When will autonomous ships arrive? A technological forecasting perspective

Ir. Carmen Kooij [A]*, Alina P. Colling [A] MSc, Christopher L. Benson PhD [A,B,C]

[A] *Delft University of Technology, Delft, The Netherlands*
[B] *United States Air Force Office of Scientific Research, United States*
[C] *Massachusetts Institute of Technology, Cambridge, United States*
* Corresponding Author. Email: C.Kooij@tudelft.nl

Synopsis

Autonomous ships have received significant attention in recent years. However, they are not widely adopted in the maritime industry yet. A wide range of predictions have been made about when the technological change will occur. This paper analyses technologies that are critical to autonomous shipping and forecasts a range of times when they will reach technical and economic viability. The researched technologies are data transfer, navigation, cargo handling, fuel cells and diesel engines. The results indicate that the GPS precision required for autonomous mooring is not yet technically feasible and the expected feasibility time frame is between 2030 and 2058. The remaining technologies all show technological feasibility, but not yet economic viability. The forecasted range for economic viability of data transfer is a range of 2026-2041, while cost of automated cargo handling will reach the current expense levels somewhere between 2037 and 2101. Finally, the cost of a medium speed diesel engine and an LT-PEMFC Fuel Cell will be approximately equal somewhere between 2025 and 2060.

Keywords: Autonomous shipping; Technology forecasting; unmanned ship; Technological Improvement Rate; Moore’s law

Biographical Notes:

Carmen Kooij is a PhD candidate at the Delft University of Technology. She is currently working on the ship design of autonomous ships and the roadmap towards unmanned or autonomous shipping. She has completed her bachelor and master’s degree at the Delft University of Technology.

Christopher Benson is an Active Duty Officer in the US Air Force with experience as an engineer with F-16s, Space Systems and Autonomous Aerial Systems. He is currently working as an exchange scientist with the Royal Netherlands Defence Academy at the Delft University of Technology, focussing on autonomous maritime ship design.

Alina P. Colling is a PhD candidate at the Delft University of Technology, working on the development of a new maritime transport project in form of a Vessel Train. She has received her bachelor degree from Plymouth University , UK and her master’s degree from Delft university of Technology, Netherlands.

1. Introduction: the Timing of the Adoption of Autonomous Shipping

There are autonomous cars and trucks on the roads, there are drones being flown remotely from across the globe and shipping industry is interested in following in the same direction. Benefits for autonomous shipping can include a lower operational cost and increased safety for both the crew and the ship. The possibility of unmanned (controlled via remote control) or autonomous (fully self-reliant and unmanned) ships is no longer a question of if, but has progressed to a question of when. There are however, some essential technologies that require more maturing before they can be implemented on ships and used towards unmanned or autonomous shipping.

The predictions on when unmanned or autonomous ships will become a reality differ greatly. In the AAWA (Advanced Autonomous Waterborne Applications) project, it is stated that the first ships for local applications can be expected as early as 2020, coastal vessels could be adapted in 2025, but ocean going ships will not be unmanned before 2030 and will not be autonomous before 2035 (Rolls-Royce, 2016). Kongsberg aims to have a small coaster sailing between two cities in Norway in 2020 (Kongsberg, n.d.). Lloyds register made the prediction that autonomous ships would become a reality by 2030, but has since stated that they expect the change to happen earlier due to the quick adaptation of the technology required for unmanned and autonomous shipping (Lloyd’s Register Group Limited, QinetiQ, & University of Southampton, 2015; Lloyds Register, QinetiQ, & University of Southhampton, 2017). The CEO of Maersk, Soren Skou, has stated that he does not expect autonomous container ships to happen in his lifetime (Christian Wienberg, 2018). Given his age, 53, and

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the average life expectancy of a European male, this means he does not think it will happen before 2058. However, none of these predictions explain how this timeframe is determined.

1.1. *Areas to investigate*

The first step of this analysis is to determine which crucial technologies are missing. In (Kooij, Loonstijn, Hekkenberg, & Visser, 2018) several technologies have been identified as potential problems in an unmanned or autonomous ship. This paper identified the following areas that need further technology development: Navigation, communication and maintenance of the equipment.

