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A task-based analysis of the economic viability of low-manned and unmanned cargo ship concepts

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ABSTRACT

While successful trials for autonomously navigating ships have been conducted, commercially available unmanned cargo ships are currently unavailable. However, there are many solutions available that will allow for low-manned ship concepts long before fully unmanned ships are possible. There are many drivers for low-manned and unmanned shipping, ranging from availability of workforce, to increased safety to economic. This article investigates the economic viability of several low-manned ship concepts as well as the unmanned ship concept for a short sea container vessel. The operating cost of these concepts are compared to those of a conventional vessel. That way, an assessment can be made on the economic viability. The results show that the low-manned concepts investigated in this article are worthwhile for the ship owner, as some savings can be achieved. The economic viability of the unmanned concept is dependent on the chosen type of propulsion.

1. Introduction

In the last decade, research and practical tests have shown that building an unmanned autonomous ship is possible. Ships have already had the ability to autonomously follow a pre-plotted path for decades. It has now also been demonstrated that ships can autonomously navigate around obstacles (Joint Industry Project Autonomous Shipping, 2019; Rolls-Royce, 2018). Processes such as mooring can be automated (Cavotec, 2017; MacGregor, 2019) and although current diesel engines require significant maintenance and monitoring, new, cleaner and less maintenance-intensive alternatives are now available. While some of these technologies need to mature before they can be used on a large scale and in real world situations, autonomous ships are technically possible.

However, technical feasibility is not the only hurdle that needs to be achieved before autonomous ships will be broadly implemented in commercial shipping. Even expected benefits such as increased safety are not enough. To achieve full commercial acceptance in a highly competitive industry like shipping, the economic benefits need to outweigh the costs. Therefore, the economic impact of the adaptations in the ship's design and operation that are required to replace all humans on board needs to be investigated. This article addresses that challenge.

1.1. Research into the economic viability of unmanned ships

In the MUNIN project, a comprehensive study of the economic feasibility of an autonomous trans-Atlantic bulk carrier is investigated (Kretschmann et al., 2015, 2017). In this research, it was concluded that only removing the crew is most likely not going to cover the increased investment cost. In Norway, a full scale autonomous ship is in production. This ship, the small short sea container vessel Yara Birkeland, is intended to sail through the Norwegian fjords between two ports. The project, which was suspended for an unknown period in the middle of 2020, has thus far cost an estimated €30,000,000 (Wee, 2019), which is approximately 5 times the cost of a conventional ship of that size. However, a significant part of these additional costs come from the fact that the ship is battery powered.

Additionally, research has been conducted on the use of autonomous and semi-autonomous ships in the transport chain (Akbar et al., 2020; Colling and Hekkenberg, 2020). However, these articles focus on the effects of low-manned or unmanned ships in the supply chain, and do not look into the detailed cost of a single ship. The examples above show that it is not a given that autonomous ships will be economically feasible. In this article, the economic viability of an autonomous cargo vessel is investigated, using a short sea container vessel as a case study. The crew cost of a short sea container vessel makes up a significant fraction of the operational cost, which makes it a promising case.

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1.2. Methodological foundation

This research builds on previous work by the authors. This research is summarized briefly. The research is built on the approach that in order to design a ship that is unmanned, one must first chart what the crew does on board, thus ensuring that all tasks are adequately replaced. The authors previously conducted a field study which resulted in a functional breakdown and a task breakdown of a short sea container ship and its crew (Kooij et al., 2018). This list of tasks was evaluated with the help of industry experts to find clusters of tasks that could be replaced or automated together. This has resulted in 10 key clusters of tasks that need to be automated or replaced in order for the ship to fulfil its main functions.

Kooij and Hekkenberg (2020) discussed the potential replacement options for these 10 clusters. The replacement options can be either technical (e.g., increased automation) or organisational (i.e., a different maintenance plan). In this article, we give a short explanation of the selected solution. More detail can be found in Kooij and Hekkenberg (2021). The 10 clusters that require replacement are:

1. Mooring; safely fastening the ship to shore and unmooring when the ship leaves.
2. Navigation; safely navigating the ship in all conditions, in port and also at open sea.
3. Maintenance on deck; maintenance of the superstructure and hull, cleaning and maintenance of the reefer containers.
4. Maintenance in the engine room; performing maintenance in the engine room, mostly on the main propulsion unit
5. Cargo conditioning; the vibrations of the ship cause the container lashings to release, this means that the lashings need to be refastened.
6. Port supervision; while the ship is in port, a port watch is set to keep track of general safety of the ship, keep track of who comes on board and check hat the loading and unloading of the ship is done correctly.
7. Administration; general administration of the ship such as ordering stores and spares, planning maintenance, checking worked hours etc.
8. Bunkering; the bunkering is done by the bunkering company, but the process is supervised and assisted by a crew member.
9. Responsibility; according to international legislation, someone on board needs to be responsible for the ship
10. Life support; providing medical care and providing food and drink.

Using a Crew Analysis Algorithm (CAA) that was set up specifically for this problem, the required crew, both in number and in skill level, for any combination of task clusters that still have to be executed by the crew can be determined. The details of this algorithm can be found in Kooij and Hekkenberg (2019) and Kooij and Hekkenberg (2020). Being able to calculate the required crew in any situation, means that it is also possible to determine the savings for the crew cost in these situations.

It is unlikely that ships will evolve from fully manned to fully unmanned in one step. Dependent on the availability of technology, several intermediate steps are expected before the final implementation of a fully unmanned, autonomous ship. The most logical intermediate steps are identified in Kooij and Hekkenberg (2021). In this article, logical steps are followed from the conventional situation towards the fully autonomous situation. Table 1 shows the results of that analysis, as also presented in Kooij and Hekkenberg (2021) and introduces the intermediate steps that will be subjected to further analysis in this article. In the first concept, the open water navigation is replaced. In the second concept, many tasks are moved to shore, either by automating them, redistributing tasks to shore personnel or hiring a service to complete the tasks. In the third concept, all navigation is automated and bunkering is outsourced. In the final concept, the last two crew members are replaced by finding a solution for the maintenance of the propulsion system. The results from that part of the research are used in this article to determine if the benefits of replacing a cluster of tasks by an alternative solution are larger than the costs of that solution. To do this a cost estimation is made of each of the 10 key clusters that were identified in earlier research by the authors.

