are common KPIs that are applicable to a wide area of projects. For example, several large investments are often appraised based on the expected Net Present Value (NPV) of the project, or the payback period where there is a return of capital and operating costs. Such KPIs have been used extensively in research in shipping. Following the designation of Emission Control Areas (ECA), many academic pieces have investigated the NPV and the payback period of scrubber investments (Jiang et al., 2014; Zis et al., 2016; Lindstad et al., 2017) as a way to comply with the low sulphur limits. Flash forward to the global sulphur cap, and the Initial IMO Strategy (of the International Maritime Organization – IMO), several works are using similar methodologies to appraise economically investments in alternative fuels (Gore et al., 2022), wind propulsion (Talluri et al., 2016) or port infrastructure (Innes and Monios, 2018).

For environmental purposes, typically most KPIs in academic literature look at either the net difference in absolute emissions (e.g. the solution saved X tons of CO_2, SO_x, or other emissions species of interest), or at the intensity level. In shipping, the first studies looking at environmental improvement focused on the impacts of slow steaming, and in these papers (Cariou, 2011; Maloni et al., 2013) the comparison was usually on the amount of CO_2 saved per voyage, over a certain period of time. As the field matured, and more data were available from shipping companies that started to optimize sailing speed and selection of routes, it was obvious that there were environmental trade-offs from most of these decisions. Installing a scrubber or using low-sulphur fuel would increase the total CO_2 emissions (Zis et al., 2021), while slow steaming could result in modal shifts towards land-based alternatives with negative environmental effects (Holmgren et al., 2014). To accurately compare ex-ante with ex-post operations, it is necessary to define what is being measured. For environmental KPIs, there are different ways to achieve this. In the ideal scenario, fuel consumption is taken from ship operators, and then appropriate emission factors (often ship and engine specific) are used to calculate the pollutant levels. Occasionally, ship operators may have sensors installed that monitor emissions live. More often, ship schedule information or Automatic Identification System (AIS) data are used to acquire information on sailing patterns and coupled with weather data, a power prediction is made allowing the estimation of fuel consumption and associated emissions. For more information on big data algorithms applied to AIS data, we refer to the literature review of Yang et al. (2019).

Social KPIs are less often used in academic research in shipping, and usually qualitative information is provided. There are however some exemptions in papers that try to link mortality with shipping emissions (see Corbett et al. (2007)), or environmental justice issues (Marshall et al., 2014), but in these cases it is arguable that these are environmental KPIs as well, and that social KPIs would focus more on income, jobs generation, safety (e.g. accident risk) and security (e.g. risk of piracy) improvements.

2.2. Research on KPIS for autonomous shipping

Most papers have focused on presenting case studies of autonomous solutions compared economically and/or environmentally with a conventional transportation solution. Jovanović et al. (2022) discuss the feasibility of using autonomous shipping in the Adriatic Sea, and utilize environmental KPIs referring to global warming potential, acidification potential, aerosol formation, and eutrophication potential. Komianos (2018) discusses operational, regulatory, and quality assurance challenges for autonomous shipping, notes that KPIs are needed to monitor different parts in the performance of the autonomous ship. Nordahl et al. (2022) define competitiveness KPIs (capital, voyage, operating, and maintenance costs) and societal KPIs in the form of emissions intensity, external costs through pollution, or lifecycle emissions. What is common in all the aforementioned works in the literature, is that a methodology to model economic and environmental costs and benefits is necessary, and typically KPIs are used implicitly or explicitly.

In the context of development of green transport corridors, there have been several EU-funded projects with relevant findings to the identification of KPIs (Psaraftis, 2016). Green transport corridors are defined as a concentration of freight traffic between major hubs and by relatively long distance where short sea shipping, rail, inland waterways, and road complement each other to enable the choice of environmentally friendly transport. The SuperGreen EU project[1] selected a set of 6 KPI groups which were concerning economic efficiency (transportation costs and quality service – time, reliability and frequency) plus two KPIs reflecting environmental performance (CO_2 and SO_x emissions).

The work described in this paper is tied to a European Funded project that aims to design autonomous vessels and automated ports. These systems will require the use of traditional and novel KPIs to assess the performance of the new system versus the business as usual case. Traditional KPIs pertaining to time, cost, emissions, and punctuality are necessary. However, despite the numerous benefits of autonomous systems, new challenges and concerns are arising which will require scrutiny and attention. For instance, concerns on liability in case of accidents, new approaches in navigation, and issues regarding cybersecurity will be crucial in ensuring autonomous shipping as a robust alternative to conventional shipping. Our paper aims to fill this gap by presenting and applying a KPI framework for this purpose.

3. Methodology

3.1. Selecting relevant KPIs

The definition of appropriate KPIs for any project is challenging task, as a successful or desirable level of operation is open to interpretation from the various stakeholders (Cox et al., 2003; Bryde, 2005; Toor and Ogunlana, 2008).

Our approach on KPIs consists of the following steps.

Step 1: Start by performing a literature review of past studies and research projects where KPIs were used to assess performance of a system. For instance, the EU FP7 project SuperGreen had developed a set of KPIs for benchmarking green corridors in Europe.
Step 2: Create an initial list of potentially relevant KPIs that can be useful for benchmarking.
Step 3: Circulate a questionnaire to project partners, relevant stakeholders, and advisory group members. The questionnaire included a presentation of the initial list of KPIs in Step 2, and solicited feedback on these.
Step 4: Expand and create an extensive list of KPIs based on the feedback and discussions from Step 3.

[1] http://martrans.org/supergreen/

Step 5: Recirculate the extensive list of KPIs, and ask respondents to score each one as “must have”, “nice to have” or “can live without” for the specific project. Use this scoring to create a shortlist of the final KPIs.
Step 6: Call for an Advisory Group (AG) and other stakeholder’s consultation, with the aim of finalizing the shortlist of KPIs and securing a consensus.
Step 7: Present the final consolidated list of KPIs based on all critical input received in previous steps.
KPIs for Autonomous Shipping

The selected KPIs represent the criteria under which the set of solutions are evaluated. This section presents a summary of the three groups of KPIs, followed by the quantitative methodological framework to calculate each one, and the necessary associated data.

3.1.1. *Economic KPIs*

The economic KPIs are concerned mainly with aspects of time and costs. Table 1 presents a subset of the KPIs chosen for assessing economic aspects of the autonomous solutions.

Other KPIs that were relevant and are not presented in this paper due to space constraints included number of cyberattacks, degree of autonomy, driving and transhipment time of cargo. It is apparent that the some of the economic KPIs are linked closely together, and the necessary data for their calculation should be readily available to collect by the ship operators.

3.1.2. *Environmental KPIs*

The environmental KPIs are concerned mainly with energy consumption and associated greenhouse gas and pollutant emissions from conventional and autonomous ship operations. Table 2 presents a summary of the KPIs chosen for assessing environmental issues.

The above being the most important environmental KPIs, but the list is not exhaustive. For instance, variants of the emissions-related KPIs may include well-to-propeller KPIs (or lifecycle assessment - LCA KPIs), in which well-to-tank emissions are also considered.

3.1.3. *Social KPIs*

The social KPIs are primarily qualitative indicators, the values of which will be determined ex-post. For several KPIs we had to use assumptions as there are several unknown variables at this stage of the project (for example the number of jobs that will be created, the number of jobs that might no longer be needed due to automation, etc.). Table 4 presents a summary of the KPIs chosen for assessing social issues.

3.2. *Calculation of KPIs*

To conduct a preliminary analysis, we circulated a data template to relevant stakeholders to solicit and to collect the necessary information on ships, routes, and ports. The format of the template was a spreadsheet file with data requirements on Ship, Route, Cargo, Port, and Other. The cells were also linked with equations that facilitated a preliminary calculation of the KPIs. In total, the full template contained 75 fields to be filled with information.