For navigation the GPS accuracy is investigated in this paper. In order for a ship to sail via remote control or autonomously it needs to know where it is located at all times. Therefore an accurate GPS position is required. While the accuracy is already relatively good, it is not precise enough for automatic mooring and the very precise navigation that that process requires. For communication, the long range data transfer via satellite is investigated. At this point the estimated cost for this type of detailed communication is significantly higher than the current cost. This means that the economic impact of switching to unmanned or autonomous shipping is very high. Another concern raised in this paper is the maintenance that the crew performs in the engine room. Currently all ships sail with an engine room crew that solve problems that occur while underway. Current state of the art ship machinery cannot operate reliably for prolonged periods without interference from the crew. One of the solutions suggested for this problem is to switch to solid state engines, with no moving parts, which would require significantly less maintenance. One of these options is a fuel cell, which is not completely solid state but has only a few moving parts as opposed to the diesel engine, which has numerous moving parts.

In addition to the previously identified problem areas cargo handling is also investigated. Across the world ports range from fully automatic with no humans involved in the loading and unloading process to limited automation where the equipment has a human operator. Out of all the ports in the world 3% are automated while 1% is fully automated (Port Strategy, 2018). In this paper only container handling is investigated due to there being more data available on this subject.

Personal research has shown that in some ports the use of port personal is obligatory while in other ports it is also possible to use the ship's crew to assist with the loading and unloading of the ship. It was found that the cost of one stevedore is approximately €400 per loading and unloading cycle and approximately 10 are required during a full cycle of unloading a short sea ship. The possibility of having the crewmembers take the place of stevedore significantly decreases the cost of the loading and unloading cycle as the crew has significantly lower wage and is payed regardless. As long as it is cheaper to hire crewmembers, sometimes even additional crew that is not strictly necessary for the operation of the ship, building an autonomous ship that is economically viable is very difficult.

1.2. *Technology Predictions*

In 1965, Moore (Moore, 1965) wrote a paper about the number of components one computer chip could hold. He stated that the number of components on a chip would double each year. He based this assumption on looking at the number of components on a chip in the past. The resulting graph, showing the relation between performance (in this case: number of components) and time, is known as Moore's law (Schaller, 1997).

In short Moore's law states that the performance of a technology increases exponentially over time (Nagy, Farmer, Bui, & Trancik, 2013):

$$y_t = Be^{mt} \qquad \text{Eq. 1}$$

In which y_t is the performance of a technology, B is a constant and m is the Technological Improvement Rate (TIR).

The goal in this paper is to determine the improvement rate for several different technologies relevant to unmanned or autonomous shipping.

How the performance of a technology is measured is not set in stone. The metric, a value that best represents the state of the art for a specific technology, that is used can be based on available data or industry standards. The determination of the TIR can be done using historical data. How this works in discussed later on in this paper.

2. Method

This paper uses a repeatable and transparent method to forecast the technical and economic time frames for autonomous ship adoption:

1. Determine the current state of the art technological/economic performance level
2. Determine technological rate of improvement (TIR) for each technology
3. Determine the performance level required for autonomous shipping
4. Find the 'cross-over' moment in which the technology reaches its threshold and becomes feasible. As future predictions are not set in stone, uncertainty is added to the results. This is discussed in paragraph 2.3

Using these elements it is possible to determine a timeframe in which the technology is available for use towards unmanned or autonomous shipping as shown in Figure 1.

