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Factors Influencing the Economic Feasibility of Unmanned Ships

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FACTORS INFLUENCING THE ECONOMIC FEASIBILITY OF UNMANNED SHIPS

Carmen Kooij[1,2]

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ABSTRACT

The research effort into unmanned and autonomous ships has increased significantly over the last decade. Although not all required technology is currently commercially available, consensus is that from a technical standpoint, unmanned shipping is possible. The next question is: is it economically feasible to operate an unmanned ship. The article investigates which operation parameters influence the economic feasibility of differently sized unmanned ships the most.

KEY WORDS

Economic viability, feasibility, unmanned ships, autonomous ships, cost benefit analysis.

INTRODUCTION

Over the last few years research and test cases have shown that unmanned ships are no longer in the future but are technically possible. Although not all technology is ready for commercial application or completely ready for implementation, this is only a matter of time. From a technical standpoint, the two largest obstacles that remain are the navigation and new propulsion of the ship. These are also the two aspects that require the most innovation and research as they are new technologies.

In the last few years several successful trials have been held with automated or remote navigation of ships. The Belgium company Seafar have a functioning shore control station from which the safely sail multiple inland ships through the Belgium waters (*Home - Seafar*, n.d.). In Finland, a project lead by Rolls Royce sailed a ferry both by remote control and by autonomous navigation between two berths (*Press Releases | Rolls-Royce - Rolls-Royce and Finferries Demonstrate World's First Fully Autonomous Ferry*, n.d.). Other trails have been conducted in countries such as Japan (Habibic, 2022) and in the Netherlands (JIP Autonomous shipping, 2019).

Economic feasibility

The examples above prove that unmanned ships are technically possible. However, when looking at the implementation of new technologies, not only the technical feasibility is important. For technologies to be fully accepted they also need to be economically and socially feasible. Figure 1 shows how the development process of unmanned ships falls along the three different types of feasibility. With the technical feasibility shows, this article focusses on the economic feasibility, looking into which factor have the largest impact on the feasibility of unmanned ships.

Only a few studies have been conducted into the economic feasibility of unmanned and autonomous ships. The first study performed was part of the MUNIN project. This research looked into the economic benefit of sailing a bulk carrier unmanned by performing a cost benefit analysis (Kretschmann et al., 2017). The project provide a detailed overview of the different cost that can be expected when operating an unmanned ship (Kretschmann et al., 2015). Other research performed into the economic feasibility of unmanned ships leans heavily on this research as it is detailed and covers many aspects (Kooij et al., 2021; Ziajka-Poznańska & Montewka, 2021). Other research into the economics of unmanned ships mainly focusses on the possibility of adding these vessel types into an existing infrastructure (Akbar et al., 2021; Msakni et al., 2020).

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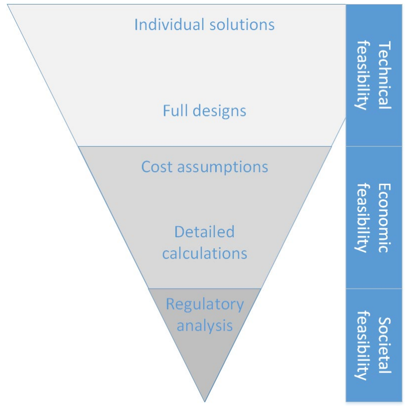

Figure 1: Different types of feasibility connected to different phases in the development of unmanned ships (Authors own creation)

RESEARCH SETUP

The goal of this article is to compare the effect of different operating parameters on the economic feasibility of four different ship sizes. For a ship to be economically feasible, the operating cost of the ship when unmanned must be equal or lower than the operating cost of a manned vessel. By comparing the cost of operating a ship under selected criteria with the savings of removing the full crew, an analysis of the feasibility can be performed.