3.3. *Calculation of economic KPIs*

The profitability of a voyage can be calculated by subtracting the various operational cost elements and fuel costs from the revenue. As seen in Section 3.2.1, the first group of KPIs refer to cost elements (capital investment, operating expenses excluding fuel, maintenance) of each ship. These can be taken as a direct input from the ship operator (actual cost of acquiring/chartering the ship, operating costs per year, cost of maintenance). The KPI on port costs for using the facility is not always easy to estimate. While typically

Table 1
Economic KPIs.

Type	Name	Units	Description
Cost	CAPEX	€	Capital expense
	OPEX	€	Operating expense
	Maintenance costs	€	Expenses to ensure the correct and reliable operation of an asset
	Port charges	€	Fees paid to port authorities
	Fuel cost	€/NM	Total amount of money spent in fuel
Time	Loading/ unloading time	H	Duration of the loading and unloading process
	Sailing time	H	Duration of the vessel voyage
	Waiting time	H	Time during which cargo is idle
	Punctuality rate	% of port calls	deviation from expected arrival/departing time.
	Recovery time	H	Time from disruption detection to full restoring of performance
	Cargo handling time	TEUs/h	Time to move goods on and off ships plus terminal handling time
Misc.	Energy consumption	KWh	Total energy needed
	Cargo carried	TEU/ship	Cargo carried from loading to discharging

Table 2
Environmental KPIs.

Type	Name	Units	Description
Emissions	CO_2	Kg of CO_2/tkm	CO_2 emissions
	NO_x	Kg of NO_x/tkm	NO_x emissions
	SO_x	Kg of SO_x/tkm	SO_x emissions
	PM	Kg of PM10/tkm	PM_{10} emissions
	Waste	Kg	Amount of waste produced
	Acoustic – Noise	dB	Noise emitted
	Light pollution	Lumens/shipment	Brightening of the night sky caused by operations
Other	Terminal area per cargo unit	m^2/cargo unit	land needed to perform operations as function of the cargo moved
	Energy consumption	kW/cargo unit	Total energy needed for movement
	Use of renewable energy sources	%	Percentage of energy consumed that comes from environmental-friendly energy sources

Table 4
Social KPIs.

Type	Name	Units	Description
Safety	Accident rate	Number	Incidents resulting in damage or injury
Safety	Fatality rate	Number	occurrences of death by accident
Safety	Fire incidents	Number	incidents involving smoke, heat, flames causing damage
Security /Safety	Crime	Number	All actions which constitute an offence and is punishable by law
work-life	labor conditions	Work-life-balance	Quality of working environment
Work-life	Employment	% of change	Influence on the occupational rate
Work-life	Income	% of change	Influence on earnings
Work-life	Worker commuting time	Distance ship-home	Total journey employees take from home to work and back again
Work-life	Training	Time/staff	Time invested in teaching an employee a particular working skill
Others	Acoustic emissions – noise	dB	Amount of noise emitted by vessel and terminal operations
Others	Traffic	# TEU/port call	Amount of goods transported in ports/terminals
Others	complaints	#	Total number of society and local complaints

ports publish their tariff information (which is case-specific), each port has its own pricing mechanism for their visiting vessels. Cargo handling tariffs for containerized cargo would typically depend on the size and type of the container and may significantly vary among ports. For Roll-on/Roll-off (Ro-Ro) cargo, tariffs typically depend on trailer size. Some tariffs are confidential between the port and the shipping company, particularly when there are discounts for large volumes. Other costs include pilotage fees, wharfage fees, request for moves per hour (higher productivity by placing more cranes), costs for handling hazardous material, refrigerated containers, etc.

Perhaps the most major cost element is the fuel consumption per each voyage. By voyage we consider the set of all sailing legs and port visits during one iteration of a repeating sailing schedule. This information can be provided by the ship operator directly or estimated with different modelling approaches. For the latter, we consider the following simplistic approach, with Eq. (1) calculating the fuel consumption during sailing.

$$FC_{sailing} = 10^{-6} \cdot \{SFOC_{main} \cdot EL_{main} \cdot EP_{main} + SFOC_{aux} \cdot EL_{aux} \cdot EP_{aux}\} \cdot (sailing\ time) \quad (1)$$

Where *SFOC* refers to the Specific Fuel Oil Consumption (in grams of fuel per kWh) of an engine with nominal Engine Power EP (in kW) when operating at the percentage Engine load EL(%) of the Maximum Continuous Rate (MCR). We multiply with 10^{-6} to convert grams into tonnes. The previous equation assumes that during sailing both the main (for propulsion) and auxiliary (for electricity and onboard energy demand) are operating. However, there might be ships that only use one engine type (for propulsion). To calculate the actual fuel cost (in € per voyage) for the cruise segment, the fuel price should be multiplied with the fuel consumption of each machinery operating onboard the vessel during sailing. The fuel consumption at port in tons per call can be estimated using a similar activity-based approach as follows in Eq. (2):

$$FC_{port} = SFOC_{aux} \cdot EL_{aux} \cdot EP_{aux} \cdot (time\ at\ berth) \quad (2)$$

By summing the fuel consumption at each leg and at each port stay, and subsequently multiplying each fuel consumption with the respective fuel price (as different engines may be using different fuel type) can lead to the estimation of the total fuel cost per voyage. It might be that the use of an alternative fuel is more expensive compared to the use of a conventional fuel, depending on the prevailing fuel and energy prices. Some of the technologies envisioned for autonomous ships are environmentally friendlier, but at the same time might be more expensive due to higher capital costs to invest in (for example hydrogen fuel, or battery-powered propulsion). We note that future fuel prices in Europe may include a fuel or carbon tax or carbon price traded in the EU carbon market.

Alternatively, to using modelling methodologies, fuel consumption at sea and/or at berth may be provided:

- directly via fuel consumption data from the shipping company
- via use of model tests in towing tanks
- via use of computational fluid dynamic (CFD) models

The second group of economic KPIs is focusing on time. The first two KPIs concern the loading and unloading time of the vessel (measured in hours) while at port, respectively. This time depends on the productivity of the terminal in handling the vessel, the total cargo that is onboard the ship (for unloading) and the cargo volumes to be loaded, and the assigned terminal resources for the task (number of cranes). An upper bound on the total loading and unloading time can be estimated based on the published schedule of the sailing service. In our work we use the following relationship to estimate the composite loading/unloading KPI, where Nmoves refers to the total number units that need to be moved (loaded and unloaded) during a port call, and the Cargo handling rate indicates how many moves per unit time can be performed with the assigned resources at the port:

$$Loading/Unloading = \frac{Nmoves_j}{Cargo\ handling\ rate} \tag{3}$$

The sailing time (expressed in hours) KPI can be retrieved either from the published schedule of service, or by considering the route's sailing distance (typically expressed in Nautical Miles – NM) and the planned service speed (expressed in knots). Adding the sailing time with the terminal time (at port of origin and port of destination) with the waiting time at the port provides the total transportation time at each leg of the voyage. Waiting can occur due to idling during intermodal changes and transhipment (from mother vessel to daughter or vice versa). Considering also the potential delays in sailing (due to weather or other unexpected events), it is possible to estimate the total transportation time. The deviation from expected sailing time is expressed through the punctuality rate KPI. Thus, the total transportation time (in hours) is retrieved by summing across all N voyages where index *i* denotes each leg, and also adding the driving time KPI (for cargo that is at some point moved via road), transhipment time spent at terminals, as well as any delays during each sailing leg in Eq. (4).

$$Transportation\ time\ = \sum_{i}^{N} Sailing\ time_i + delay\ time_i + Loading/unloading_i + transhipment\ time + drive\ time \tag{4}$$

Finally, there is also the recovery time KPI which refers to the total time required until the system returns to full level of performance following a disruption. However, this information can only be collected long after the future demonstration phases of autonomous shipping, when a sufficient number of ships are operational and many trips have been performed. Thus, we do not include it in our modelling framework.