2. Method

To determine the economic feasibility of autonomous ships, a cost-benefit analysis is performed for each step presented in Table 1. To perform the cost-benefit analysis, it is important to know the details of the technical and organizational changes that are required to replace each of the clusters of tasks and determine the cost and benefits of each of the solutions.

For the analysis, the standard cost breakdown of a conventional ship is used. This breakdown is commonly used to analyse the different costs that a ship incurs in its lifetime (see, for example: Ghaderi (2019); Kretschmann et al. (2017); Ros et al. (2020) and Zhu et al. (2020)). Not all cost aspects of a conventional ship are expected to change for each replacement solution. The first step is, therefore, to investigate which cost aspects are going to change when changes to the ship design are made. Next, the costs are quantified for each of the replacement solutions. Since several solutions are not commercially available yet, there is still uncertainty about their cost. Due to this inherent uncertainty, this article does not claim to present highly accurate cost calculations. It does, however provide values that are accurate enough to judge if a solution is significantly cheaper, significantly more expensive or approximately equally expensive as not replacing the affected task clusters, and thus if it is likely that a solution is economically viable.

2.1. The case study

The analysis method used in this article applies to all cargo vessels, but the calculations are performed using a short sea container vessel as a case study. The original crew for this ship, as well as the monthly cost for

Table 1
Concepts from conventional situation to autonomous unmanned situation with the monthly cost savings per *solution* (Kooij and Hekkenberg, 2021).

Concept		Required crew			Cumulative cost reduction [€/year]	Percentage wise cost reduction of total crew cost
		Loading and unloading	Arrival and departure	Normal sailing		
1	Base case	9	9	11	0	
2	Replacement of open water navigation	9	9	8	67,200	5.7%
3	Replacement of mooring, maintenance on deck, port supervision, administration, cargo conditioning and redistributing the cooking task	3	3	3	566,400	48.3%
4	Replacement of near shore navigation, bunkering and moving responsibility to chief engineer	2	1	2	782,400	66.6%
5	Replacing maintenance in engine room, responsibility and life support	0	0	0	1,173,600	100%

the ship operator for each of these crew members is given in Table 2. The costs for all the crew members are provided by JR Shipping, a Dutch company that operates, among others, several short sea container vessels. 2 Full crews are required to allow the ship to sail year round, as crew members also have time off after working on the ship for a period of time.

The ship used in this case study is a 135 m long, 750 TEU, short sea container vessel operating between Belfast, Ireland and Antwerp, Belgium. The ship has a gross tonnage of 7680 GT (Confeeder Shipping & Chartering, n.d.). The building cost of the ship is calculated according to Martínez-López et al. (2013):

$$C_{build} = -4 \cdot 10^{-8} \cdot GT^2 + (0,0029 \cdot GT - 2,5447)\left(\frac{10^6}{1,29}\right) = €15,292,500$$

The conventional ship is crewed by 11 crew members, as per Table 2. For a standard operating year, 360 sailing days are assumed (Aalbers, 2000). Of these 360 days, 180 are spent in port and 180 are spent sailing, the remaining 5 days the ship is idle. This analysis is performed on a ship that sails for three days and then spends three days in port for loading and unloading. This means that the ship arrives in port 60 times per year.

2.2. The cost structure of a conventional ship

The costs of a ship can be split up into several different elements. Some of these costs will change between a manned ship and an unmanned ship, and some will remain the same. To perform a cost-benefit analysis, only the factors that change are of interest. The cost structure of a conventional ship is investigated to find which factors will change.

For this work, the cost of operating and owning a ship is defined according to Stopford (2009):

$$C = OC + PM + VC + CHC + K$$

In which:

OC = Operating Cost (i.e., crew cost, stores, repair and maintenance and insurance)
PM = Periodic Maintenance Cost (i.e., interim dry-docking and special surveys)
VC = Voyage Cost (i.e., fuel costs, port and canal dues)
CHC = Cargo Handling Cost
K = Capital Cost (i.e., depreciation, interest)

The expected impact of manning reduction on these cost items, and the reasoning behind this can be found in Table 3.

2.2.1. Changes in the operating cost

The operating cost are the cost of day to day operation of the ship. These costs are further split up according to (Stopford, 2009):

$$OC = M + ST + MN + I + AD$$

Table 2
Cost for the ship owner per *crew member* per *month [Data provided by* (JR Shipping, 2019)].

Crew member	Monthly cost [€]	Original crew
Captain	9000	1
Chief Engineer	8900	1
Chief Officer	7500	1
Second Engineer	7400	1
Second Officer	4200	1
Bosun	2400	1
Cook	2700	1
Able Bodied Seaman (ABS)	2000	2
Deck boy (DB)	1400	2
Total crew cost (2 crews)	**97800**	

Table 3
Expected changes of the different cost factors.

Cost item	Change expected?	Reasoning
Operating cost	Yes, decreasing	As the size of the crew becomes smaller, the crew cost will decrease. Other costs, such as maintenance and repair and insurance will change due to newly installed systems and changed maintenance strategies.
Periodic maintenance	No	Costs for dry-docking and special surveys are assumed to be constant. Additional maintenance costs due to changes in maintenance strategy are covered under new costs for solutions to replace crew tasks.
Voyage costs	Only when the propulsion is changed	The routes and speed will not change, therefore the voyage costs will remain the same. While a smaller crew will lead to a lower auxiliary power use, this effect is deemed negligible. A change in fuel cost is expected if another type of propulsion is selected. The fuel cost is assumed to remain constant for all other changes.
Cargo handling cost	No	The cargo capacity of the ship is assumed to be constant and the cargo is still handled with the same shore-side equipment.
Capital cost	Yes, increasing	New systems will increase investment cost, thus also increasing the depreciation, interest and insurance. For unmanned ships, the accommodation can be removed, saving on building costs.

In which:

M = Manning
ST = Stores (i.e., Food and drink, lube oil)
MN = routine Repair and Maintenance
I = Insurance
AD = Administration Cost (i.e., management fees, registration cost etc.)