The article starts with an overview of the selected ships. After that, the cost of enabling a ship to sail unmanned is discussed. Some of these costs will be fixed, for example when a specific system needs to be purchased, some of these costs will be dependent on an operating parameter. For example, the yearly cost of port operations is directly related to the number of port calls a ship makes during that year. For each ship, a base case of standard operating parameters is selected. In these standard operating conditions, the feasibility of the ships is compared to each other. This should give an insight on which size of ship would be the most feasible option to sail unmanned.

After determining the feasibility of the base case, several changes are made:

- The number of port calls
- The nationality of the crew and the flag state of the ship
- The speed at which a ship sails
- The building cost of the ship and the changes in building cost when sailing unmanned

For this analysis, four container vessels of a different size and crew are selected for comparison. The key characteristics of the ships can be found in Table 1. These characteristics are based on average values taken from multiple reference ships.

Table 1: Overview of the four ships analyzed in this article, ship sizes are an estimation based on average values of multiple reference ships

	Small Feeder	Feeder	Panamax	ULCV (Ultra large container vessel)
Ship length [m]	89	135	294	400
Speed [kts]	10	14	17	19
Total crew	10	11	20	22
Number of TEU	150	750	5.000	18.000
Building cost (Lim, 1998) [€]	3.500.000	17.300.000	73.300.000	167.400.000
Turnaround time [h] (Park & Suh, 2019)	22	27	51	97
Installed power [kW]	1.800	4.200	27.000	64.000

Table 2 shows the crew for each of the different reference ships. Once again, these are average crews for the size of the ship. Factors such as company policy, route, age of the ship and capabilities of the crew members influence the exact number of crew members that are available on the ship. Simply said, the money spend on the crew, is the money available to make the ship sail unmanned.

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Table 2: Crew distribution and cost of the reference ships, based on European wages [(Kooij et al., 2021) and industry experts]

	Yearly cost for ship operator [€]	Ship type			
		Very small feeder	Small feeder	Panamax	ULCV
Captain	108,000	1	1	1	1
First officer	90,000	1	1	1	1
Second officer	50,400	1	1	1	1
Third officer	33,600			1	1
Chief engineer	108,000	1	1	1	1
Second engineer	90,000	1	1	1	1
Third engineer	50,400			1	1
Bosun	33,600	1	1	1	1
Cook	33,000	1	1	2	2
Electrician	60,000			1	1
Able bodied seaman (ABS)	28,800	1	2	2	3
Ordinary seaman (OS)	21,600	1	1	2	3
Deck boy	16,800		1	3	3
Wiper	21.600			2	2
Total crew		9	11	20	22
Total crew cost one crew		972.000	1.188.000	2.160.000	2.210.400

The cost of sailing unmanned

The research described in this article is based on earlier research performed by the author. In this research, the effects of replacing specific (groups of) tasks on the crew composition of a short sea container ship was investigated (Kooij & Hekkenberg, 2020). In total, 11 clusters of tasks were created that need to be replaced, either by automation of by changing policy, in order for the ship to become fully unmanned. Of these 11 clusters, 8 require an investment from the ship owner, the other 3 can be changed without additional cost, or cost savings. The cost of replacing each of these clusters has been determined by using industry sources as well as academic sources (Kooij et al., 2021). The costs that were determined in this article are used as input for this article too. A summary of the costs can be found in Table 3 and Table 4.

The cost of adapting a ship to sail unmanned is split into three parts; investment cost, yearly operating cost and shore crew cost. The investment cost is a onetime cost incurred by investing in new equipment. In this article a straight-line depreciation is assumed. This means that each year of the equipment's lifetime, a fixed fraction of the cost is incurred. The operating cost are yearly returning costs, sometimes dependent on factors such as the number of kW installed or the number of port calls made. The crew cost is based on the skills that the new crew members require with an extra margin based on having the lowest wages meet the Dutch minimum wage.

Cost equal for all ship sizes

Some of the cost factors will be equal for every ship type regardless of ship size. These clusters are; mooring, navigation, administration and port supervision. The cost of these aspects are listed below and are summarized in Table 3.