In order to compare the autonomous solution with the baselines, it is vital to be able to compare time and cost. For example, a fully autonomous vessel may end up being more cost efficient (due to the optimized sailing and operating conditions), but might come at increased total transportation time due to potential transhipment delays, lower sailing speeds, etc. It is therefore important to be able to compare the two solutions when a solution is not a clear winner in all KPIs. The issue of estimating the value of time in maritime transportation is a recurring one in the academic literature (Notteboom, 2006), and real-world information and data on this value is scarce. The value of time is also different depending on the shipping sector examined, and predominantly the type of cargo transported. Perishable and time-sensitive cargoes with a limited shelf-life tend to depreciate much faster than certain other cargoes.

The next subset of KPIs refers to cyber-attacks, and the recovery time for the restored level of performance following an attack. The autonomy level of the vessel is a descriptive KPI that can either be linked with the description of the IMO for Maritime Autonomous Surface Ships (MASS) or any other standardized description. In our template we used a simplified description as "Fully manual/ Operator Controlled/Automatic/Partial Autonomy/ Constrained Autonomous/ Fully Autonomous". The last economic KPI is the frequency of service (sailings per week), which can be used to estimate the revenue generated by the deployed services.

3.4. Calculation of environmental KPIs

The key data for the environmental KPIs are the consumption of each engine at its design operating levels, and the route information (distance, sailing time, time spent at port where auxiliaries are running). With this information, the calculation of each KPI is possible. The emissions KPIs are defined as grams of emissions per ton-kilometre. This would facilitate comparisons with the emissions intensity of other transportation modes. McKinnon (2007) has produced a set of average carbon emission factors for 40–44 tonne trucks assuming different levels of payload and levels of running empty. The emissions intensity ranges from 39.7 up to 151.1 depending on how loaded the truck was although since 2007 there have been improvements in the fuel efficiency of diesel engines for trucks. However, it might not always be easy to retrieve information on the actual payload of the ships, which in turn would affect the fuel consumption of the vessel. This fuel consumption can be multiplied with an appropriate emissions factor, to calculate emissions generated. Dividing these emissions by transport work, will return the first four KPIs. Transport work can also be described in terms of TEU-NM, TEU-km, ton-NM, or ton-km depending on how the information of the actual cargo onboard the vessels is given. Mathematically, these are shown below, taking the fuel consumption either as input from the ship operator, or through calculation.

$$CO_2 = 10^{-6}\frac{EF_{CO2} \cdot FC_{sailing} + EF_{CO2} \cdot FC_{port}}{\frac{Nmoves}{Unit\ weight} \cdot 1.852 \cdot Voyage\ distance} \tag{5}$$

Where EF_{CO2} is the dimensionless CO_2 emission factor that needs to be multiplied with the fuel consumption of each engine. As the fuel consumptions are given in tons (and thus also the CO_2 emissions), we multiply with 10^{-6} to convert these into grams of CO_2 per ton-km. We multiply the voyage distance with 1.852 to convert nautical miles into kilometres. We then divide the estimated grams of CO_2 per km with the total number of containers or lanemeters of cargo moved (depending on whether the ship is carrying containers or trailers as in the case of Ro-Ro ships). To convert the number of loaded containers or trailers into mass of cargo carried, we define *Unit* *weight* as the average weight in tons per TEU or tons per lanemeter (lm), of each container or lane meter of cargo transported onboard the vessels respectively. A similar expression can be used for all other emissions KPIs, so long as the appropriate emission factor is used (for NO_x, SO_x, PM, and any other where available data exists). Table 3 presents a summary of the fuel emission factors that are predominantly used in the literature.

The waste emissions KPI is expressed in kg. Waste emissions refer to any disposal of waste streams during a voyage. Traditionally these include sewage, greywater, hazardous waste, bilge water, ballast water, and solid waste. Some of these streams will be minimized or even eliminated due to the absence of crew in the transition to a fully autonomous ship, however some streams will remain (for example ballast water). This is a KPI that may not be feasible to quantitively assess before the actual deployment of the vessels.

The acoustic emissions KPI is measured in decibel (dB) and we can consider two main areas of attention. Noise near the shore and at ports due to the sound of marine engines, cargo handling operations, and intermodal transport operations. The second concern has to do with underwater noise, that can significantly affect marine life. This is actually a very important concern for marine mammals (Erbe, 2012), with significant research efforts that are mainly targeting the West Coast of the Americas (Madsen et al., 2006). Moving to autonomous shipping and autonomous port operations can result in some reductions of noise levels, particularly for the case of using electricity as a power source. The last KPI that falls under the category of emissions KPI is the light pollution (to be measured in lumens). This is a concern during night-time for nearby communities to ports, as well as residents near shores with nearby ship traffic. Lighting requirements would be reduced for fully autonomous operations at a port, although even in such cases there would still be staff monitoring the operations on the spot.

3.5. Calculation of social KPIs

Unlike the case with the economic and the environmental KPIs, social KPIs are not linked with the fuel consumption data and information on the actual energy sources powering the vessels. To estimate the social KPIs values it is necessary to materialize the solution and observe the relevant data. For instance, it is currently impossible to estimate the number of potential cyber-attacks (crime KPI) or fire incidents, before the solutions have been rolled out for a sufficient timeframe. Among various methods, the use of historical data and/or derivation of data from first principles will be looked at. The complete list of social KPIs, as seen in Table 4, should be seen as generic. The required input-data needed to calculate each KPI, may not be available in all use cases. The key input data for computing the social KPIs are all related with the number of staff required for the different tasks at the port during loading and unloading operations, and with cybersecurity issues that might arise during operation of the autonomous vessels. The last sub-category of social KPIs requires data on the number of incidents and accidents occurring annually. Having presented the KPI framework the next section will present in brief the three Use Cases that are being developed.

4. Use case study analysis

4.1. The examined routes

Three Use Cases have been selected to compute the KPIs. The values for the KPIs will serve as criteria to evaluate the solutions, and will facilitate cost-benefit analyzes (CBA) of future solutions. In this section, we briefly present the three use cases, the contemplated scenarios, and the current baseline transportation options. We note that the use cases have different levels of maturity, and data availability varies for each scenario and associated vessel designs.

4.1.1. Use case A

This covers transport from large ports in Europe (Rotterdam) to smaller destinations along a less populated coast of Europe (Norway), focusing on short sea transport between rural terminals mainly based on a Lift-on/Light-off (LoLo) service. The objectives are to:

- Develop a new short sea transport system using small autonomous shuttles to complement higher speed coastal liners.
- Investigate urban terminals in city centre, probably using Ro-Ro solutions with Automated Guided Vehicles (AGV)
- Investigate rural terminals, either with crane on shuttle or using Ro-Ro.
- Look at effects of standardized shuttles, similar to inland barges.
- Provide public recommendations on how to increase waterborne transport along Norwegian coast.

On average eight vessels are sailing out of Rotterdam to the west coast of Norway on a weekly basis. Average capacity for the fleet is

Table 3
Fuel based emission factors for key pollutants (g of pollutant/kg of fuel). Source: IMO (2020).

Fuel	CO2	SO2	NOx	PM
HFO	3114	0.1	75.9–78.6	6.96–7.53
MDO	3206	0.02	52.1–57,6	0.92–0.97
LNG	2749–2753	0.03	5.6–10.9	0.11
Methanol	1375	0	10.54	0.000736

estimated to be about 750 TEUs per vessel, hence a total weekly capacity of about 6000 TEUs. The cargo volume for bigger terminals is quite stable, but varies for smaller ports. One vessel can serve the Trøndelag region in Norway on a weekly basis and including Rørvik and the inner ports of the fjords if introducing feeder lines, such as daughter vessels. We consider two scenarios that are seen in Fig. 1. International transport between Rotterdam and Hitra Kysthavn, Sandstad, and domestic transport within the Trondheimsfjorden region (Norway).

