Co2 reduction in Container shipping

What are the best possible measures?

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Abstract

The public's growing environmental awareness is pushing the container shipping sector to decrease its significant carbon footprint. This thesis presents an overview of current available measures to do this and tests those measures on several case studies. The main goal is to find out what type of measures are the best, operational measures like slow steaming or technological ones like hull design. The selected measures are tested on five different case studies, commonly used routes of different length have been selected. The measures are assessed on effectiveness and efficiency, so both Co2 emissions and costs play a big role in this research. The results are a clear indication that operational measures are outperforming the technological ones. Further, recommendations have been offered on the question what measure is best used under what conditions. It turned out that operational measures are effective in almost all of the case studies while technological measures are mostly only effective on the longest routes. Slow steaming was by far the best measure, reducing both Co2 and costs in all scenarios. The usage of fuel cells however is not yet useful. This measure proved to be subject to high costs and was even increasing emissions on the shortest routes.

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Introduction

The container shipping market is dominated by only a couple of big players. Due to an ever increasing urge to reach economies of scale, the bigger shipping lines have merged with each other or acquired their smaller competitors. This leaves a market that almost resembles an oligopoly (Sys, 2009). This race to economies of scale has everything to do with the volatile state of the markets' driving profit generator: the freight rate. When the economic crisis hit the international trade markets quite hard, the main transporters, i.e. the container shipping market, suffered greatly. Suddenly, demand fell and newly ordered ships were suddenly useless. This state of overcapacity made the price drop to abysmal levels. Shipping lines tried to bring down the costs per transported container by enlarging their networks and ships at the same time. This has until today not had the desired effect. The market is still in a state of overcapacity, the fall of the oil price serves only to cover this up. Apart from the economic crisis, the market has seen another phenomenon appear: the publics rising awareness of transport's carbon footprint. Leading slowly but surely to a more critical view of global shipping.

In reaction to more environmentally aware customers, shareholders and governments, the players in the container shipping market have done a lot to decrease their carbon footprint (Lai, Lun, Wong, & Cheng, 2011). Lots of measures are currently in use or being developed that have an enormous potential to reduce emissions by global shipping (Crist, 2009).

One of the most popular measures is an operational one, where only the way a ship is used needs to change, slow steaming. Slow steaming is in practice for many years as a measure to reduce fuel costs per trip. The basic idea is that when a ship takes longer to travel a given distance, it will be more efficient whit its fuel, thus reducing the costs for carriers (Meyer, Stahlbock, & Voss, Slow steaming in container shipping., 2012). An interesting side aspect of this is that slow steaming also reduces the pollution of the ship by reducing the fuel consumption. It is therefore logical that carriers have used this as an argument to implement slow steaming, after all, deep sea shipping is one of the most polluting sectors in the world and thus under pressure to reduce its emissions (Yin, Fan, Yang, & Li, 2014). There is lots of evidence that slow steaming decreases fuel usage per trip, but there is a downside to speed reduction. Simple logic dictates that, when a carrier wants to maintain a certain service level for a port, say a weekly call, and he implements a speed reduction extra ships will be needed to maintain the same service level (Notteboom & Cariou, 2013).

Other operational measures are available to use instead of or together with slow steaming, using alternative routes or changing the type of fuel used. However, the technological measures, that make use of innovations in relevant industries are also very interesting when the aim is emission reduction (Sherbaz & Duan, 2012). The goal of this research is to find out if technological measures are better than operational measures like slow steaming. The main research question is therefore: are operational measures to reduce the carbon footprint of global shipping outperformed by technological ones?

To find out if this is true, the first step will be to select operational and technological measures from the literature and assess their overall effectiveness in reducing emissions. The second step will be to set up different case studies on which the measures will be tested. The third step will be comparing the effectiveness and efficiency of the different measures to provide an answer for the research question. After the results have been presented, as outlined in step three, several recommendations will be made, both on where to use the different measures and on how to preform further research.

1 Theoretical framework

In recent years, there has been a lot of scientific research regarding the carbon footprint of shipping. Those articles that are relevant for this study will be reviewed here. As these kind of researches have been performed in all kinds of ways, they will be split up in categories.