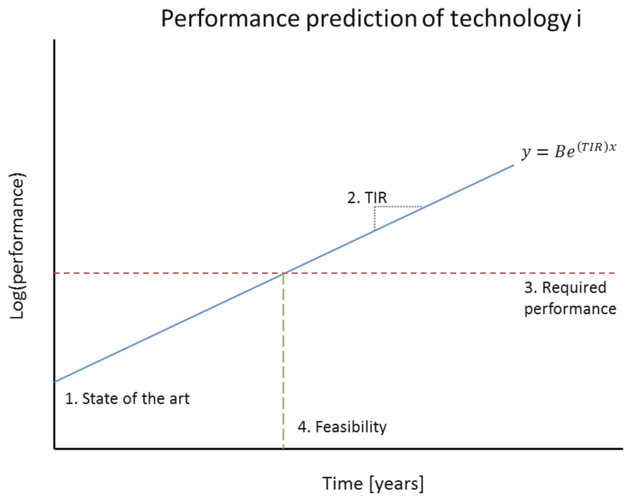

Figure 1: Stepwise explanation of the method used.

2.1. *Determining the Technological Improvement Rate*

For each of the above-mentioned technologies the technological improvement rate (TIR) has to be determined. This is done using historical data about the performance of a technology (Benson, 2014). This historical data is used to get a picture of how the technology has improved over time. As is shown in Figure 1 the data is plotted in a graph which depicts the log of the performance of the technology over time. To find the TIR an exponential trend line, which has the same form as Moore's law in equation 1, is plotted through the data. This method is only usable if the data shows enough correlation with the trend line. Therefor the R^2 value, or the coefficient of determination, is also calculated. If $R^2 > 0.60$ the data is accepted as usable (Benson, 2014).

2.2. *Determining the Threshold Values*

There are two reasons why a technology cannot be used for unmanned or autonomous shipping at this point:

a) The technology has not matured enough and as a result does not meet the required operating parameters (e.g. The GPS accuracy is currently 0.715 m and needs to be 0.1 m if the ship has to dock autonomously)
b) It is technologically feasible to meet the operating parameters, but at this point it is not financially viable yet. (e.g. The cost of a fuel cell is much higher than that of a medium speed diesel engine)

Finally, there is a third category, technologies that meet the threshold for the operating parameters and are financially viable, which means they could be implemented on the ships at this moment, although they might still require significant engineering effort to be turned into usable products. There are many technologies in this last category, but they are outside the scope of this article.

The threshold values are based on literature and the investigation of the state of the art. The threshold can either be an operating parameter, such as accuracy in meters, or a cost parameter, such as euro per kilowatt. The

TIR and de threshold together determine when the technology will be available and cost effective to be used in unmanned or autonomous shipping.

2.3. *Uncertainty in the Predictions*

There is inherently significant uncertainty regarding future technological progress which needs to be taken into account. The main intent of this technological forecasting method is not to predict a specific time when one technology will be ready, but rather to reduce the uncertainty around the time frame in which it can be reasonably expected to be technically feasible and financially viable. Previous studies have shown a normal distribution for technological improvement rates (Farmer & Lafond, 2016) and that a reasonable value for the standard deviation, σ, of the technological improvement rate is 50% of the overall technological improvement rate (Triulzi, Alstott, & Magee, 2017). This leads to a feasibility and viability time range rather than a prediction consisting of a single point. This is shown in Figure 2.

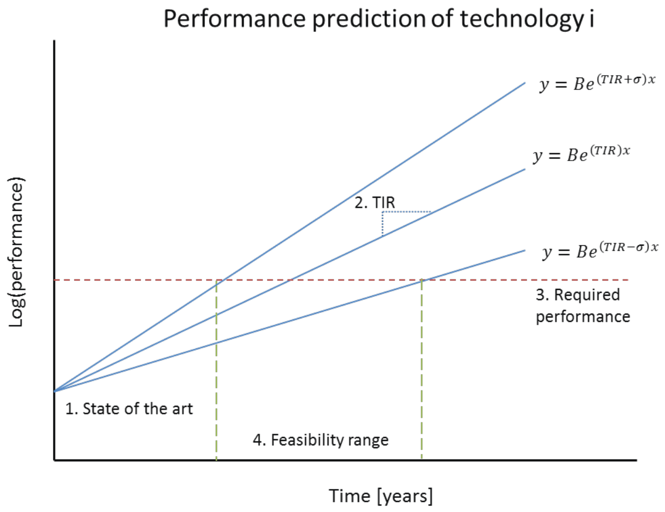

Figure 2 Method explanation with uncertainty added

3. Description of Technologies Critical to Autonomous Shipping

In this section technologies that are critical to autonomous shipping are described. A performance metric that is used for the determination of the TIR and the threshold that the technology needs to reach for it to be technologically viable are then determined. The datasets that are used in the determination of the TIR can be found in Appendix A.