The islands Hitra and Frøya had a salmon production potential of 300,000 tons (in 2020) and the Rørvik area had foreseen a production of 175,000 tons in 2021, according to factory concessions in the areas. More recent estimates of this production are currently not available, although the volume should be in similar levels. This number equals about 500 TEUs per week, which is transported mostly by road today. The idea behind the concept is to have one or several mother vessels sailing between Rotterdam and Norway with large cargo volumes, not calling all ports as it does today, and with a higher level of automation to achieve benefits due to economy of scale. When the mother vessels travel along the west coast of Norway, a number of daughter vessels can accommodate the transport of cargo between a set of regional ports and the mother vessel. The idea of the daughter vessels in the region 2 is to increase the potential cargo volumes to be transported by sea both within region 2, and to feed cargo to/from region 2 from/to region 1. In region 2 this can be realised by allowing the transport system to access smaller ports that lacks infrastructure to accommodate larger vessels, offering new services in a region that is mainly served by trucks today, and developing more environmentally friendly transport systems.

The actual envisioned vessel concepts for the Use Case A are summarised in Table 5.

For this use case, a mother-daughter concept was identified as a feasible solution. Hitra, an island outside the Trondheim fjord, was chosen as the hub for the transhipment between the mother and the daughter vessels. One mother-daughter scenario was defined between a fish factory on the island of Frøya and the transhipment port on Hitra (daughter vessel) and a further transportation to Rotterdam (mother vessel). For the mother vessels, two different concepts were developed: one for short sea shipping from Rotterdam to the Trondheim region with a capacity of approx. 1000 TEU and a second, much smaller vessel of 200–250 TEU for a coastal feeder line sailing outside the fjord and collecting cargo at coastal ports or bigger production sites, e. g. fish factories. In both concepts, the propulsion system will be powered by a green and easy-to-store fuel, such as methanol or ammonia.

For the daughter vessel in use case A, two different concepts were studied and designed. A self-propelled (fully electric) shuttle with a capacity of approx. 60 TEU can operate inside the Trondheim fjord, collecting cargo at different smaller ports or industry sites. Instead of a self-propelled shuttle, pushed convoys consisting of a push boat and several barges are a second feasible concept.

4.1.2. Use case B

Use Case B examines short sea and inland interface in Belgium and the Netherlands. Rotterdam, located in the Netherlands, is the busiest port in Europe, and one of the greatest hub ports in the world. The second busiest European port is Antwerp, in Belgium. Freight transportation through the inland waterways is already well developed, but there is still space for more cargo to be distributed via waterways.

The objectives of Use Case B are to:

- examine the short sea and inland interface in Belgium and Netherlands, focusing specifically on an area uninvolving the ports of Rotterdam, Antwerp, Ghent and Zeebrugge.
- consider the possibility of bringing cargo as close to the last mile as possible with small vessels with zero emission propulsion (battery, fuel cells, alternative fuels).

Fig. 1. Use Case A, International and domestic trade.

Table 5
The mother and daughter vessel specifications for Use Case A.

Ship	Mother Vessel #1	Vessel #2	Daughter Vessel #1	Vessel #2	Vessel #3
Vessel Type	container Short-Sea Shipping (SSS) vessel	container SSS vessel	container	mixed cargo (container/bulk)	Pusher for barge convoy
Route	Rotterdam - Hitra	Hitra - Rørvik; Orkanger - Ålesund	inner fjord (round trip, with Orkanger as hub)	Frøya- Hitra	Frøya - Hitra
Loa	143.8 m	103.5 m	61.0 m	33.0 m	33.4 m
Breadth	25.5 m	13.4 m	12.4 m	9.8 m	10.8 m
Draft	14.1 m	4.7 m	4.3 m	4.0 m	3.0 m
Main Engine Fuel Type	methanol (at the beginning diesel/methanol)	batteries	batteries	batteries	H2 fuel cells + batteries
Design Speed	15 knots	12–15 knots	10 knots	5 knots	5 to 6 knots
capacity	1046 TEU/lane meters	160 TEU/lane meters	60 TEU/lane meters	36 TEU/lane meters	–
Autonomy Level	Partial	Partial, later Constrained	Constrained, later Full	Constrained, later Full	Constrained, later Full

- Address possible administrative and regulatory challenges and bottlenecks

The port of Rotterdam was found to have the highest inflow of Ro-Ro goods, which supports the argument of using this port as a distribution hub for the inland waterways. The goods coming into Rotterdam are evenly distributed throughout the course of the inland waterways going from Rotterdam towards Belgium. From the current service operated, the cargo was found to be primarily Lo-Lo goods going from Ghent to either Zeebrugge or Antwerp, with the latter giving the option of further distribution to Rotterdam and smaller ports in the inland waterway. Use Case B has defined a micro scenario, where three different routes have been identified. The first is from Vlaardingen to Ghent, the second is an IWW from Ghent to Zeebrugge), and the third is from Zeebrugge to Antwerp. Fig. 2 shows the routes in the scenarios.

The envisioned vessel concepts and their characteristics for Use Case B are presented in Table 6. The different vessel sizes result from limitations of the waterways. They mostly affect the vessel's breadth and draught. Draught should be as low as possible (in the range of 2.5 m) to allow sailing even on low water levels during summer periods. CEMT class II is restricted by a maximum vessel breadth of 6.5 m (CEMT stands for the different standards of the Classification of European Inland Waterways - Conférence européenne des ministres des Transports, CEMT). This allows only for two trucks/trailers parked side by side. With a double deck loading a capacity of 10 trucks or 12 trailers is realized. For CEMT class IV, a maximum breadth of 9.5 m allows for four trucks/trailers side by side, which results in a capacity of 21 units at a double deck, longitudinal loading. With a maximum breadth of 22.8 m for CEMT class IV+ a transversal loading of trucks or trailers can be realized. Therefore, a Ro-Ro concept with a capacity of thirty-eight trucks/trailers was designed with a resulting vessel breadth of 18.1 and 15 m for trucks and trailers, respectively.

Data	Vessel #1	Vessel #2	Vessel #3
Vessel Name	IWW CEMT Class II	IWW CEMT Class IV	IWW CEMT Class IV+
Vessel Type	Ro-Ro IWW vessel	Ro-Ro IWW vessel	Ro-Ro IWW vessel
Route deployed in	Zeebrugge - Ghent	Ghent - Antwerp	Vlaardingen - Ghent
Loa	55.0 m	85.0 m	85.0 m
Breadth	6.6 m	9.5 m	15.0 m / 18.1 m
Design T	2.3 m	2.5 m	2.5 m
Draft	6.7 m	7.0 m	7.0 m
Main Engine Type	Electric / two Azimuth thrusters + one rotable bow thruster		
Main Engine Fuel Type	batteries		
Design Speed	7 knots		
Vessel capacity	10 trucks / 12 trailers	21 trucks/trailers	38 trucks/trailers
Cargo Handling Equipment	Lift and ramp; optional AGV (if only trailer)		
Autonomy Level	Constrained Autonomous, later Fully Autonomous		

4.1.3. Use case C

Use Case C examines cargo traffic in the areas around Vordingborg and Aalborg and looks at possibilities to increase the use of waterborne transport by increasing automation of cargo handling and ships. The potential gross volume that can be shifted from road transport to short-sea shipping in Denmark, categorized by different types of goods, can be significant. Any road transport would need to be more than 150 km for a shift to a short-sea-shipping mode to be economically viable (ECMT, 2001). Approximately one million tonnes of goods are transported to/from Northern Jutland (mostly of relevance to Port of Aalborg) and Zealand (mostly of relevance to Port of Vordingborg). Applying a scenario-based analysis, it was estimated that 177.540 tonnes of national goods, covered by 9.899 truck movements, could be shifted yearly in Denmark. Moreover, it was estimated that a median scenario included a conversion of 4.864.392 tonnes in Denmark for international truck transport. Collectively, it was thus estimated that the potential gross volume of goods that can be shifted from road transport to SSS in Denmark is approximately 5 million tonnes yearly, or about 18% of the relevant