The first category is composed of studies that focus on the performance of a multitude of measures. In 2009 Philippe Crist presented such a study to the OECD and the International Transport Forum. Here he presented a big list of both technical and operational measures to reduce emissions, giving information he found in specific literature per measure. Important information is the reduction potential in percentages and the payback time. He favours a mix of both operational and technological measures and makes a strong case for slow steaming (Crist, 2009). Miola, Marra and Ciuffo also did a study on measures to reduce shipping's emission, but combined this with advice to policy makers on how to push international shipping to a greener path. They propose a cap on emissions by setting up an international emission trading scheme (Miola, Marra, & Ciuffo, 2011).

In a similar study, Prpić-Oršić and Faltinsen estimated the effect of speed loss and technological measures like hull optimization and propeller polishing on emissions by ships. They did this by finding the kind of waves the ship was most likely going to encounter and calculating the optimal speed, hull shape and more. They also make a case for slow steaming, but thechnological measures are also found to be important emission reductors (Prpić-Oršić & Faltinsen, 2012). In 2011 Eide also did a research that looked at the effectiveness of several measures to reduce emissions. The interesting part about his research is that he adapted a formula used by the International Maritmie Organisation to rate safety measures in shipping. Eide used almost the exact same formula, dividing costs of implementation by the reduction in emissions. This allowed him to assess the cost effectiveness of the different measures. Slow steaming for instance had low cost effectiveness, but weather routing and optimizing hull design did (Eide, Endresen, Skjong, Longva, & Alvik, 2009). The work done by these authors gives a framework to choose emission reduction measures from, this makes that, although this paper does not take costs into account, it will not advice measures that are too expensive to implement.

The second category consists of papers that handle only one measure. First, the literature about slow steaming will be reviewed. In 2012 the financial impact of slow steaming on both the shipping line and its customers was handled by Meyer, Stahlbock and Voss. They found that slow steaming was decreasing the fuel use per trip, but the fact that more trips were needed per time period decreased this benefit. The customer was found to face most of the negative effects because of speed loss (Meyer, Stahlbock, & Voss, 2012). One year later, Maloni, Paul and Gligor found similar effects of slow steaming, and suggested that the customer should be compensated for the loss in service. They also divided the general term slow steaming into different categories, descending in speed, slow steaming, extra slow steaming and super slow steaming. They found that all of them where reducing emissions per trip when compared to full speed, but the returns were definitely diminishing fast (Maloni, Paul, & Gligor, 2013). Yin, Fan, Yang and Li investigated the causes and results of slow steaming. The found that it was mostly caused by high fuel prices, low freight rates and overcapacity of shipping space. The environment had less to do with it, but it still turns out to be benefiting from slow steaming, as it is decreasing fuel consumption of international shipping (Yin, Fan, Yang, & Li, 2014). In the same year, a study by Woo and Moon was published, where the environmental effects of slow steaming where the main target. They did a case study where evidence of substantial emission reduction was found. However, another result was that the positive environmental effects of slow steaming started to decrease when using bigger ships (Woo & Moon, 2014). Psaraftis and Kontovas wrote to papers about slow steaming, one in 2010, where they warned for the impact of a shift to rail and air by expensive cargo because of longer delivery times. The latter could have a big impact because these two modalities are more polluting per tonne transported than ships (Psaraftis & Kontovas, Balancing the economic and environmental performance of maritime transportation., 2010). And an overview in 2015 where they had a look at the current literature available and found that most of it still focusses on costs instead of emissions. They also stated again that slow steaming can decrease emissions per trip significantly (Psaraftis & Kontovas, 2015).