Fig. 1 gives an overview of the distribution of these costs for conventional ships carrying a maximum of 999 TEU (Moore Maritime Index, 2019). Using the crew cost as an input for the ship used in the case study, the costs can be determined.

The decrease in manning cost is given in Table 1. It is assumed that the stores will decrease proportionally to the decrease in crew size. The changes to the operational costs are based on the percentages in Fig. 1. In general, maintenance costs are estimated on the basis of the initial investment cost of the engine, number of running hours, installed power or cost of fuel (Hekkenberg, 2013) on the total initial investment cost (Aalbers, 2000). In this case, the total initial investment cost is used to calculate the maintenance costs for the suggested adaptations. Using the calculated maintenance cost from Fig. 1 and the total investment cost (€15,292,500) the percentage of maintenance cost can be calculated. This is 2.4% of the total investment. The administration cost for the ship will remain the same regardless of manning. Finally, the fuel cost will only change is there is a change in propulsion type.

2.2.2. Changes in the capital cost

The capital cost are the obligations incurred due to investments to pay for the vessel. For this research, only the interest, insurance and depreciation are important. The addition of new systems to the ship will change the total investment cost of the ship and therefore the interest and the depreciation. The interest is set at 5% of the total investment annually. The insurance is calculated based of the data in Fig. 1. Following the same calculation method as for the maintenance cost, the yearly insurance is calculated to be 0.4% of the total investment cost.

Cost factor	Yearly cost [€]
Crew cost	1,173,600
Maintenance and repair	356,400
Stores	168,000
Insurance	62,400
Administration	314,400
Fuel consumption	3,267,000

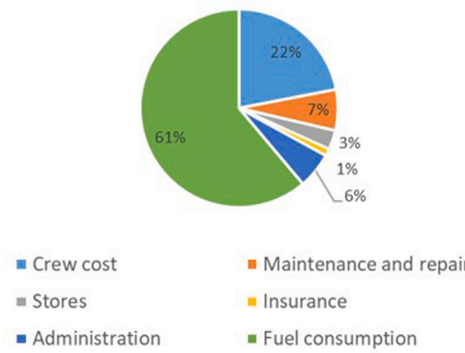

Fig. 1. Yearly operational expenses [crew cost obtained from JR shipping, fuel cost calculated from (Confeeder Shipping & Chartering, n.d.) and MGO cost on March 12, 2021 and other percentages taken from (Moore Maritime Index, 2019)].

For each of the systems that are installed, a lifetime is assumed. For this research, it is assumed that the value of the system reduces to zero, as the remaining value is unknown. By assuming that the remaining value of a system is 0, the worst case scenario is investigated. A linear depreciation is assumed, meaning that each year, the value of the system decreases with the same fraction. The depreciation of the newly installed systems needs to be covered by the savings due to the reduced crew.

2.3. Quantifying cost for replacement solutions

Next, the costs for each of the replacement options for the task clusters need to be quantified. There are three types of solutions:

1) a technical solution where a system is placed on board or on shore.
2) an organisational solution where shore-based personnel is used to perform tasks, and the company has the personnel on the payroll, i.e. administration personnel or Shore Control Centre (SCC) personnel.
3) a solution where a service is hired from another company (i.e., hiring a maintenance crew or a shore crew). In these cases it is not profitable for the ship owner to have the personnel permanently available. In that case, it is assumed that services are offered by established companies, even if these services do not currently exist.

For each of the solutions for the replacement of a task cluster, the expected cost to the ship owner are determined. Some solutions are already commercially available. In that case, known costs are used. However, in many cases, solutions are not commercially available, making cost estimations more difficult. In that case, best estimates are used, using either comparable solutions that are available (i.e., from other industries or similar but not exact solutions) or using the costs of different elements to estimate a total cost.

3. Cost assessment of individual solutions

This section discusses the estimated replacement costs of each of the clusters mentioned in section 1.1. These estimations are based on academic literature, data on existing systems and logical analysis of the processes to be replaced. As mentioned before, the aim of this article is to judge if a solution is significantly cheaper, significantly more expensive or approximately equally expensive as not replacing the affected task clusters, not to provide a highly detailed cost-benefit analysis.

Depending on geographical location, on board crew members can be significantly cheaper than people working on shore. This is e.g. the case on the investigated route of the case ship, which operates between European ports. In the Netherlands, minimum wage, for jobs that require little specific training, is €1635 per month (Rijksoverheid, 2021). Ghaderi (2019) states that the overhead cost on top of the salary of crew member is 36%. This means that the cost of employing a low skilled crew member on shore is 59% higher than that of an equally skilled crew member on board. This article uses a lower limit (presented in Table 2) and an upper limit (59% above these costs) to have a reasonable range for the crew cost.

As shipping is a 24/7 business, many of the services offered are also 24/7. This means personnel needs to be available at all times. Kretschmann et al. (2015) state that to cover a full time service, 5.7 FTE (Full Time Equivalent) is required per position.

3.1. Concept 1

3.1.1. Automated open water navigation

In the first step towards unmanned ships, as defined in Table 1, navigation in open water is automated. In this concept, 2 crew members are removed. Navigating in open water is easier than navigation near shore and in busy traffic lanes. Therefore, a relatively simple autonomous navigation system is required. Such a system is not yet commercially available and, therefore, there is no detailed cost information available. It seems that the autonomous navigation systems will work with the current sensors on board, which means that no further changes to the ship are required, as long as the ship is modern and is equipped with electronically controlled steering, radar, AIS and ECDIS. In the NOVIMAR project, a vessel train concept is designed in which several ships automatically follow a leading vessel in close proximity. The project estimates that the smart navigation system in this concept costs €80,000 (Hekkenberg et al., 2020). So, this value is assumed for lack of better data. This lifetime of this system is assumed to be 5 years.

3.2. Concept 2

In concept 2, the mooring, maintenance on deck, port supervision, administration and cargo conditioning task clusters are replaced. In this concept, only 3 crew members remain, the captain, a chief engineer and a second engineer.

3.2.1. Mooring

To replace the mooring task, two options are considered. The first is to take a shore-based mooring crew on board that performs all the required mooring tasks, while the second is to use an automatic mooring system. In general, there are two types of automatic mooring systems, a shore-based system (Cavotec, 2018), or a ship-based system. Both of which preferably interface with the existing system of lines and bollards (MacGregor, 2019). Díaz et al. (2016) assume a cost of €1000 per port call, for the use of a shore based mooring system, which amounts to €60, 000 per year with 60 port calls.