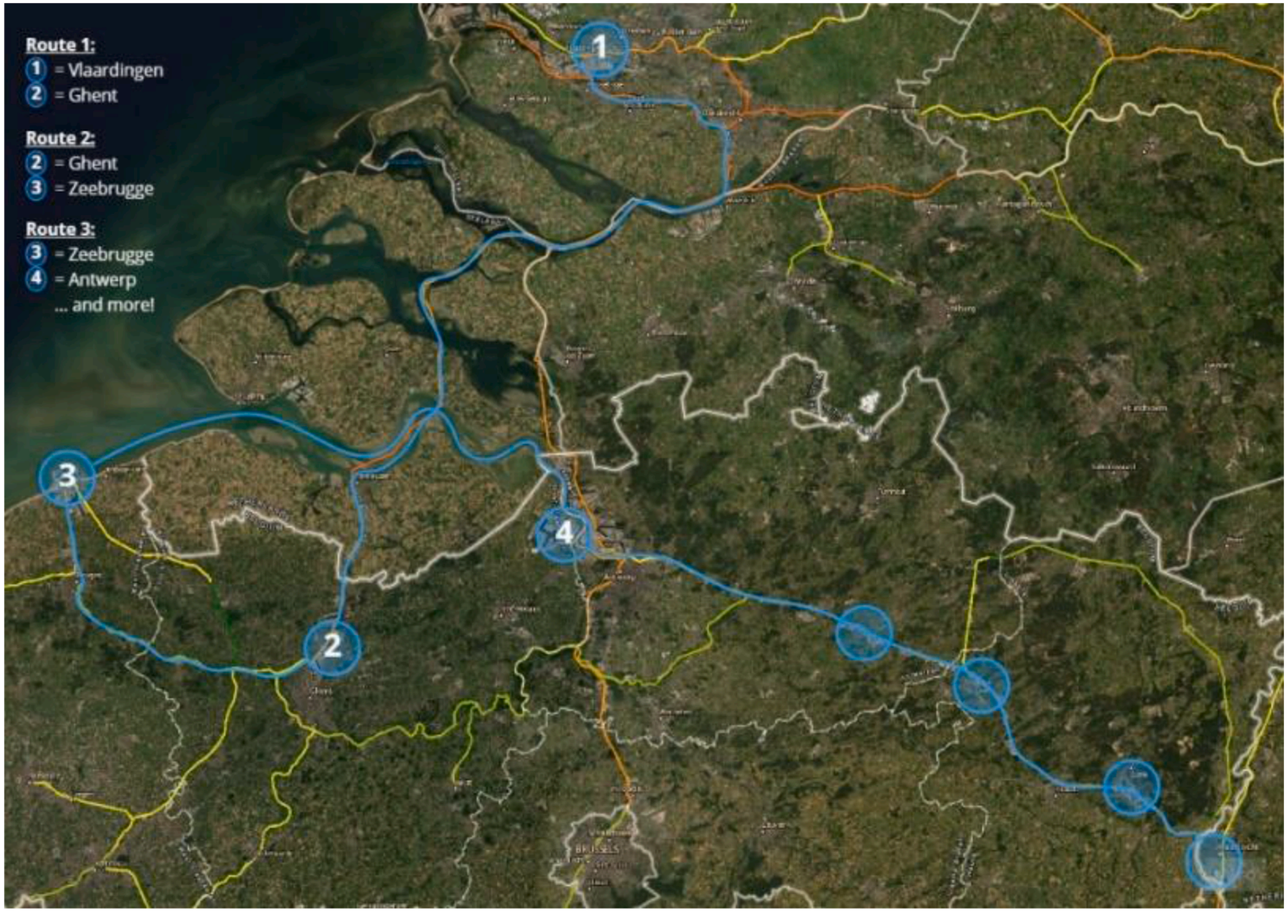

Fig. 2. Use Case B routes.

Table 6
The two envisioned ships for Use Case C.

Ship	Vessel #1	Vessel #2
Vessel Type	combined SSS and IWW (inland waterway) vessel	
Loa	71.0 m	85.0 m
Breadth	10.9 m	9.5 m
Design T	2.8 m	2.5 m
Draft	7.3 m	5.5 m
Main Engine Type	hybrid electric / two Azimuth thrusters + one rotable bow thruster	
Fuel Type	methanol/ammonia combustion + batteries	
capacity	128 TEU/lane meters	620 DWT
Cargo Handling Equipment	triple-joint crane (lightweight) with grabber	telescopic gantry crane on guide rails w/ grabber or spreader
Autonomy Level	Constrained Autonomous, later Fully Autonomous	

goods by truck as long as the SSS solution is not more expensive. Potential routes could be from Copenhagen to Gothenburg or from Aalborg to Gothenburg. The envisioned vessel concepts for Use Case C are presented in Table 6.

Both concepts are either powered fully electrically by batteries (plus H2 fuel cells) or by a hybrid solution containing of a methanol or ammonia combustion engine plus batteries.

4.2. Application of KPI methodology on use cases

In this section, the first initial results and attained values for the KPIs from the three cases will be presented. Information has been collected for the mother and daughter vessels envisioned for each Use Case. As can be expected, the information was partial, as there are data that need to be collected in operation. To conduct an initial estimate on the KPIs, we have made certain assumptions to fill-in missing data. As of January 2023, data contain partial information on each of the concept vessels (mothers and daughters). In summary, for the 10 vessels a total of 250 data entries (cells in the spreadsheets) were requested and 103 were returned with data (approximately 40%).

4.2.1. Economic KPIs

This section will present the first findings for economic KPIs on each Use Case. Use Case A uses Lo-Lo vessels with a capacity of around 800 TEUs. Scenario 1 focuses on the route between the hub in Orkanger and ports in the inner parts of the Trondheimsfjord. Currently, there are no cargo vessels sailing with fixed schedules in the region. In KPI terms, the mother vessels will compete with existing sailing services linking Rotterdam with Norway. The scenarios are not finalized, so at this stage it is not possible to make a thorough comparison of the different options. However, some preliminary discussion points can be raised. In terms of economic KPIs, the first important difference has to do with energy costs. From the two examined mother vessel designs, the first is electric while the second would use a dual fuel engine running on methanol and diesel. For the electric case, the actual energy cost depends on where the vessels would be charging. There is no information yet on the actual energy consumption for the electric case (e.g., what power requirements will be necessary, and thus how many batteries will be installed), but a typical energy cost per kWh in Norway is €0.082, while in the Netherlands it is around €0.105. There might be some reduction in carrying capacity to accommodate for the space used by the batteries.

For the methanol case, the nominal engine power is expected to be 5800 kW and the vessels would sail with a design speed of 15 knots. Methanol has a lower heat value than diesel fuels, and more fuel is consumed to provide the same power. The specific fuel oil consumption of a (fully) methanol powered marine engine will be in the range of 322–350 g of methanol per kWh. With a current trading price of €350 per ton, the cost would be €0.116/kWh. For MDO, the typical SFOC is in the range of 170–190 kWh and the price is at €630 per ton, thus a cost per kWh would be similar at 0.107–0.119. With a blend of the two fuels, the price per kWh would be in this range depending on the exact ratio used. The cost will be comparable with the existing sailing service solutions, and to be able to compare the two options (autonomous vs business as usual) there needs to be more information on the load utilization of each solution. The autonomous case might have the advantage at this point since due to the autonomy levels it offers, a sailing can commence when the vessel is fully loaded instead of simply sailing on a fixed schedule as in the case of conventional routes.