Other operational measures are also broadly described. The use of the Northern Sea route, for instance is discussed in a paper by Stephenson, Brigham and Smith, who did research to accessibility throughout the year and the current use of the NSR by ships, with or without assistance from an icebreaker. They also had a look at the current speed most used along the NSR and saw that it was very low, even comparing with slow steaming (Stephenson, Brigham, & Smith, 2014). Two of the former three authors also presented a study to future access to the NSR, where they base their expectations on climate data, and the expectations regarding the melting of sea ice in the arctic region. Their timeframe ranges up to 2050 and they expect more and more use of the NSR (Smith & Stephenson, 2013). Another interesting research was done by Francois and Rojas-Romagosa in 2014. They investigated the differences in sailing distance between various regions, comparing the standard sea route through the Suez Canal and the Northern Sea route. The differences where all in favour of the NSR and major routes, like Western-Europe to China saw significant decreases in distance because of the NSR. Another research about an operational measure was done by Zis et. al. they wrote a paper about the possibilities to reduce the emissions of ships in or near ports. They found that a zone of very slow steaming around the port would gain substantial benefit and that if the port was able to deliver power to ships, this could be very beneficial for the environment. Their results were obtained by comparing the emissions of ships in and near different ports, who did or did not implement measures to reduce shipping's carbon footprint (Zis, North, Angeloudis, Ochieng, & Bell, 2014).

The third category will focus on literature regarding technological options to reduce emissions in global shipping. The improvement and innovations in weather routing for instance are discussed by Shao, Zhou and Thong in 2012. They did an experiment to find out if incorporating more variables in the currently used software was beneficial and found that it indeed could decrease the power needed by the engine significantly (Shao, Zhou, & Thong, 2012). A year later, another group of scientists found a totally new way of modelling the weather routing software and tested it in several case studies. It was found to give better results than the old software (Lin, Fang, & Yeung, 2013). In 2015 another paper on this subject was presented, that discussed the use of new weather prediction systems. These systems were developed to both predict the weather and sea conditions, but also give more information about the strength of those predictions. Orlandi et. al. proved that this can be useful in weather routing software (Orlandi, Rovai, Benedetti, Romanelli, & Ortolani, 2015).

Technological options to reduce emissions considering the hull of the ship have also been an interesting field for scientists. The effect of biofouling, or the growing of organisms on the hull of a ship, has been researched by Chambers, Stokes, Walsh and Woods, by simulating sea conditions in water tanks, they found the impact of these organisms on the ships hydrodynamics. This impacted the power needed by the engine significantly (Chambers, Stokes, Walsh, & Wood, 2006). The design of the hull could also be changed however, this was stated in a paper by Harries, Abt, Herman and Hochkirch, who also simulated sea conditions in water tanks, but used this to test different hull forms. They found that slight alterations at the hull could make the ship cut through the water with much less resistance (Harries, Abt, Heimann, & Hochkirch, 2006). Other ways to decrease resistance faced by the hull include coating and cleaning. The first is researched by Schultz in 2007, who placed plates of steel used in ships their hulls in salt water with different coatings and found that even the best coating needed regular cleaning (Schultz, 2007). The latter used to be hard, but Schultz found, in cooperation with others, that there are currently innovation ways to do this. Underwater robots significantly decrease the time and costs needed to clean the hull. According to Schultz, Benedick, Holm and Hertel, this means that cleaning will be done more reguraly by shipping lines. The latter decreasing the ships resistance and thus fuel usage significantly (Schultz, Bendick, Holm, & Hertel, 2011).

That the propeller also faces problems because of biofouling is made clear by a recent research from Xiao, Huang and Fei in 2016. By looking at multiple case studies, they found that a lot of maintenance is needed to make sure that the propeller does not get too affected by biofouling. The latter would make the propeller work non-optimal and increase the power needed by the engine to uphold the same speed (Xiao, Huang, & Fei, 2016). Von Lukas and others researched the best way to make sure that organisms do not attach to the propeller and they found that, instead of cleaning, regular polishing was a more effective method (von Lukas, Quarles, Kaklis, & Dolereit, 2015).

1.1 Economical background

The theoretical framework has described the state of scientific research regarding pollution by shipping and the measures to reduce it. Here, in the economical background, some information will be presented regarding the timeframe of the problem. It remains interesting that most shipping lines have started acknowledging and working on their carbon footprint quite recently. After all, it was long known that the sector was very polluting. Here, it is explained why the sector is taking action now, instead of decades ago.