The cost of mooring a ship with an automatic mooring system is assumed to be €1.000, regardless of the ship size. A large ship requires more mooring systems to safely moor in all conditions than a small ship. However, there is very little reliable data available regarding the cost of operating or using a mooring system. Therefore, the value is €1.000 is used for all ships.

To sail this ship autonomously, a system is required that can navigate the ship in all situations. The cost of such as system is assumed to be €160.000 with a lifetime of 5 years. In addition to this system, a shore control station is required to monitor the ship. In this case, it is assumed that the ship is part of a network of unmanned ships and an established shore control station is in place. The additional cost of office equipment for the shore control station is calculated to be €7.400 once again with a lifetime of 5 years. The crew cost of the Shore Control Centre are split over the number of ships that it monitors, per ship, this adds up to €195.700. The cost of administration personnel is estimated to be €20.000 per ship.

When the ship is in port, it needs representation. This includes monitoring workers that come on board, communicating with the port officers and ensuring that the ship and its cargo is safe. To make this possible, alarm and security systems are

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required at a cost of €22.500 and a lifetime of 5 years. Additionally a ship's agent is hired. This agent represents the ship while it is in port. Due to the high responsibility of this agent, the cost is based on that of a chief officer. The cost of hiring an agent to monitor the ship the whole time it is in port adds up to €2.200 per day the ship is in port.

The current diesel engine that propels the ship is not very well suited for unmanned operation.The engines have been designed assuming that an engineer is on board and the engines require significant maintenance and repairs while the ship is enroute. Therefore, it has been suggested that either a steady state propulsion system such as batteries and fuel cells are used, or the ship is equipped with multiple generators to increase the redundancy and with that the reliability. In this article, the ships are equipped with generators, as it is, currently, the most cost effective solution. The cost of a generator is generally higher than that of a diesel engine (Abma et al., 2018; Interreg Danube Transnational Programme, 2019). The difference is calculated to be 130 € per installed kW.

Table 3 Overview of the costs that are the same for each ship type, per year unless otherwise indicated

Cost factor	Investment cost	Usage cost	Crew cost
Mooring	-	€1.000 per port call	-
Navigation	€167.400	-	€195.700
Administration	-	-	€20.000
Port supervision	€22.500	-	€2.200 per day in port
Maintenance in the engine room	€130 / kW	-	-

Cost for maintenance and general upkeep
Maintenance of the ship on deck can be split into two parts, the first is general upkeep, which is performed when the ship is in port between trips. There is also maintenance of the deck and superstructure which encompasses tasks such as painting, anti-corrosion measures and larger repairs. These cannot be performed when the ship is in port between trips. It has to be performed during the survey and docking periods. The cost of these two types of maintenance is based on a maintenance crew consisting of a bosun and several lower ranking crew members performing cleaning or maintenance work over a few hours or days.

Benefits from removing the crew
Finally, the building cost of the ship decreases when it is fully unmanned. Due to the removal of several supporting systems, such as HVAC, plumbing, fresh water and also the super structure of the ship the building cost is estimated to decrease by 15% for smaller ships and 7% for larger ships (Frijters, 2017). This is additional capital that can determine the difference between a feasible investment and a non-feasible investment.

Table 4 Overview of the cost changes per replaced cluster for each of the four ships

	Small Feeder	Feeder	Panamax	ULCV
General upkeep – crew cost	€480 per port call	€ 800 per port call	€ 1.920 per port call	€ 3.840 per port call
Maintenance on deck and superstructure - yearly crew cost	€11.600	€19.600	€38.600	€77.200
Design changes – investment cost	€525.000	€2.595.000	€5.131.000	€5.131.000

ECONOMIC FEASIBILITY OF THE SHIPS

In this section, the feasibility of the four different ships is investigated. First, a base case for each of the ships is determined. From this base case, several changes are made to investigate how they affect feasibility.