3.1. *Long Range Satellite Data transfer*

Data transfer is an area that is even more important for unmanned than for autonomous shipping. In case of remote control, a controller on shore needs to know what is happening on board at all times. This requires data from sensors, cameras and navigation equipment to be sent to shore quickly and reliably. It is estimated that for advanced remote operation (such as navigating in a busy area) a speed of approximately 4000 kbps is required (Rødseth, Kvamstad, Porathe, & Burmeister, 2013). This speed can be reached via satellite transfer at this point in time. However, it is estimated that sending all this data, at this speed from the ship to the shore will cost €125.000 per month (Porathe, Prison, & Man, 2014). At this cost, operating an unmanned ship in a competitive way is very difficult, if not impossible.

Currently the usage of data ranges from low, 100 MB per month, to high, 1000 MB per month (Tuczynski, 2009). The average between these two values, 550 MB, is taken has the reference usage, with the corresponding cost of €500 per month. It is assumed that the cost of the data throughput will decrease with the TIR. This means that it is possible to determine when something that costs € 125.000 today, will cost € 500.

3.2. *GPS Accuracy*

For either a remote human operator or a computer to safely steer the ship they need to know exactly where the ship is in relation to other obstacles. The metric of choice for this is GPS accuracy which is expressed in meters. Research by Smart (2013) has shown that for general navigation an accuracy of 10 meters is required, in ports the accuracy needs to be at 2.5 meters and for automatic docking an accuracy of 0.1 m is needed. In 2016 the global user error was ≤ 0.715 m 95% of the time (US Air Force, 2017). This means that in order for ships to moor using GPS the technology still needs to improve but for normal usage the technology has reached its technological threshold. However, mooring is an important challenge to overcome on an autonomous ship as currently the crew is still a big part of this operation.

The TIR is determined using the 95th percentile error. This means that 95% of the time, anywhere in the world the GPS accuracy is lower than the given threshold. This also means that in this case it is not the state of the art that is measured but a relatively common accuracy. This means that it is also affordable. Therefor it is assumed that when the technology reaches its technological threshold it will also still be affordable for general usage.

3.3. Propulsion

The propulsion system is one of the most vital systems on board. The technology of the current propulsion system requires a large amount of monitoring and maintenance during the operation. This can be a challenge when the crew is no longer on board. There are three approaches to consider these challenges on autonomous ships:

1. Improving the existing diesel engines to allow for maintenance and repair to be performed only while the ship is in port.
2. Eliminate the need for regular maintenance and repair on board. This can be achieved by getting rid of rotating machinery on board and instead creating a propulsion system based which is less mechanically complex than a diesel engine.
3. Reduce the effect of an element breaking by increasing the redundancy of the propulsion plant, for example by equipping the ship with two main engines.

The reliability of the researched marine diesel engines does not seem to improve significantly over time. This can partly be explained by the given fact that there are crewmembers available to maintain the engine. This means that there is very little drive to improve the reliability of the engine. Increasing the redundancy of the propulsion plant by adding a second main engine is a good solution from a reliability standpoint, as it will allow the ship to return to port even if one engine breaks. However, this solution also has its challenges. For example, there is a possibility that the maintenance on the engines will take longer if it is only done on shore. Both these options are mainly an economical problem. If one is willing to invest money on either a better engine or multiple engines, at least a partial solution to the maintenance challenge is found.

From a technology forecasting perspective the second approach is the most interesting of the three, especially when other technologies are compared to the medium speed diesel engine. In this case the comparison is made between the diesel engine and propulsion by the means of fuel cells. The fuel cell was chosen due to the availability of data however, there are more possibilities that should be investigated such as capacitors or batteries.