First of all it is important to acknowledge what emissions are in the economical way of thinking. According to the theory of externalities, there are two parties in a transaction that accept the consequences of that transaction willingly. The demand side and the supply side of the equation come to an agreement to exchange goods. The effects of this agreement must be beneficial to them, otherwise they would not have agreed upon it. However, the agreement can also effect other actors who had no say in its construction. These effects are called external effects. They can be positive or negative, but they will always effect other people beside the ones agreeing upon a transaction. In the case of international shipping, it is clear that the emissions produced are a negative external effect. They have a negative impact (pollution of the environment), not only on the actors in the transaction but on the entire planet. The costs produced by this negative external effect however have not always been internalized in the costs of the transaction (Cornes & Sandler, 1996). Only quite recently the general public has become aware of effects such as global warming and that is when the external costs of shipping have begun impacting the transaction itself. The public is now starting to force the sector to decrease the external costs, which is a key reason for shipping companies to try and decrease their emissions.

Second of all, it is important to realise that for a shipping company, the measures to reduce emissions presented in this paper are an investment. Investments will be empirically assessed by companies to see if and when they should be implemented. It is the latter that is important in this case. The company has the option to invest now or later. The costs are reasonably certain to them, but the benefits are depending on the highly volatile freight rate, together with the market's ongoing problems with overcapacity. When an investment has been made, its way of financing (private equity, loans) is pressing on the balance sheet.

It is therefore important that the investment starts generating extra profit as soon as it is implemented.

Reducing emissions will reduce fuel costs for the company, but this is useless when the freight rate is on a very low level. In this case it means that even after the investment, it is too expensive to keep the ship out of lay-up. And in lay-up, the ship makes no money, but the investment is still paid for. While this may seem like a very extreme occurrence, it is unfortunately not that rare. The freight rate has been very low on various points in the last decades, caused by the ever present overcapacity. This scenario will certainly be on ship owners' minds when deciding upon investments. The so-called 'value of waiting to invest' is therefore high in global shipping. This theory means that, in cases of high uncertainty, it is better to wait and see in what state the market will be before investing. After all, when the market turns out to be in a very bad state, the investment will not make money fast enough, so the risk is very high (Ingersoll Jr & Ross, 1992).

This tendency to wait with investments, together with the fact that the generated pollution is an external cost, has caused a tendency of waiting. This tendency is only recently being broken because of the public becoming more aware of the problem.

2 Operational Measures

The review of the possible measures to reduce the carbon footprint of shipping will be split up in two parts: first are the operational measures. Those measures that are changing the way a ship is operated, things like the speed or route of the ship can strategically be changed to decrease emissions. The first operational measure discussed is weather routing, or how to deal with the different weather conditions a ship can face. Second in line is an overview of the possible fuel types, thirdly, the arctic sea route is discussed and slow steaming is fourth in line here. Fifth and last, a small discussion of the possibilities to reduce emissions in and nearby ports is presented.

2.1 Weather routing

The concept of weather routing is very straight forward. The optimal route of the ship is not only determined by ports of call and safety, but also by looking at the weather conditions. As extreme weather is able to delay a ship or bring it in hazard, simply sailing around it can reduce delays and increase safety. Apart from increasing safety and increasing voyage speed, avoiding bad weather does however also have positive effects on fuel consumption. In non-optimal weather conditions, the ship has to use more power to reach the same speed. It is not hard to understand that taking weather into account is beneficial in terms of fuel consumption. In recent years, the advances made on forecasting systems like these are substantial, so much that weather routing is making a big impact (Takashima, Mezaoui, & Shoji, 2009). That, in combination with the fact that it is widely used in the shipping industry makes it an attractive and realistic option to reduce emissions (Lin, Fang, & Yeung, 2013).

In 2012 an interesting new research was published. It contained a calculation of fuel consumption reduction because of a new way of weather routing. Instead of only taking the route to sail as a variable, the authors set up a model that was able to change the route, and the power settings of the ship. The latter allows the weather routing software on board to pick the optimal engine power and propeller rotation speed for each weather condition and location on the sea (Shao, Zhou, & Thong, 2012). This gives a ship the option of braving a storm with optimal power delivered by its engine and propeller instead of making a big detour.

The adding of extra variables to the model has already improved weather routing, but there is more to gain. On the field of weather and sea condition predictions, there are new systems available that do not only take predictions into account, but also calculate the power of those predictions. This information can be used in weather routing software. This means that the ship will have better alternatives and an overall better preparation for when the weather forecast turns out to be wrong. The only downside is that this system requires expensive software and is still in an experimental phase (Orlandi, Rovai, Benedetti, Romanelli, & Ortolani, 2015).