Base case

The base case for each of the ships consists of setting a route for the ship to sail. Based on the distance of this route, and the speed of the vessel sails at, the costs and benefits of sailing this route unmanned can be determined. The savings per year when the ship sails unmanned can be determined by:

$$Savings = Crew\ savings + \frac{Design\ changes\ savings}{Ship\ lifetime} - C_{unmanned}$$

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$$C_{unmanned} = C_m \cdot PC + C_{ps} \cdot DP + C_{gu} \cdot PC + \frac{C_{I_{nav}}}{L_{nav}} + C_{c_{nav}} + C_{c_{adm}} + \frac{C_{I_{ER}}}{L_{ER}} + C_{c_{md}}$$

In which;

C_m	Mooring cost	L_{nav}	Lifetime navigation
PC	Number of port calls	$C_{c_{nav}}$	Crew cost shore control station
C_{ps}	Port supervision cost	$C_{c_{adm}}$	Crew cost administration
DP	Days in port	$C_{I_{ER}}$	Investment cost engine room
C_{gu}	General upkeep cost	L_{ER}	Lifetime engine room
$C_{I_{nav}}$	Investment cost navigation	$C_{c_{md}}$	Crew cost deck maintenance

Table 5 Overview of the savings per ship type in their selected base case

	Small Feeder	Feeder	Panamax	ULCV
Route	Antwerp – Hamburg	Antwerp – Belfast	Rotterdam New – York	Rotterdam Shanghai
Travel time [h]	43	56	195	632
Port time [h]	13	27	64	116
Number of trips (one way) in 1 year	154	105	33	11
Savings due to unmanned sailing	€ 303.300	€ 552.100	€ 1.672.600	€ 1.908.500

Table 5 shows that for all ships, there are significant savings possible per year for the base case. The calculations compare the conventional situation (manned) with the future situation. To that end, costs that are expected to stay the same regardless of the manning situation of the ship, such as fuel cost and interest are not taken into account in these calculations. For cost such as insurance, it is currently unknown what will happen. Therefore, this has also been assumed constant and is not taken into account in this article.

Changes to the base case

To investigate the effects of different characteristics of the ship, several changes are made to the base case to investigate the effect of these changes. The changes that are made are; the number of port calls, the nationality of the crew and the flag state of the ship, and the sailing speed of the ship.

Number of port calls

From the cost calculations it can be determined that the number of times a ship comes into port, as well as the duration of these port calls has a significant influence on the cost of sailing unmanned. While the ship is at sea, the costs are relatively low, as one officer in a shore control station can monitor multiple ships cutting down on cost. In port, however, the costs are high. This is also shown in Table 5 where the smaller ships, which have a higher number of port calls have lower savings, or even negative savings than the larger ships.

Figure 2 shows the effect that the number of port calls has on the feasibility of the ships. There is a significant difference in size between in Panamax vessel and the ULCV. However, the difference in savings, even without taking the cost of port calls into account is not very significant. The difference in crew is small, 22 versus 24. This represents the single biggest saving for the ship when going unmanned. The savings on building cost are not very significant when offset over the lifetime of the ship and almost completely countered by the additional cost of the propulsion system. Therefore, the initial savings of both vessels is close together. However, due to the significantly higher cost of the large vessel in port, mostly due to maintenance and port supervision cost, the savings for the ULCV decrease significantly faster than those for the Panamax vessel. However, the savings for the ULCV are only diminished completely at 135 port calls, a value that is not the norm for these types of vessels.