In terms of the travel time KPI, the autonomous solution with the mother and daughter vessels might be slightly slower in speed. However, as the ships will not call at all ports, it is expected that the overall travel time will be competitive. We should also note that a higher number of ships overall can have an effect on the punctuality rate KPI in the event of unexpected delays or unforeseen problems in one of the ships at a specific voyage. The extent of these trade-offs on the travel time KPI and punctuality rate can only be determined after several voyages and cannot be estimated at this stage. In terms of cargo handling time, the mother vessels will be equipped with their own cranes, and this might require additional time when compared with a typical Lo-Lo ship that is being handled at the port by dedicated cranes. For the daughter vessels and the 3 scenarios, the autonomous solution will compete mainly with existing road infrastructure, as the expected shipments in both cases are on demand services. However, for this scenario to work it is necessary that charging infrastructure will be in place at the smaller ports where the daughter vessels will be calling. The electricity cost in Norway was €0.083/kWh (industrial rate) and based on the expected capacity we can make some initial calculations on the cost per ton-km. As a baseline, the energy requirement of the daughter vessels were given as 150 kWh per one NM when sailing at 5 knots. We assume the same sailing speed, although we notice that for certain cargoes perhaps a slightly faster sailing speed might be required. We note that the actual cost per ton-km will depend on the load factor of both the ship, and the container (or trailer) itself. When compared with a truck, the cost for the daughter vessel is lower.

For the second case the comparison is conducted between the autonomous solution and the traditional road haulage option. The economic KPI that we can assess relates with the fuel consumption KPI. There are stricter rules regarding the environmental efficiency of trucks in European roads. When a truck is crossing environmental zones it must have technology Euro 6 to be allowed in. As Rotterdam has established such zones, we consider a EURO 6 standard for the current road transport scenario for Use Case B. Typical fuel consumptions for such trucks with a payload of 26 tons (total weight of 40 tons), range between 0.21 and 0.26 l per km of transport. With an average diesel price of €1.6 per l, the fuel cost is between €0.336 and €0.416 per km. Table 7 shows an estimated breakdown of costs for the road option following discussions with relevant stakeholders.

The loading and unloading time at each port will depend on the number of cargo units to be transported, and the cargo handling equipment that has been selected to manage the trailers. We provisionally examine the option of an autonomous solution for the cargo handling at each port. One illustrative example of autonomous cargo handling, is the Volvo "Vera" vehicle. This is a fully electric autonomous tractor running on batteries, and it is already operated in Gothenburg, linking a warehouse facility of a shipping company to the port. These are to be supervised by employees working at the same control room monitoring the ships. The shipping cost of a single trailer will be lower as there is no requirement to transport both the trailer and its tractor. In addition, there would be no requirements for employees at the port to assist with the loading and unloading, and the only infrastructure requirement would be that of a ramp, for the shuttle to move between ship and quay. Therefore, handling costs would be lower than a typical manually operated solution. The main issue is the total time required for these operations, which are typically slower than human-driven operations. We consider a total time of 8 min to load/unload a trailer, which is translated to approximately 3 h for the full vessel (of 21 trailers). Table 8 provides a breakdown of the time KPIs for Use Case B.

The existing battery technology allows for a range of up to 100 km without a requirement for recharging. In the first two Routes (R1 and R2), the overall distance is shorter and as such the solution would work with only requirements to charge at each port. For R3, the total distance is 170 km, and thus a recharge operation on battery swap would be necessary at a midway point. Based on the vessel specifications, and under an assumption of a sailing speed of 6.5 knots, the required energy for a one-way trip (95 km) without recharging is 6460 kWh. Accounting for potential losses and a safety factor, a capacity of 7000 kWh is selected. From existing technologies, the solution of Corvus Energy was selected as an illustrative scenario. This system can cover the propulsion requirements with two packs of six strings of batteries, each providing 3612 kWh, at a total weight of 61.1 tons. It is evident that this solution would slightly reduce the carrying capacity of the vessel both in terms of weight, and perhaps more importantly in terms of volume occupancy onboard the vessel.

The use of alternative fuels and fuel cells technology is meant to significantly reduce emissions and other pollutant emissions. There are already some fuel cells technologies that can be used in marine propulsion systems. The one examined by Podiotis and Daskalaki (2021) was the High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFCs) that uses hydrogen. Such technologies have a maximum output of 200 kW, and a systems electrical efficiency in the 50–60% range. Thus, 9 such systems would be required. The capital cost investments for Use Case B are expected to be higher due to the higher acquisition costs, and the fact that some small battery will also be required to also offer secondary power requirements. In summary for Use Case B, the battery option is more likely to cost less than a fuel cells technology, but it would have a slightly reduced carrying capacity. In addition, particularly for R3 the battery powered solution would result in additional time cost due to the recharging or battery swap operation midway the voyage. For both cases, the energy cost is slightly lower than the current road-based solution, but albeit a much slower transport option.

Use Case C provisionally concerns a transportation service between Copenhagen and Gothenburg. There are currently two vessels under consideration for this scenario, both hybrid electric and methanol powered. We will focus on the first one, a small containership with a capacity of 128 TEUs. The transport corridor does not have any SSS services connecting the two ports, as the distances are very short, and there is a straightforward competing land-based alternative. Peripherally relevant services include the Copenhagen-Oslo passenger vessels (that may also carry a few trailers), and several SSS routes from Gothenburg to Belgium, Germany, UK and Norway. For cargoes with an origin/destination near the cities of Copenhagen and Gothenburg, none of the existing connections are convincing alternatives to road transport. Thus, we will focus only on the competition of a potential new route with autonomous vessels linking the two ports, and the land-based alternative via the Oresund bridge. This is shown in Fig. 3.

Moving cargoes away from road and through the proposed maritime link would require some port fees. We anticipate that some jobs would be created to remotely monitor the autonomous ships, and to also cater for the loading and unloading operation at each port. The cargo unit cost will depend on the actual fuel consumption and sailing speed chosen for the trip. In Denmark, since 2019 there are low emission zones in the four biggest cities (Copenhagen, Aarhus, Odense, and Aalborg). Therefore, a EURO 6 truck is considered for this option. For the alternative road-based solution, we use the same assumption as in Use Case B, with an estimated transportation cost of €1.34 per km, or €0.041 per ton-km (assuming a 33 ton payload per truck). From this value, the actual fuel cost is around €0.011

Table 7
Breakdown of truck costs (Podiotis and Daskalaki, 2021).

cost type	percentage (%)	cost value (€/km)	cargo unit cost (€/t-km)
labor	50	0.67	0.0257
Fuel	30	0.4	0.0154
Other expenses	20	0.27	0.0104
Total	100	1.34	0.0515

Table 8
Time KPIs and duration of main transport activities for Use Case B.

Operation	Information	Duration
Time of loading/unloading 1 trailer	Speed of autonomous vehicle	8 min
Sailing time per 100 km	Sailing speed of 6.5 knots	8 h
Recharging time/battery swap for R3	Required time to stop midway and swap batteries	1 h
Time at port to load/unload a full vessel	With 8 min per trailer	5.5 h
Total time for R1 (63 km)	One way trip	11 h
Total time for R2 (95 km)		13 h
Total time for R3 (160 km)		19 h

per ton-km. This will naturally vary significantly and depend on the actual payload of each truck.

Vessels will either run on methanol or ammonia that is used in combustion engines, or a fully battery-powered solution. We first consider the fully battery-powered propulsion solution. Similar to Use Case B, the actual energy cost will depend on the power source that powers the batteries at each port. The total sailing distance is 137 NM and as it would be on the Baltic Sea, the option of recharging or battery swapping may not be realistic. The electricity would be provided by the Swedish and Danish grid in the respective ports of Use Case C. We made an assumption that the vessels would sail at approximately 10 knots, and thus require approximately 1500 kW at that sailing speed. Due to the cheaper grid in the two Scandinavian countries (compared to Use Case B), if the vessels would be fully electric then the energy cost per ton-km would be much lower than the typical road-based transportation. The autonomous solution will also be significantly better in environmental terms. However, there is a significant economic trade-off considering the time-associated KPIs. We will consider the "worst-case" scenario where the vessels in Use Case C will be powered by methanol.