Instead of using an automated mooring system, it is also possible to use a mooring crew. This crew would come aboard (for example with the pilot), perform the mooring operation and leave again. The length of a mooring operation differs between ships, port layout, weather conditions and many other factors. Therefore, it is difficult to estimate how long a mooring operation will take. In this article, it is assumed that the whole mooring process, including sailing to or from the ship, takes between one and 3 h. Mooring of the ship requires 7 crew members at different levels of training: a second officer, 2 bosuns and 4 deck boys. The total monthly cost for 1 such crew ranges from € 14,600 to € 23,200. However, the crew needs to be available 24/7 year round to a total cost of € 998,400 - €1,586,400. However, as this is a hired service, the ship only pays for the time the crew is used.

It is possible for the mooring crew to travel to or from the ship with the pilot. This is an existing service. In the port of Rotterdam, the cost of this service is €500 for the whole crew. The full calculation for the mooring cost is listed in Table 4. From this table it is concluded that the cost of using a mooring crew is significantly higher than using an automated mooring system.

3.2.2. Maintenance on deck

Much of the maintenance on deck is general upkeep of the ship, such as cleaning and painting. While a significant portion of the workload of the deck crew consists of these tasks, it is difficult to quantify how much of the work is strictly required and how much is done because the crew is available anyway. For the purpose of this study, the following replacement solution is assumed, based on interviews with industry experts (i.e., teachers from different Dutch nautical schools, each with sailing experience):

- Every month a team is sent on board to clean the walkways and other internal spaces to keep them accessible and safe.
- The hull maintenance (i.e., cleaning and painting) is performed during survey and docking periods.

The cleaning crew will consist of two people that are hired for 8 h each, while the ship is in port. The skill level of these people is assumed to be equivalent to that of a deck boy. In the five days that the ship is not in service, the maintenance of the hull and superstructure needs to be performed. This includes chipping, painting and other general maintenance. As this task is normally performed while the ship is at sea, it is difficult to predict the amount of maintenance and the time it will take to complete it. In this article, it is assumed that the maintenance is performed by one team, consisting of a bosun and between 10 and 20 deck boys. Table 5 gives the full calculation of the cost.

3.2.3. Port supervision

While the ship is in port, several supervision tasks are performed by the crew. The most important tasks are supervision of the loading and unloading process and access control of the ship. Currently, these tasks are performed constantly, mostly in combination with other tasks. Access control and monitoring of the ship can be solved relatively easily and cheaply with electronic access gates and cameras, costing an estimated €2.500 (Kompareit, n.d.) for the access gate and €20.000 for the security system (Butler Durrel Security, 2017; Richmond Alarm, n.d.).

Table 4
Cost calculation for mooring crew.

Factor	Value	Unit	Total per year
Port operations	120	Per year	
Usage of mooring crew	1–3	Hours per operation	120–360 h
Crew cost	€114 - €181	Per hour	€13,600 – €65,200
Crew transport	€500 (Nederlands Loodswezen, 2021)	Per operation	€ 60,000
Overhead and profit (50% of crew cost)	€ 3400–15,400	Per year	€3400 – €15,400
TOTAL			**€ 77,000 – €140,600**

Table 5
Cost calculation for maintenance on deck.

Cost factor	Value	Unit	Total cost per year
Cleaning – deck boy	€100 - €160	Per day	€6000 – €9600
Maintenance - Bosun	€450 - €715	Per day	€2300 - €3600
Number of deck boys	10–20	Per day	
Maintenance - Deck boy per day	€100 - €160	Per day	€5000 – €16,000
TOTAL			**€13,300 – €29,200**

For these systems, a lifetime of 5 years is assumed.

Monitoring of the loading and unloading process as well as the access control can be done by the ship's agent. This agent will represent the ship as long as it is in port. For a fully unmanned ship, this means letting external personnel on board, representing the ship with port authorities and customs, providing the required documents and ensuring that the loading plan is followed. Due to the relatively high level of responsibility of this task, it is assumed that the agent's pay is equivalent to that of a chief officer. The ship is in port for 180 days out of the year. This results in a total personnel cost of €253,000 - €402,300 per year.

3.2.4. Administration

Based on expert interviews, it is assumed that in case of full automation, 2 h of administration work is required daily for one ship. The administration mostly pertains to the cargo, customs and insurance. All this work can be performed from an office. The person that works on the administration, requires a skill level of a second officer. This means that one administrator can cover 4 ships, splitting the cost between them. The yearly personnel cost ranges from €12,600 to €20,000 per ship. The yearly cost of one office space, including office supplies, furniture etc. is approximately €9800 (Hoogendoorn and Litjens, 2019). This means a cost of €2500 per ship per year.

3.2.5. Cargo conditioning

To ensure that the containers remain fixed in place even in bad weather and without a crew to refasten the lashings, the ship can be equipped with cell guides that extend above the main deck. According to industry experts, the loading and unloading speed of a ship equipped with cell guides is similar to that of a standard ship. Additionally, the steel weight of the cell guides, is offset by the fact that the ship no longer requires hatch covers (Bendall and Stent, 1996). Using the steel weight as the indicator for the cost of this solution, means that using cell guides does not change the investment cost of the ship.

3.3. Concept 3

In concept 3, the near shore navigation is replaced, along with the bunkering and life support clusters. For this concept, only 2 crew members, the chief engineer and the second engineer remain.

3.3.1. Automating near shore navigation

When automating near shore navigation the navigation system must be able to also navigate in port, and place the ship next to the quay to be moored. This means that the navigation system needs to be more precise than a system that only operates in open water. For this research, the cost of the system is assumed to be double that of the open water navigation system, i.e., €160,000. The lifetime remains the same at 5 years.

In this step, when near shore navigation is implemented, there will no longer be bridge personnel on board. This means that the possibilities of the remaining crew to react to problems with the navigation system are limited. This implies that a shore control centre (SCC) is required, since nautical operations still need to be monitored. According to the MUNIN project, 1 operator is able to monitor 6 ships. In addition to this, a backup operator and a supervisor are required for every 5 (or less) operators (Kretschmann et al., 2015). This means that, ideally, a company operating a shore control centre would monitor a multiple of 30 ships, as it would be the best distribution of resources.