The marine industry has performed considerable research on the potential of applying fuel cells since it provides the potential to have an all-electric ship (Allen, Ashey, Gore, Woerner, & Cervi, 1998; Minnehan & Pratt, 2017; van Biert, Godjevac, Visser, & Aravind, 2016)**.** Therefor this research is focused on determining the improvement of this specific technology. The advantage of fuel cells compared to the current diesel engines is that they are composed of only few mechanical moving parts and hence can be left unattended during operation. (Allen et al., 1998).

The implementation of other types of energy generation and propulsion depend on three factors, volume weight and cost. Volume and weight form a physical limitation on the size of the equipment. If the new form of propulsion is bigger or heavier than the diesel engine it will be at the expense of the amount of cargo that the ship can carry. For this reason the power density (W/m^3), the specific power (W/kg) and the cost (€/kW) of each of the propulsion types are compared to the diesel engine.

Table 1 shows the comparison between the medium speed diesel engine and a LT-PEMFC fuel cell. From this table it becomes clear that with regards to performance the fuel cell has the same, or even better capabilities than the medium speed diesel engine. The fuel cell only performs worse than the diesel engine in cost per kW.

Table 1: Metric comparison between medium speed diesel engine and LT-PEMFC fuel cell

Propulsion type	Power density $\left[{kW}/{m^3}\right]$	Specific power $\left[{kW}/{t}\right]$	Cost [€/kW]
Medium speed diesel Data from: (Stapersma, 2010)	36 - 250	50 - 200	140 - 240
LT-PEMFC Fuel cell Data from: (van Biert et al., 2016)	250 - 1000	300 - 1550	1000

3.4. *Cargo Handling*

To keep up with the increase of the transport of goods over water, ports have also undergone a transformation over the last century. The increasingly larger ships forced the ports to invest in modern equipment such as stacking cranes and automated guided vehicles (Ligteringen, 1999).

In order for autonomous or unmanned ships to become a reality it must either be cheaper to make use of stevedores instead of the crew or the use of human personnel should not be required at all.

To determine the improvement rate of the cargo handling equipment, the productivity of the stevedores is used. The equipment stevedores use is continuously improving, hence among other factors, the productivity of a stevedore is a reflection of the technological improvements of cargo handling equipment.

The sources on the cargo handling cost differ greatly. The cost can be as high as 354.0 euros per TEU (European Competition Commision, 2009) and as low as 39.3 euros per TEU (F. Lundoluka, R. Hekkenberg, H. Blaauw, 2005). Assuming an average weight of a TEU of 15 tonnes, this amounts to a cost ranging from 2.62 €/t to 23.6 €/t. The prices fluctuate based on the port size and infrastructure as well as its geographic location and the local economy. These factors also influence the change of the port being converted to (fully) automated.

As automated ports now make up 3% of the total number of ports it is assumed that the unloading costs are economically competitive. They are no longer trial projects that are typical at the start of the adoption of a new technology but an integrated part of the loading and unloading industry. However, as automated ports are state of the art, the cost are most likely on the high end of the spectrum. Therefore it is assumed that the handling cost of an automated port is currently 23.6 €/t.

3.5. *Summary of the Technologies*

To summarise this chapter Table 2 gives an overview of the state of the research, as well as the threshold that needs to be reached in order for the technology to be used on an unmanned or autonomous ship.