Methanol has a significantly lower heat value than typical bunker fuels, and thus requires more fuel to provide the same power. The specific fuel oil consumption of a (fully) methanol powered marine engine will be in the range of 322–350 g of methanol per kWh. With a current trading price of €350 per ton, the cost would be €0.116/kWh or €0.0061 per ton-km. The latter is higher than the land-based alternative. Regarding time-related economic KPIs, a similar picture is observed as with Use Case B. As with Use Case B, there will be a reduction of employee needs for cargo handling at each port. We assume a speed of 20 moves per hour for one crane (assuming containers), and a similar time for the Ro-Ro vessel case (assuming cargoes are trailers). The land-based alternative is a distance of 316 km and would take around 4.5 h. For a maritime connection, the sailing distance between the two ports is estimated at 137 NM which would require approximately 14 h to transit.

4.2.2. Environmental KPIs

For Use Case A, mother vessels will compete with a shipping option from Rotterdam to Norway, and in environmental terms it is evident that the autonomous solution will have better KPI values. For the battery powered options, the associated emissions can be estimated based on the grid powering the batteries. Emissions will be much lower for the autonomous solution, particularly due to the Norwegian grid that is far cleaner (16 gs of CO_2 per kWh). In the Netherlands the grid is not as clean (441 gs of CO_2 per kWh), but the charging will be done in both countries and thus an average value should be used for comparison. In case a methanol/diesel propulsion system is used, the emissions intensity will be comparable. These grid emission factors are taken from online sources that include Eurostat, and national statistical services. The specific fuel oil consumption of a methanol powered marine engine will be in the range of 322–350 g of methanol per kWh. With a CO_2 emission factor of 1.375 the emissions per kWh will be between 422 and 481 gs of CO_2. Both solutions will also have a much better performance in other pollutant emissions due to the much lower emission factors for SOx, NOx, and PM emissions. A typical fuel consumption for a EURO 6 truck of 40 tons (with a payload of 26 tons range of 0.21 to 0.26 l/km is provided by Volvo (2021), but this will also depend on prevailing traffic conditions, route geography (inclines), weather conditions and other environmental factors. Table 9 shows an estimation of emissions for a road option using a EURO truck 6.

We note that these numbers refer only to the tank to wheel emissions, and do not consider lifecycle emissions (from well to wheel). For instance, Perimenis et al. (2011) estimated that including the well to tank emissions for a typical truck, would increase emissions by 18.9%, although this would also vary significantly with different driving conditions.

For the fully electric vessels, emissions can be estimated based on the average grid emission factor of the country (or region in case this significantly differs) providing this energy. To quantify these factors, it is vital to know the energy mixture powering the country. For Use Case B, the average CO_2 grid emission factor of the Netherlands is estimated at 441 g/kWh, whereas for Belgium it is lower at 207 g/kWh. For SO_x, NO_x, and PM emissions there is currently not detailed information on average grid emission factors. For the Belgium national grid, Zis et al. (2014) used a value of 0.125 g/kWh for SO_x, 0.397 g/kWh for NO_x, and 0.059 g/kWh for PM, while also using 207 g/kWh for CO_2. Therefore, it is evident that these four KPIs will be much lower with the autonomous solution compared to the use of trucks. It has to be noted however that as road transportation will also gradually move to electro mobility, a similar environmental benefit will be enjoyed if electric trucks are to be used in the future.

The use of alternative fuels and fuel cells technology also the potential to reduce GHG and other pollutant emissions. The reaction taking place within the cell is only forming water, so there would be virtually no CO_2, NO_x, SO_x, or PM emissions. From a lifecycle perspective, there might be some emissions depending on how the hydrogen has been produced (e.g. Blue, green, brown, etc.). As a reference, we note the life cycle assessment of Wulf and Zapp (2018) for on-shore production, distribution and consumption of hydrogen stored in LOHCs shows that the aforementioned processes have a Climate Change impact indicator of 5,85 kgCO2 / kgH2.

For the remaining environmental KPIs, it is anticipated that noise levels will be reduced when the autonomous solution is used (even more if also the mother ship is electric), and similarly light pollution will be lower. Some minor cargo terminal area might be

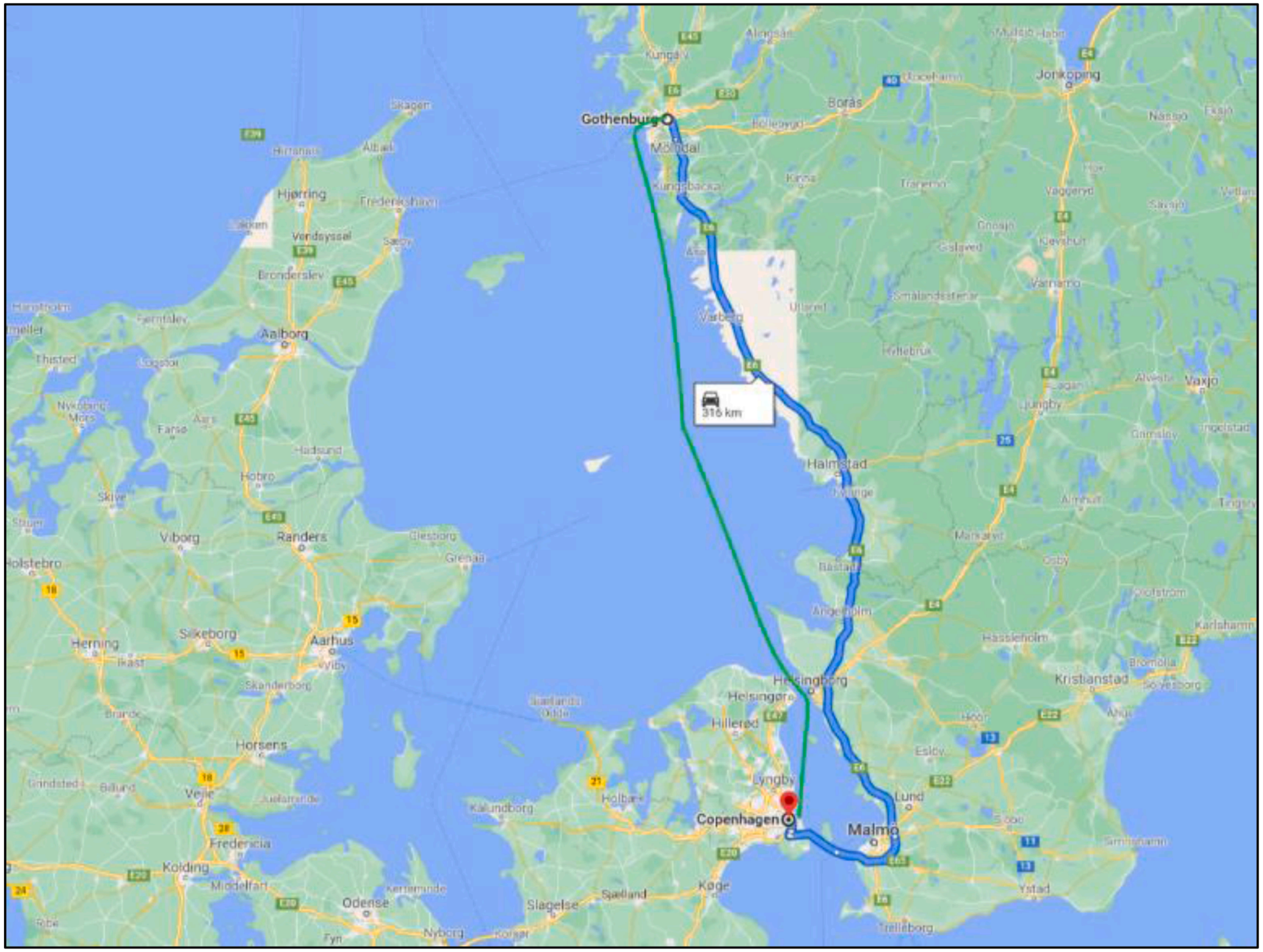

Fig. 3. A hypothetical connection between Copenhagen and Gothenburg.