The office space of an operator is used 24/7 instead of only during normal business hours. Therefore, the costs incurred for the personnel to function (e.g., coffee, catering, office supplies), at a value of approximately €1000 per year are tripled (Hoogendoorn and Litjens, 2019). This means that the total cost for one 24/7 work station adds up to €11,800. Additionally, the work station of an operator is not the same as that of a regular employee. To monitor 6 ships, the MUNIN project (Kretschmann et al., 2015) assumes a computer with significant processing power and 5 screens (one per ship) is required. The cost of such a setup is €2600 per work station on top of the standards office cost. The lifetime of this equipment is estimated at 3 years.

According to the MUNIN project, a situation room is required per 15 ships (Kretschmann et al., 2015). This room is used in emergency situations. The cost of a situation room, which is capable of handling both engineering and navigation related emergencies is estimated to be €210, 000. The lifetime of the situation rooms is estimated at 8 years, as they are used only occasionally, in emergency situations. For the propose of this research, the cost of a situation room only for navigation emergencies is assumed to be half of that, €105,000. As the SCC monitors 30 ships, two situation rooms are required. The full cost calculation can be found in Table 6.

3.3.2. Bunkering

The bunkering process is already mostly performed by a third party. However, before bunkering, there is a check on the quality of the fuel. Furthermore, one crew member assists with the bunkering process. The ship's agent, introduced in the port supervision section above can also play a role here. At this point in the analysis, an agent is available to perform these tasks (see section 3.2.3), therefore this incurs no additional cost.

However, should this task be replaced separately, a crew member with the skill of a second engineer would be required. Monitoring the bunkering process can take anywhere from 1 to 4 h. How often a ship bunkers depends on factors such as its cargo, the location where the ship sails, the distance a ship sails and the availability and cost of the fuel, to name a few factors. In this case, it is assumed that the ship bunkers after two complete trips. This means that bunkering takes place 30 times over one year. This results in a crew cost ranging between €1700 and €11,000.

Table 6
Cost calculation of automated near shore navigation.

Factor	Value	Unit	Total cost per year for one ship
Cost of operators	€3,078,000 - €4,894,000	30 ships per year	€102,600 – €163,100
Cost of supervisors	€615,600 – €978,800	30 ships per year	€20,500 – €32,600
Cost of office space 24/7	€82,600	For all crew for 30 ships	€2700
Depreciation navigation system	€160,000	5 years	€32,000
Depreciation hardware cost	€433	3 years	€144
Depreciation situation rooms	€7000	8 years	€875
TOTAL			€138.300 – €231,400

3.3.3. Life support

The tasks that fall under life support, (i.e., medical care and preparation of food and drink) need to be performed as long as there is a crew on board. When the crew is no longer on board, these tasks do not need to be performed any more.

In step 3 and 4 denoted in Table 1, having a dedicated cook on board is deemed unnecessary, as the crew is very small. In that case one of the other crew members could cook, without incurring additional costs. The remaining crew members all have medical training as part of their skill set. It is assumed that this training is sufficient in case of most medical problems.

3.4. Concept 4

In concept 4, the remaining clusters; maintenance in the engine room and responsibility are replaced. This ship is now fully unmanned, which means that some additional design changes are possible.

3.4.1. Maintenance in the engine room

The diesel engine that is used as the main propulsion unit on most ships, requires a significant amount of attention from the crew. Ships, therefore, have an engineering crew on board. Especially rotating parts of the machinery are deemed maintenance-intensive and failure sensitive. A more steady state propulsion, such as fuel cells or batteries offer a solution for this (Kongsberg, n.d.; Tvete, n.d.). In this article, fuel cells are selected for comparison to the conventional diesel engine, since batteries form a very heavy and expensive solution for ships such as the case ship. Another way to decrease the possibility of failure in the engine room is to make use of redundancy. Instead of propelling the ship with one large diesel engine, several smaller diesel generators could be used to ensure that, should one fail, the ship can still sail to safety.

Table 7 gives some key cost parameters for a medium speed diesel engine, two types of fuel cells and a diesel electric configuration that uses 3 diesel generators. Currently, the investment cost of a fuel cell is approximately 10 times higher than that of a diesel engine.

For each of the engine types, the new cost for the propulsion system (i.e., fuel cells and supporting systems) is calculated. The additional depreciation cost per year is calculated by:

$$Depreciation\ per\ year = \frac{(Cost\ of\ propulsion\ system - cost\ of\ medium\ speed\ diesel)}{service\ life\ of\ new\ propulsion\ system}$$

Regardless of the type of propulsion that is selected, an engineer is also required in the shore control centre. This engineer can monitor the data coming in from several ships and determine the maintenance that needs to be performed. One engineer can monitor 30 ships at the same time (Kretschmann et al., 2015). The skill level of this engineer is set as chief engineer. This means that the yearly costs for one ship are €20.300 to €32,300 for the crew and €2700 for the work space.

As mentioned above, the SCC is equipped with situation rooms in case of emergencies. A second situation room, for engineering problems, is now required. The additional investment for these more detailed situation rooms is €210,000, with a lifetime of 8 years. Per ship, this is an additional investment of €7,000, over 8 years.

The fuel cost of the 7200 kW medium speed diesel and the generators is calculated at €3,267,000 per year. For the PEMFC, the fuel cost ranges between €3,569,200 and €8,111,900. The maintenance cost of the diesel engine and the diesel generators is €279,900 per year, assuming 24/7 operation at full power for all 180 active days. For the PEMFC, these costs range between €115,200 and €324,000. It is, therefore, assumed that the maintenance cost for these systems are comparable and they are

Table 7
Key costs of different propulsion types.