Table 2: Summary of the technologies showing the metric, threshold and current state of the art

Technology	Metric used	Threshold	State of the art now
Satellite data transfer	Overall cost/month	€500 per month	€125.000 per month
Navigation	Accuracy [m]	0.1 m	0.715 m
Propulsion: Diesel engine	Cost per kilowatt $\left[{€}/{kW}\right]$	N/A	140 $\left[{€}/{kW}\right]$
Propulsion: Fuel cell	Cost per kilowatt $\left[{€}/{kW}\right]$	140 $\left[{€}/{kW}\right]$	1000 $\left[{€}/{kW}\right]$
Cargo handling	Cost per ton $\left[{€}/{t}\right]$	2.62 $\left[{€}/{t}\right]$	23.60 $\left[{€}/{t}\right]$

4. Results

4.1. The Technological Improvement Rate

For each of the areas of interest the TIR is determined. The data was found in a range of papers and technical publications. For each technology the sources can be found in appendix A. Table 3 gives the calculated improvement rates. All data also meets the requirement of a comprehensive data set, all have an R^2 value well above 0.60. Figure 2 shows the data points used to determine the TIR and the corresponding exponential trendline.

Table 3: TIR of the researched technologies and the corresponding R^2 value of the data used

Technology	*TIR*	R^2
Satellite data transfer	*48.8%*	*0.94*
GPS accuracy	*9.5%*	*0.97*
Propulsion: Fuel cell	*19.2%*	*0.98*
Propulsion: Diesel Engine	*0.25%*	*0.73*
Cargo handling	*4.6%*	*0.74*

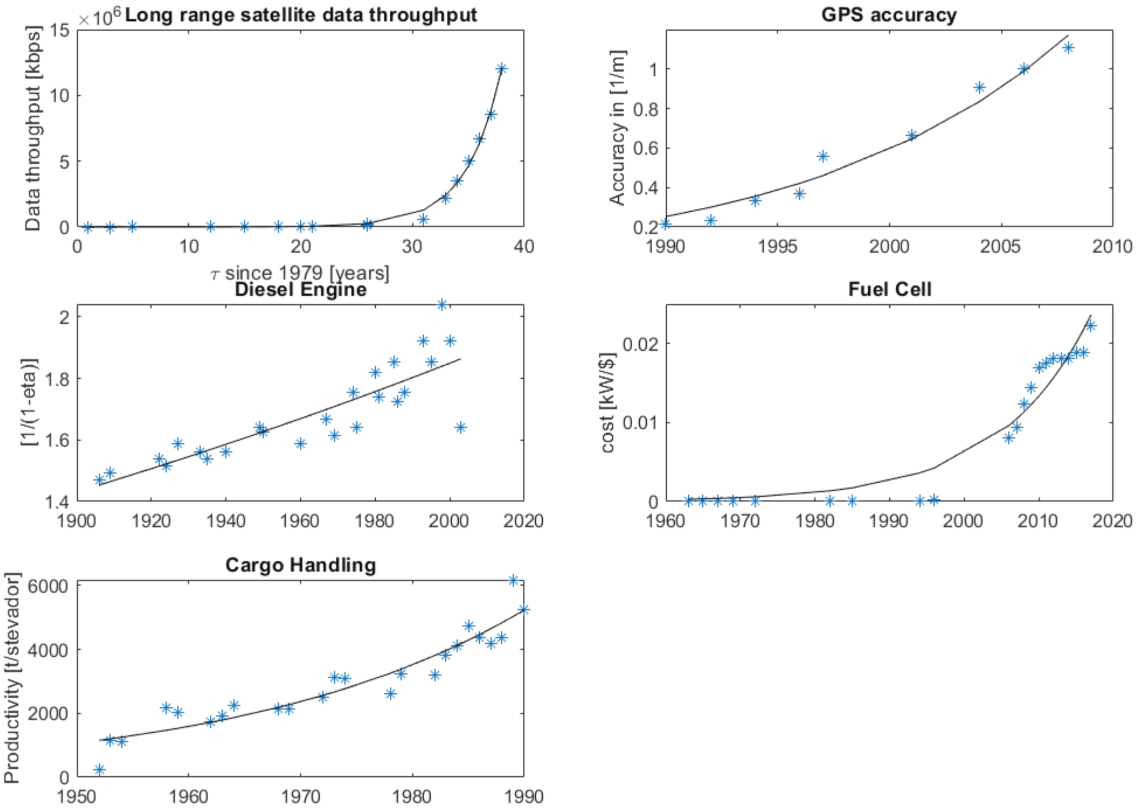

Figure 3: Historic data plots showing the data points and trend lines used to determine the TIR for each of the researched technologies

There is a large difference between the slowest improving TIR and the highest improving TIR. It is clear that technologies that are not only related to shipping, such as GPS accuracy and satellite communication develop much faster than marine diesel engines or the cargo handling.