Table 9
Basic emissions calculation for a EURO truck 6. Data source: (Volvo, 2021).

Pollutant	Emission factors (g/l)	Fuel consumption per ton transported (l/tkm)	Emissions (g/tkm)
CO_2	2600	0.0078	20.48
SO_2	0.01	0.4	0.000078
NO_x	0.9	0.27	0.000709
PM	0.01	1.34	0.000078

required at each port of call, but as the daughter vessels will be carrying small number of containers, it is possible to rely on just in time logistics, and thus there will not be as much requirement for terminal space.

4.2.3. Social KPIs

For all Use Cases, staff would be required at the shore for the operation of the vessels, and a control centre would be necessary for monitoring as well as for prevention of cyber-attacks. In general, the staff working at the control centre would need to have a higher education level and receive some training to effectively monitor operations. Provisionally, 8–10 employees should be sufficient to successfully monitor the autonomous vessels per Use Case, allowing also for a rotation of shifts between staff. For the cargo handling operations, it is expected that one member of staff is required to operate each crane assigned to the ship. For the handling of mother vessels, due to the higher capacity, up to five cranes could potentially be required to operate simultaneously (to allow for a reasonable turnaround time of the vessel), while for the daughter vessels only one crane would be enough. It is anticipated that for the feeder services (smaller ports in Trondheimfjorden) new jobs would be created. As the mother services would not replace existing services, there would not be jobs lost. The feeder services would result in some reductions of road transport, but due to the low cargo volumes that will shift in the beginning, we do not anticipate reduction of jobs immediately.

For the other social KPIs relating to fatalities, injuries, accidents, and incidents, it is too early to estimate these values. Some cargoes would alternatively be moved by road options, which have a higher accident rate than waterborne modes. In 2019, 1 269 lives of truck drivers were lost in road accidents in Europe (Eurostat 2021), while 60% of these fatalities were concerning light goods vehicles (up to 3.5 t capacity). On average, 2.8 fatalities per million inhabitants in Europe were attributed to goods vehicles. Therefore, some reduction in the risk of a fatality rate can be expected by this modal shift. For maritime modes, no country specific data are available, but in 2019 there was only one fatality in the North Sea with cargo vessels involved. For comparison purposes, it is worth noting that fatalities of truck drivers are also a very important issue in the USA. In 2019, 843 truck drivers were killed, while 1 005 light-truck drivers perished as reported by the U.S. Bureau of Labor Statistics (2019), which constituted this profession as one of the most dangerous (7th in 2019) in terms of 26.8 deaths per 100,000.

On cyber security and associated recovery risks, it is expected that the risk of cyber-attacks is low. The vessels would only transport a very small number of trailers (or containers), and for the IWW case, due to the constraint passage and easy access from the shore (the banks of the river way), it would be easier to recover the vessel in case of an attack.

5. Conclusions and further research

This paper presented the first findings in the context of an ongoing H2020 project focusing on autonomous shipping and port operations. The objective of this paper was twofold. To present a novel set of Key Performance Indicators (KPIs) that could be useful in assessing future autonomous maritime transport solutions and construct a methodological framework that facilitates comparisons with conventional transportation modes. Such benchmarking tools will be crucial in the coming years to demonstrate how autonomous solutions are economically and environmentally viable, while also satisfying traditional societal criteria. KPIs can be particularly useful in benchmarking different solutions and alternatives, but can only act as decision support, and not provide a clear optimal decision. Essentially, there will always be trade-offs when one option can be more efficient in environmental terms, but score lower on some traditional economic criteria such as overall transportation time. In these cases, it can be very subjective on what solution is preferable, and it will depend on the priorities set by the decision maker. For example, in the ongoing discussions on some of the proposed case studies in the context of the project, the final decision on which ship design to select, will be made on the actual type of cargo to be transported, and the overall capacity of the ship design, rather than the actual values scored in some of the proposed KPIs. Therefore, it is important to emphasize that any KPI framework can be very useful in assisting a decision, but it cannot offer a clear ranking of alternatives, considering the multi-objective nature of the decisions at hand when considering autonomous shipping.

The second objective of the paper, was to attempt a preliminary analysis of the three illustrative Use Cases in the context of the project. From the analysis conducted thus far, the following would seem to summarize where we stand as regards the main economic (cost and time), environmental (energy and emissions), and social KPIs for each case.

In economic terms, initial results are not favourable to the autonomous solutions due to the anticipated higher costs, and significantly slower transportation options for most examined cases. In addition, some of the use cases are inconclusive as these will depend on the actual power option used at the implementation stage, and the prevailing market conditions as regards the fuel and electricity prices.

In environmental terms, it would seem that the autonomous solutions are better than the baselines in terms of KPIs. It is important to note that a life cycle approach would be beneficial for some comparisons between the alternative solutions examined. For instance, when comparing fossil-fuelled powered engines with electric vehicles or alternative fuels, the emissions for the production and transportation of the fuel should also be considered, along with energy consumed for building each solution. Building on the attained environmental KPIs, a discussion on the impact on biodiversity will also be important, considering the number and type of affected flora and fauna by the operations of the transportation alternatives examined. Biodiversity impact is one of the biggest challenges and most likely a measure that needs to be reported on by companies in the future.

On the social aspects, due to lack of concrete data for the estimation of social KPIs, no concrete conclusions from it can be drawn at this stage of the project. As things stand, it would seem that the potential reduction of fatalities due to the shift of freight from road to sea would be one of the social benefits, accompanied by the creation of higher paid jobs for people manning the autonomous system control centres. However, more analysis is needed to shed more light into these and other social KPIs.

As seen in this paper, there are some trade-offs emerging as it would be expected for any novel technology. As such, economic KPIs that in general are not currently favourable to the autonomous solution, are compensated by the generally more favourable environmental performance vis-à-vis the business-as-usual alternative. The development of win-win solutions is the overall aim of the project, and it remains to be seen how this can be achieved in the future, bearing in mind that we are moving towards a polluter pays principle in maritime shipping, that may play a crucial role in the further adaption of such technologies.

As this paper was being finalized, there are several aspects of recent EU regulatory activity that we think are directly relevant for the autonomous ship system under consideration. The first is the impending inclusion of shipping and road transport within the EU Emissions Trading System (ETS). This inclusion will be in the context of the "European Green Deal" and the "Fit for 55″ package and (see EC (2021, 2022a), EP (2022)). For shipping, compliance with the new legislation would require the purchase of emissions allowances for all of the CO_2 emissions of intra-European Economic Area (EEA) trips, 50% of the CO_2 emissions of all trips incoming to the EEA, 50% of the CO_2 emissions from all trips outgoing from the EEA, and all at-berth CO_2 emissions at EEA ports. Vessels of 5000 gross tons (GT) and above would be included in the scheme. Perhaps more important, also included in the scheme would be transport of goods by truck, with a designated cap of €45/tonne of CO_2 on carbon price. Such an inclusion would surely favor the autonomous ship solution, given that (a) maritime CO_2 emissions are expected to be lower than those of the road transport alternative, and (b) many of the autonomous vessels would fall below the 5000 GT threshold and thus would be excluded from the ETS cost.

The other piece of EU legislation that is coming soon online is the FuelEUMaritime Regulation (see EC (2022b)). This is a Regulation that promotes the use of alternative, low carbon marine fuels, and electric propulsion, very much in line with energy sources contemplated by the autonomous ship solution.

Conversely, and because of the above considerations, and also because the expected reduction of road accidents and fatalities brought about by the autonomous ship solution is an important societal goal, it is expected that these type of vessels will be very much in line with the overall EU policy framework.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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