Propulsion system	Capital cost	Maintenance cost per year	Fuel consumption	Fuel price	Service life
Medium speed diesel engine	220 €/kW (Abma et al., 2018)	0.009 €/kWh (Hekkenberg, 2013)	33 t MGO/24hr (Confeeder Shipping & Chartering, n.d.)	MGO 550 euro/t	25 years
PEMFC	2500 €/kW (industry expert)	16–45 €/kW (Saito, 2018) 0.0037–0.01 €/kWh (assumptions below)	$\frac{26,08}{500} \cdot P$ kg/hr (Saito, 2018) Or 9 t H_2 /24hr	2200 - 5000 euro/t (KPMG Global, n.d.)	15 years
3 diesel generators	350 [€/kW] (Interreg Danube Transnational Programme, 2019)	0.009 €/kWh (Hekkenberg, 2013)	33 t HFO/24hr (Confeeder Shipping & Chartering, n.d.)	MGO 550 euro/t	25 years

not taken into account as a difference between the systems. Additionally, the 2,4% increase of the maintenance cost is not used in this case, as it would significantly and erroneously favor the diesel engine.

3.4.2. Responsibility

As long as a captain remains on board, the responsibility will remain with them. If that is no longer the case, the responsibility of the ship will be transferred to the SCC. This transfer of responsibility will not bring along additional cost, assuming the SCC is already in place and manned by qualified operators.

Currently transferring the responsibility to shore is not permitted by IMO regulations, which state that a captain must be on board. However, IMO has been working on adapting their regulations towards low and unmanned ships (International Maritime Organisation, 2021) and it is assumed that allowances for this will be made in due time.

3.4.3. Design changes for unmanned ships

When the ship is fully unmanned the accommodation and several crew supporting systems can be removed from the ship. The removal of these systems will decrease the building cost of the ship. Frijters (2017) estimates that the cost savings for a container feeder are 15%. For the ship in this analysis, a saving of 15% adds up to €2,300,000. With a lifetime of 25 years, this translates to a decrease of the depreciation of €92,000 per year.

4. Cost-benefit analysis

To determine the economic viability of the 4 scenarios, the savings due to the removed crew are compared to the increased costs of the replacement solutions.

4.1. Economic viability

The first step is to investigate the economic viability of the 4 scenarios. A scenario is deemed economically viable if the monetary benefits outweigh the additional costs. This is determined by comparing the additional costs that are incurred due to selected solution and the additional OPEX with the savings that come from removing the crew and the savings on stores.

Table 8 gives the total costs and benefits for the 4 scenarios. The table shows that the first three scenarios have a monetary benefit. The fourth scenario has a significant additional cost, which is mainly explained by the high cost of the PEM-Fuel cell and the potentially high cost of the fuel. Equipping the ship with 3 diesel generators would make the scenario viable.

There is only a small monetary difference between the first three concepts and especially between concept 2 and concept 3. Within the uncertainty, it is very possible that there is no monetary benefit to make the step between concept 2 and 3.

4.2. Distribution of cost factors

With the changes made to the organisational structure, the distribution of the OPEX factors also changes. Fig. 2 shows the yearly cost for each of the concepts in the best case scenario (i.e., with the lowest additional cost). The total cost decreases until the concept 4 with the fuel cell, where there is an increase. The main reason for the decrease of the total cost is in the decrease in the crew cost (i.e., crew cost and shore crew cost combined). For the final scenario, the increase in the investment cost due to the use of the fuel cell significantly increases the interest and depreciation. The fuel cost increase as well, but only by a small margin. Together, this causes a significant increase in the cost. In this best case scenario, the cost of the multiple generators is very similar to the cost of the standard diesel engine. This means that many of the costs do not change significantly and that this scenario takes full advantage of the reduced crew.

In the worst case scenario, the differences between the first three scenarios and the reference ship are smaller (see Fig. 3). This is mainly due to the higher shore crew cost, which reduces the effect of the lower on board crew cost. For the PEMFC concept, the main challenge is the increased fuel cost. While at its lowest price point, the cost of the hydrogen barely differs from the cost of the MGO (mainly due to the lower fuel consumption), at maximum cost, the hydrogen costs more than 2 times what the MGO costs.

Table 8
Net benefit for the best and worst case scenarios.

Scenario	Total yearly cost [€]	Net benefit per year [€]	Cost change [%]
Base case	6,718,100		
Concept 1	6,642,600	75,500	-1.1%
Concept 2	6,377,400 to 6,672,000	318,700 to 146,000	-4.7% to -2.2%
Concept 3	6,300,400 to 6,573,600	417,700 to 144,500	-6.2 % to -2.2%
Concept 4 Diesel generator	5,710,400 to 6,034,000	1,007,700 to 684,000	-15.0% to -10,2%
Concept 4 PEMFC	7,541,400 to 12,771,000	-823,300 to -6,052,900	+12.3% to +90.1%

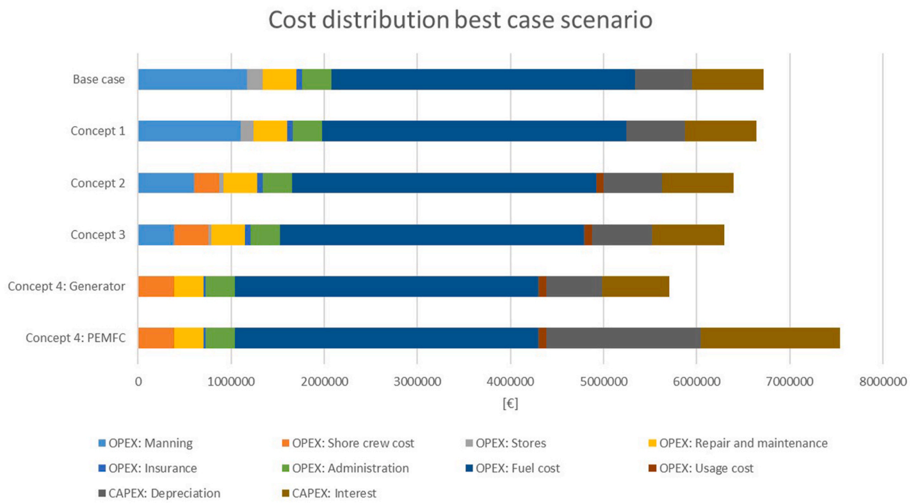

Fig. 2. Distribution of cost factors best case scenario.