4.2. *Looking to the Future*

With the determination of the TIR it is possible to look towards the future. Figure 3 shows the 4 prediction plots, each showing the estimated implementation timeline for their technology. Table 4 also shows these results.

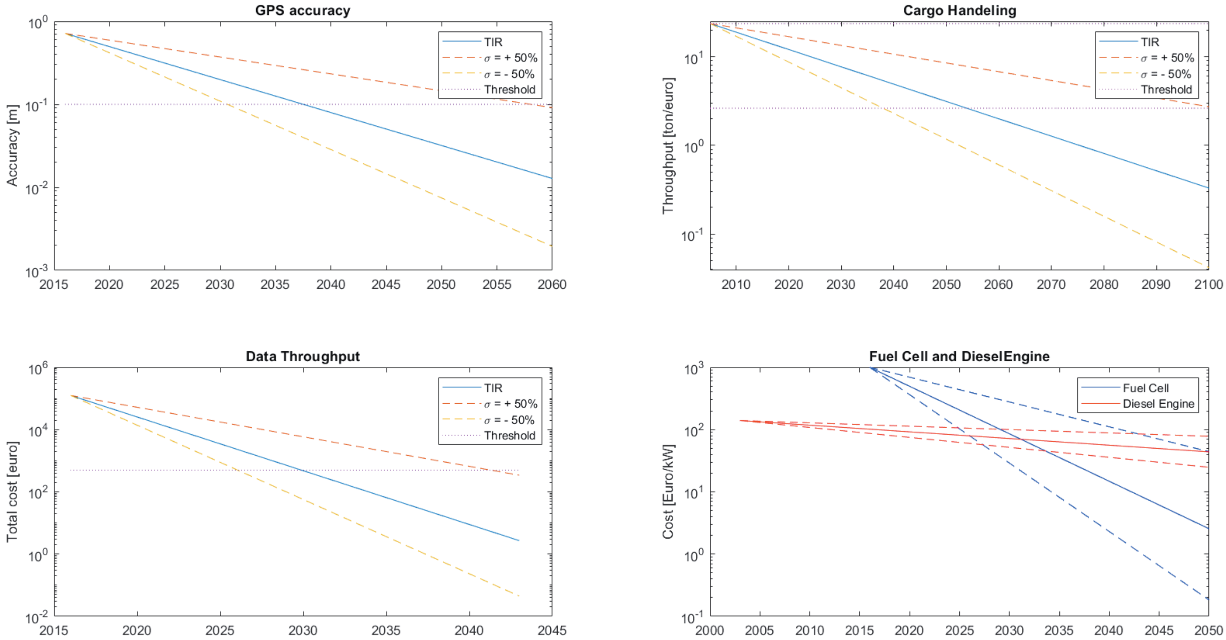

Figure 4: Overview of the future predictions of the researched technologies

Table 4: Expected time range in which the technology becomes available for autonomous shipping

Technology	*Current point*	*Reference point*	*Availability time range*
Data transfer	*€ 125.000 /month*	*€ 500 /month*	*2026 - 2041*
GPS accuracy	*0.715 m*	*0.1 m*	*2030 – 2058*
Cargo handling	*23.6* $[€/t]$	*2.60* $[€/t]$	*2037 - 2101*
Diesel engine	*140* $[€/kW]$	*N/A*	*N/A*
Fuel Cell	*1000* $[€/kW]$	*Diesel engine performance at that point in time*	*2025 - 2060*

5. Discussion and Conclusion

There are several aspects that can be taken into account for future research. The most important ones are discussed here.