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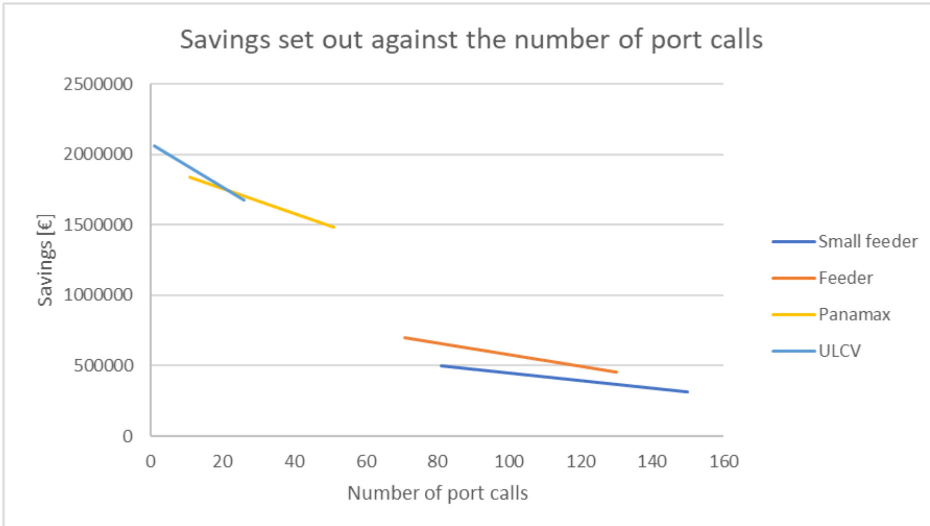

Figure 2 Effect of the number of port calls in the savings when compared to a conventionally manned ship of the same size

Flag state and nationality of the crew

As mentioned before, the savings on the crew cost are the most influential factor on the feasibility of unmanned shipping. Up to now, this article has used crew cost provided by a Dutch ship owner, operating a ship under Dutch flag. This means that the wages of the crew are high, as both Dutch wages are high and Dutch crew members are expensive. When the same calculations are performed on a ship sailing under a flag of convenience, with a crew from a low wage country, the feasibility could be very different.

The calculations in this article are made based on a Dutch ship (high wage country) with a Dutch crew (high wage expectations). To compare, three other combinations of flag states and crew nationality are investigated; a Norwegian ship with a Russian crew, a ship registered in Antiqua and Barbuda (low wage country) with the same Russian crew and a ship and crew from Algeria. The difference in crew wages is shown in Table 6.

Table 6 Differences in wages between flag states and crew nationalities [Data obtained from (Silos et al., 2012), corrected for inflation and converted to €]]

Case	Flag state	Crew nationality	Average difference in wages to a Dutch crew on a Dutch ship
1	Norway	Russia	23% lower
2	Antiqua and Barbuda	Russia	44% lower
3	Algeria	Algeria	78% lower

In Figure 3 the effects of lowering the crew cost are displayed. Over the four graphs, it becomes clear that the small feeder is the least affected by these changes. Because the crew cost is already lower, changes have a smaller impact on the overall savings percentage wise. The other savings, such as the design changes are much larger in comparison, leaving the total savings relatively high compared to the other ship types for which the savings on the crew cost make up the most significant part of the total savings. As expected from the previous section, a lower crew cost means that ships have to make a smaller number of port stops for the concepts to remain feasible. This works in the favor of the ULCV, which is generally used on longer routes. Comparatively, the largest vessel is impacted the least by the different crew cost. For the ship from Antigua and Barbuda the very small feeder is no longer feasible for the selected route. The ship would need to sail larger distances. The feasibility of the base cases for the two remaining vessels only changes for the Algerian ship and crew. For these extremely low crew cost, the cases selected for the Panamax and feeder vessels are no longer a feasible option. Both ships would need to reduce the number of port calls. The small feeder is not feasible at all in this case, even with the ship making no port calls.

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Figure 3 Comparison of the different crew cost and its effect on the savings of the four ship types. To better show the differences between the four ship types and the four situations, a wide range of the number of port calls is used. However, not all situations displayed here are realistic.

The cost of the shore crew is related to the cost of the crew on board (Kooij, 2021). This means that the cost of the shore crew is also assumed to be relatively high. If the cost of the shore crew is lowered to simulate the ship operating in a low wage country, with the shore control station also located in a low wage country, the savings for the ship would improve again. Figure 4 shows the savings of the four ships with an Algerian ship crew as well as an Algerian shore crew. While the margins are significantly smaller then with the Dutch ship and crew (600.000 compared to over 2.000.000), it is clear that sailing the ships unmanned remains feasible for with a significantly higher number of port calls.