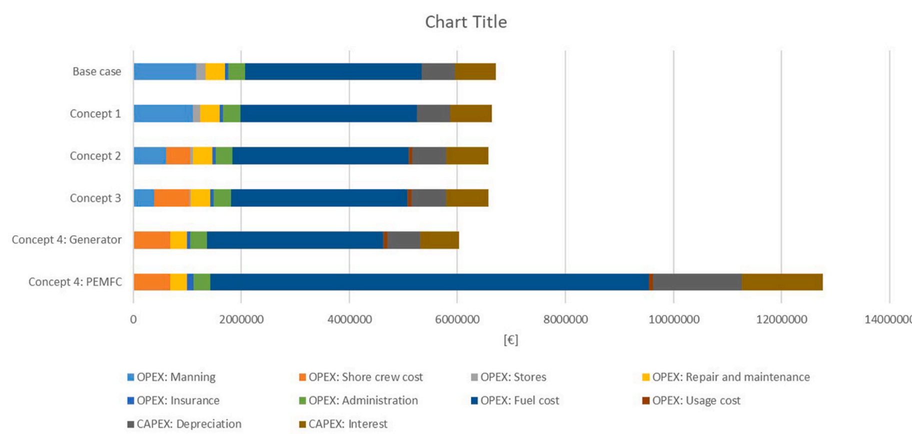

Fig. 3. Distribution of cost factors worst case scenario. Note that the scale of the x-axis is different from Fig. 2.

Table 9
Comparison of changes in cost factors between the base case and the final scenario.

	Base case	Best case		Worst case		**Difference in change between best and worst case**
		Scenario 4: Fuel cell	**Change**	**Scenario 4: Fuel cell**	**Change**	
OPEX: Manning	1,173,600	0	−1,173,600	0	−1,173,600	0
OPEX: Shore crew cost	0	538,600	538,600	1,204,300	1,204,300	665,700
OPEX: Stores	168,000	0	−168,000	0	−168,000	0
OPEX: Repair and maintenance	356,400	314,900	−41,500	317,300	−39,000	−2500
OPEX: Insurance	62,400	121,100	58,700	146,500	84,100	25,400
OPEX: Administration	314,400	314,400	0	314,400	0	0
OPEX: Fuel cost	3,267,000	3,569,200	302,200	8,111,900	4,844,900	4,542,700
OPEX: Usage cost	0	84,300	84,300	116,300	116,300	32,000
CAPEX: Depreciation	611,700	1,680,000	1,068,380	2,116,500	1,504,800	436,400
CAPEX: Interest	764600	1498900	734,300	1,816,000	1,051,300	317,000
TOTAL	6,718,100	8,121,600	1,403,500	14,143,200	7,425,100	6,021,700

Table 9 compares the changes in each of the important cost factors in the best and the worst case for scenario 4 with the fuel cell. The largest changes between the best and the worst case take are in the fuel cost, the shore crew cost and the depreciation. Out of these costs, the shore crew cost is the most interesting, as it holds the most uncertainty. To better define what the cost of the shore crew will be further research is required.

4.3. *Worldwide difference in Manning cost*

In this article the crew cost and wages of a Dutch company are used to determine the crew cost. However, the cost of manning a ship varies significantly dependent on where a ship is registered and where the crew comes from. Fig. 4 shows the different cost of a captain, a chief engineer, a bosun and an ABS for a Dutch crew (high wages) on a Dutch ship, a Russian crew (medium wages) and an Algerian crew on an Algerian ship

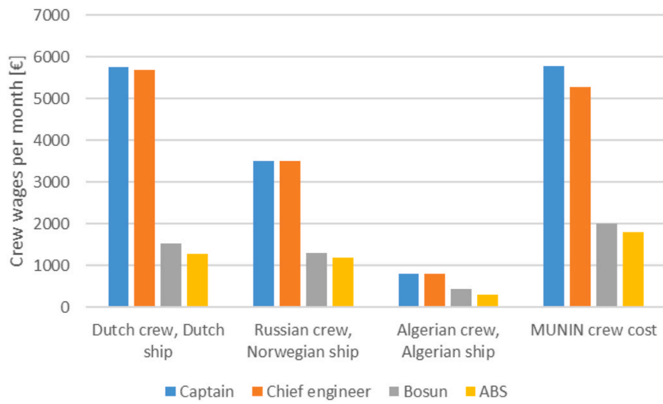

Fig. 4. Different crew wages for different flag state and manning situations. Dutch wages from JR Shipping, MUNIN crew cost from (Kretschmann et al., 2015), other cost from (Silos et al., 2012).

(low wages). As the largest savings for low manned and unmanned shipping comes from the crew cost, this is an area that requires further investigation. A ship crewed by an Algerian crew costs less than 20% of the cost of the Dutch crew used in this research. That would mean that all concepts proposed in this research would not be economically feasible. This means that a significant part of the world fleet, especially ships registered under the so called flags of convenience, would not benefit from low manned and unmanned ship concepts, especially if the ship calls at ports where the shore crews that are used to replace the crew members are not as cheap. Ships that are feasible are ships with a highly paid crew, for example sailing short sea shipping routes or performing specialised tasks in Europe, where the salaries are high.

The same is true for the location of the SCC. If the SCC is placed in a location with high wages the costs of the on shore crew would be significantly higher than when the SCC is located in a low wage region.

5. Sensitivity study

In this section, the sensitivity of the results presented above is investigated. This is done by investigating the maximum possible change in the investment cost and in the total cost that is possible before each of the selected concepts changes from economically viable to not viable.

5.1. Increase of investment cost

The investment cost for the newly required systems have been estimated based on available data. In this part of the sensitivity study, the investment cost of the systems is increased until each of the concepts is no longer economically viable. This is done for both the best case scenario and the worst case scenario.

Table 10 shows that in the best case scenario the increase in the investment cost can be a minimum of 340%. This means that the cost of the navigation system can increase from €80,000 to €352,000 before the costs and benefits of the concepts become equal. For the worst case scenario, the costs can increase with a minimum of 48%, which means that a significant increase is still possible. This means that the investment cost of the new systems is not a significant factor in the economic viability of low and unmanned ships.

Table 11
Possible increase of all cost related to the proposed changes for the best case scenario.

Concept	Initial cost [€]	Maximum total cost [€]	Increase of total cost
Concept 1	80,000	352,000	340%
Concept 2	460,300	584,600	27%
Concept 3	755,200	1,238,500	64%
Concept 4: Generator	1,828,800	3,566,200	95%

Table 12
Possible increase of all cost related to the proposed changes for the worst case scenario.