5.1. Data used

The research in this paper is relies heavily on available data. Research into unmanned and autonomous shipping is only just beginning, meaning that there is limited data available, especially with regards to the thresholds required for each of the technologies. Therefore the thresholds are not based on a widely accepted facts but on anecdotal values. The precision of the thresholds and therefore the results will increase with further research into unmanned and autonomous shipping.

Another challenge with using data sets is that by using a different data set, or another metric, the results are likely to vary from the results presented in this paper. In this paper comprehensive datasets from one or multiple sources are used. The data was chosen based either on availability or on the metric of the threshold. However, it is feasible that another metric will lead to a different TIR and therefore a different result.

5.2. Number of Researched Solutions

In this paper a number of technologies have been researched which were identified as a challenge in previous research. However, there might also be other solutions to the same problem that were not mentioned in this paper. For example. The GPS accuracy required for automatic docking is said to be 0.1 meters. However, using the GPS location to moor the ship might not be the only solution. The use of cameras or proximity sensors, combined with an automatic docking system might also be a solution. Especially since the GPS accuracy is one of the slowest technologies that have been researched. This solution has not been researched in this paper as previous research had indicated that GPS accuracy might be a challenge not just for mooring but for the whole navigation process. A more detailed analysis of the different solutions can be made once they have been identified in a later research stage.

5.3. Remote Operation

Opinions vary on whether or not remote operation is a good intermediate point on the way to autonomous shipping. One of the arguments is the high cost of the data transfer that is required to give a remote operator a good view of what happens to the ship and that would not be there in case of a fully autonomous ship. However, the results in this paper show that the satellite data transfer is one of the fastest improving technologies researched and the break-even point is reached well before that of other technologies.

5.4. Technologies not researched

Not every single challenge that stands between now and autonomous shipping has been researched. As mentioned in the beginning of this paper the most important unsolved challenges identified in earlier research were used. However, Kooij et al. mention one more challenge that has been left out of this paper, the interaction between the crew and the ship, for instance during mooring. It was found that the markets for these technologies are so small that there is no usable historic data. This means that using this method, it is not possible to say something about their implementation timeframe. Further research in this area is important however as these are the areas where the crew is highly involved which means that in order to remove the crew from the ship these areas need to be solved.

The change towards unmanned or autonomous ships does not only depend on the technical feasibility and economic viability of a technology. There are many other aspects that also need to be taken into account. National and international legislation are currently not designed to handle autonomous or unmanned ships. Additionally new technologies bring new risks with them, the GPS signal of the ship could be jammed or the data signal could be hacked. The speed at which these risks are identified and mitigated also plays a role in the adoption speed. These elements could also be investigated in further research.

5.5. Conclusions

For the four researched technologies the time range in which they reach either technological or economic viability has been calculated. The only one where the technology still needs to develop is the GPS accuracy. While the accuracy is good enough to navigate the ship in the open sea and in busy waters it will take till somewhere between 2030 and 2058 before the accuracy is high enough to allow for mooring.

For the other technologies the operating parameters required have all been reached but the use of the technologies is currently more expensive than manned options. This means that autonomous shipping is mostly an economic problem and not a technology problem.

The economic viability of the different technologies researched will be reached somewhere between 2026 and 2041 for data transfer and 2037 and 2101 for cargo handling. The fuel cell will cost approximately the same as a medium speed diesel engine somewhere between 2025 and 2060.

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Appendix A: Data sets for HDA

Technology	*Timeframe*	*Source*
Shipping	*1947 – 2009*	*(Stopford, 1988)*
Satellite data transfer	*1979 - 2009*	*(Amaya & Magee, 2008)*
	2011-2016	*(Låg, Andersen, Vartdal, & Knutsen, 2015)*
GPS accuracy	*1990 - 2006*	*(US Air Force, 2017)*
Propulsion: Diesel Engine	*1906 - 2003*	(Stapersma, 2010)
Propulsion: Fuel Cell	*1960 - 1990*	*(Seebregts, Kram, Schaeffer, & Bos, 2000)*
	2006 - 2017	*(Wilson et al., 2017)*
Cargo handling	*1952 – 1990*	*(Todd, 1994)*