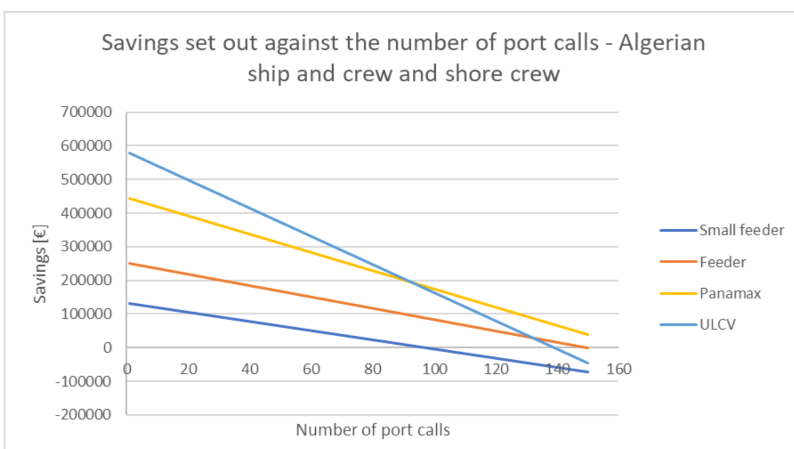

Figure 4 Savings set out against port calls for low cost ship and shore crew

Sailing at a different speed

Not all ships sail at the same speed. As the speed determines how many port calls a ship can make in a year, it could have an effect on the feasibility of the cases. For that reason, the effect of this speed change is investigated for the different sizes of ships. For this analysis, the route the ship sails is not changed, only the speed at which it sails this route, which will affect the number of port calls the ship makes. In the case of the Dutch ship manned by the Dutch crew, the effect of sailing at a

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different speed is negligible. The difference between the number of port calls a ship can make before sailing it unmanned is no longer feasible is significantly different from the number of port calls the ship makes as is shown in Table 7. The same holds true for the Norwegian ship with the Russian crew. However, for the other two cases, changing the speed might have an effect on the feasibility of the ship. For that reason, these are displayed in more detail in Table 7.

Table 7 Maximum number of port calls for each ship type to remain feasible in operation

	Small feeder	Feeder	Panamax	ULCV
Base speed	10	14	17	19
Number of one way trips in base case	154	105	33	11
Port calls at 20% decrease	128	90	27	9
Port calls at 20% increase	176	118	37	13
Maximum number of port calls in base case	>200	>150	>150	135
Maximum number of port calls Case 2	107	113	111	71
Maximum number of port calls Case 3	0	17	28	22

The table shows that for the small feeder, reducing the speed by 20% is not going to be enough to reach lower the number of port calls required for economically feasible operation. However, when looking at the feeder in case 2, some changes in speed would have an effect. Increasing the speed by 20% means that the maximum number of port calls is exceeded, meaning operating that ship is no longer feasible. Decreasing the speed by 20% would give more security regarding the feasibility when sailing unmanned. This shows that small changes in speed or route could have a significant effect on the economic feasibility.

Savings due to design changes

Other than the crew, the largest contributing factor to the savings are the design changes. There are very few and very scattered assumptions on the savings or increases in cost when a ship is transitioned to unmanned. Therefore, the effect of this aspect is also investigated. The savings assumption used in the base case is optimistic compared to others. For example, the MUNIN project assumed a 10% increase in the building cost of unmanned ships (Kretschmann et al., 2017). In this analysis, the base case is used to see what effect changing the building cost of the ship as on the feasibility of the ship. The results are presented in Table 8.