Concept	Initial cost [€]	Maximum total cost [€]	Increase of total cost
Concept 1	80,000	352,000	330%
Concept 2	632,900	648,700	2%
Concept 3	1,009,700	1,141,000	13%
Concept 4: Generator	2,162,900	2,995,600	38%

5.2. Increase of all costs

From the section above, it is known that the investment cost of the new systems is not a driving factor for the economic viability of the low and unmanned ship. Therefore, a second analysis is made where all the costs, i.e., shore crew cost, investment cost and usage cost, are increased by the same amount. The results of this analysis are shown in Table 11 for the best case and Table 12 for the worst case.

In the best case scenario, the total additional cost of each of the concepts can increase significantly. In the worst case scenario, this number drops down to only 2% for concept 2. This shows that this concept is the most sensitive to changes in the cost, and would be the first to switch from viable to not viable. However, in this scenario, higher crew costs are already assumed.

5.3. Increased container capacity

Removing all crew members from the ship means that the accommodation of the ship can also be removed. This removal of the accommodation means that there is potential for an increase in container carrying capacity, as the accommodation takes up deck space and weight.

It is difficult to determine the exact monetary benefit of the additional capacity will have. Container ships are generally loaded to between 80% and 100% of their capacity (Alphaliner, 2020), dependent on their location and the cargo requirements for their destination. This means that increased cargo capacity does not automatically mean that the ship will generate a higher revenue. However, the increase in capacity is expected to be small. Frijters (2017) calculates a 1.8% increase

Table 10
Possible increase in investment cost without changing the viability of the concepts.

Concept	Original investment cost [€]	Maximum investment cost best case scenario [€]	Maximum increase best case scenario	Maximum investment cost worst case scenario [€]	Maximum increase worst case scenario
Concept 1	80,000	352,000	340%	352,000	340%
Concept 2	102,500	772,300	653%	151,700	48%
Concept 3	269,900	1,565,400	479%	647,800	140%
Concept 4: Generator	1,205,900*	4,210,400*	415%	1,979,500*	235%

* This value does not include the savings that occur due to the removal of the accommodation, which have been estimated to be €2.000.000.

in capacity, while de Vos et al. (2020) use a 5% increase in capacity in their work. As there is no standard for the size of the accommodation, it is difficult to exactly determine the increase in capacity.

6. Discussion

When investigating the cost of something that is not commercially available, there is always uncertainty regarding the cost. The costs used in this article are based, as much as possible, on existing situations, comparable systems or published research. When these were insufficient to describe solutions, logical reasoning and discussions with experts were used to fill gaps. To account for the uncertainty that this approach leads to, significant margins were taken on the cost of the shore crew and some other aspects showing that, in many cases, the viability does not change with significantly changing costs.

In addition to the uncertainty of the cost of the solutions, there is also uncertainty regarding other operating cost of the unmanned ships. In this article, it is assumed that costs such as port and canal dues will not change. However, if further research shows that additional systems might be required to monitor the unmanned ships approaching ports or passing through canals, the dues might increase. To make a definitive statement on this, further research and further developed systems are required. However, the port and canal dues are only a small part of the voyage costs, which in turn are only a part of the total operating cost. Therefore, this is not expected to have a very large influence on the economic feasibility of the unmanned ships.

The monetary benefit of the first three concepts does not differ greatly from each other and is only small compared to the base case. This means that there is only a little economic incentive to implement these concepts. However, there are more reasons to implement low-manned ships. Even today, skilled maritime personnel is hard to find, and in 2025 a significant shortage of officers is expected (BIMCO & ICS, 2015). Additionally, autonomous navigation has been suggested to lower the possibility and the consequences of accidents. However, this does not take into account the inherent human creativity in solving complex problems which might prevent many accident from ever occurring (Ahvenjärvi, 2017).

Another aspect that can be investigated further is the crew on board. While economically it might be beneficial to have a crew of only 2 or 3 crew members remaining, this might not be the case from a social standpoint. Additionally, the skills of the crew members that remain on board could be adapted. In this article, the shore control station is added in concept 3 as all crew members with navigation skills are removed from the ship. Dutch companies have used double skilled (as an officer and an engineer) crew members (Serné, 1998). Using these crew members could delay the requirement for an SCC while lowering the required number of crew.

Equipping the ship with a PEM fuel cell is not economically feasible, even if the hydrogen can be bunkered at a very low price. However, there are more aspects of installing a fuel cell that need further investigation. A hydrogen fuel system will require more space on board, which could negatively impact the amount of cargo that could be taken. On the other hand, removing the accommodation could increase the cargo capacity of the ship. The effects of these changes needs to be investigated further.

Finally, further research has to be performed on the changes in weight and volume that these changes will have on the ship. The changes for the first three scenarios will likely be small. The final scenario, where the crew supporting systems are removed and a new propulsion system is installed might have a larger effect. These changes require a full recalculation of the ship's parameters. It might also affect the weight of the ship and the number of containers that can be carried. Furthermore, the need to store large volumes of hydrogen for the fuel cell option, will impact the carrying capacity of the ship to some extent.

7. Conclusions

This article analyses the economic viability of four development steps from a conventional ship to an autonomous ship. Based on the assumptions in this article, the first three scenarios are economically viable. Additionally, the benefits of removing the crew members are large enough, that the costs of the suggested solutions can increase significantly without changing the viability. The final scenario where all crew members are removed, however, is not economically viable when a the ship is powered using fuel cells.

At its current price point, the fuel cell is too expensive to make the scenario viable. The cost of the fuel is the biggest factor in this. At a low fuel price, the scenario is 12.2% more expensive than a conventional ship, which could be worth it if the ship is powered by green propulsion. However, with a higher price, the difference with the conventional ship quickly increases. The cost of green propulsion systems is expected to drop as they become more popular. Therefore, it is likely that green ships and autonomous ships will go hand in hand.

CRediT authorship contribution statement

C. Kooij: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – Revision. **A.A. Kana:** Supervision, Resources. **R.G. Hekkenberg:** Supervision, Conceptualization, Resources, Methodology.

Declaration of competing interest

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