Table 8 Effect of changing building cost on the savings for each ship type in base case

	Small feeder	Feeder	Panamax	ULCV
Savings base case	€ 303.300	€ 552.100	€ 1.672.600	€ 1.908.500
Savings no change in building cost compared to manned ship	€ 282.300	€ 453.600	€ 1.437.400	€ 1.376.500
Savings with 10% increase in building cost	€ 268.300	€ 384.400	€ 1.144.200	€ 616.500
Increase in building cost possible before base case is no longer profitable	200%	65%	49%	18%

Table 8 shows that the building cost has an effect on the savings of the different cases, however, the feasibility of the base case is not affected. The smallest ship is the least sensitive to changes in the building cost. Even when the building cost is increased by 10% (compared to the conventional ship) the savings per year are significant. This is also shown by the last row of the table, that shows that even with a 200% increase in building cost, the ship is still feasible. The ULCV is the most sensitive of the four ships analysed. In the base case, the savings are almost 2 million euros. This drops by a significant margin if the building cost increases. This is because percentage wise, changes in building cost are larger for this ship than they are for a smaller ship when compared to the crew cost.

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The table above is calculated for the European ship and crew. For a lower wage crew or flag state, the changes in building cost would sooner have an effect on the feasibility of the case.

CONCLUSIONS

In this article, several factors that influence the economic feasibility of sailing unmanned are investigated. The feasibility is investigated for four different sizes of container vessels; a small feeder, a feeder, a Panamax vessel and a ULCV. In the base case selected for each of the ships, they are all economically feasible.

The largest contributor to this feasibility is the savings due to the removed crew. For ships registered in a high wage flag state with a high wage crew, many cases are feasible. When the cost of the crew is lowered by moving to a lower wage flag state or sailing with a lower wage crew the savings diminish. With lower savings from the removal of the crew, operating the two smallest vessels is no longer economically feasible in many cases. For the smallest vessel, sailing with a very low wage crew but operating in a high wage area means that there is no single operating profile in which it would be feasible to operate the ship as the cost of the shore crew becomes too much to cover with the savings of the ship crew.

The two larger vessels are less affected by this, as they make a lower number of port calls. This means that the cost of the shore crew is lower compared to the cost of the on board crew. For that reason the savings remain on the selected routes. However only a small increase in the number of port calls is possible before sailing unmanned is no longer feasible. Sailing in an area where a lower wage shore crew can be hired increases the feasibility again.

Other parameters, such as the speed at which a ship sails, or the number of port calls a ship makes are related to the savings from the on board crew and the cost of the shore crew. In general, the speed at which a ship sails does not significantly influence the feasibility of a concept. Only when the ship is already at the very edge of the feasibility area would such a change have an effect. The number of port calls has a larger effect, however, in general, the ships perform well in the areas that they generally operate in. On long routes, the larger ships have higher savings than the smaller ships. However, the cost of a port call is higher for the larger ships, meaning that when a shorter route is sailed, the smaller vessels slowly overtake the larger ships in terms of savings.

Finally, the effect of the building cost has been investigated. In this case, larger ships are more vulnerable than smaller ships. The difference between the building cost and the crew cost is much larger for the large ships, meaning that the effect of increasing the building cost is more pronounced. Therefore, this works in favor of smaller vessels

To summarize, the factor that has the largest influence on the economic feasibility of unmanned ship, is the nationality of the crew and the flag state. For that reason, it is expected that ships registered in high wage countries are more likely to transition to unmanned than ships registered in a low wage country. When looking at the operation of the ship, the number of port calls is the most influential. Making more stops in port costs money, as additional crew is required to perform services to the ship. This is especially true for large vessels, who require more crew to perform tasks such as maintenance and general upkeep than smaller ships. Therefore, it is not expected that large vessels sailing a relatively short route will be the first to transition to unmanned.

In short, the first ships to transition to unmanned are not likely to be the very small or very large vessels. The small vessels are very dependent on the savings made from removing the crew, which isn't very large to begin with. The fact that they generally sail a short route means that most of the savings from removing the crew are directly spend on shore crew to take over their tasks. The large vessels are to sensitive to a change in building cost or number of port calls. Therefore, the first ships to transition to unmanned commercially are likely to be European registered mid-sized ships, sailing longer continental routes or shorter intercontinental routes.

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