Basically both measures mean an upgrade for the software at relatively low costs, but it will add more routing options and provide the means to adapt as best to the weather as possible. When the authors calculated this model on different case studies, it was actually proven that the new method gave better results. The older models were outperformed with 3.1 percentage points on average considering deep sea shipping (Shao, Zhou, & Thong, 2012). The calculation of the power of forecasts was estimated to be able to decrease fuel use with 10% by the authors, although it should be noted that the implementation of these systems will require more expensive software that is not yet in use and that this percentage was estimated according to conditions in the Mediterranean sea (Orlandi, Rovai, Benedetti, Romanelli, & Ortolani, 2015). This are substantial benefits, and with other evidence of the ongoing modernization in weather routing (Lin, Fang, & Yeung, 2013), more than enough reason to compare weather routing to other methods of emission reduction.

2.2 Changing fuel type

Traditional fuel types used by the shipping industry were cheap and of lower quality then crude oil. These heavy fuel oils are unsurprisingly causing a lot of emissions. It is thus useful to consider alternative fuels to use, both in the near as in the distant future there could be environmentally friendly alternatives.

The environmental benefits for all the different available alternatives to heavy fuel oils were assessed by Byrnolf, Fridell and Anderson. They compared the emissions generated by liquefied natural gas (LNG), methanol (MeOH), liquefied biogas (LBG) and bio methanol (Bio-MeOH to heavy fuel oils (HFO).

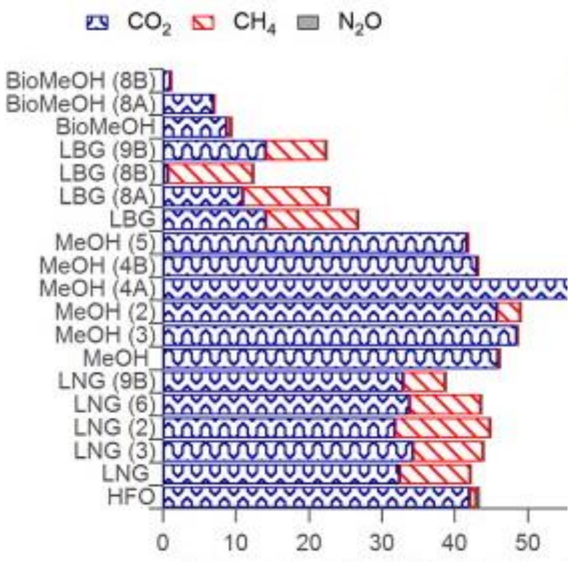


Figure 1 Emissions in grams per tonne kilometre compared (Byrnof, Fridell & Anderson, 2014).

In figure 1, we clearly see that bio methanol and liquefied biogas are a lot better for the environment than the other fuel options. LBG has a benefit of about 10% less emissions and bio methanol decreases emissions to one fourth compared to HFO. Liquefied natural gas and methanol’s benefits are in comparison very small (Brynolf, Fridell, & Andersson, 2014). This makes it obvious that the fuel alternative implemented by the shipping industry in the future should be generated from renewable resources, as is the case with LBG and bio methanol.

It is however important to note that the choice between LBG and bio methanol should be made while taking the performances of the different specialised engines into account. These technological developments can make or break the different forms of bio fuel (Brynolf, Fridell, & Andersson, 2014). Apart from the technological viewpoint, there is also the fact that bio fuels are often produced from crops that could also be used to feed people or livestock. However, LBG and bio methanol do not take valuable food crops to be produced, but are made by chemically processing organic waste (IEA-ETSAP& IRENA , 2013).

Another interesting option is a fuel cell. A fuel cell can be seen as a battery that needs continuous input of fuel to produce electricity. Fuel cells exist in many forms and can be suitably for many fuels, but the most promising option is probably the hydrogen fuel cell. This fuel cell will still need a fuel to be converted to hydrogen, be it fossil or natural, but can produce electricity from the hydrogen, producing significantly less emissions than normal fuel usage. Depending on the type of fuel used to produce hydrogen, the gain can be up to

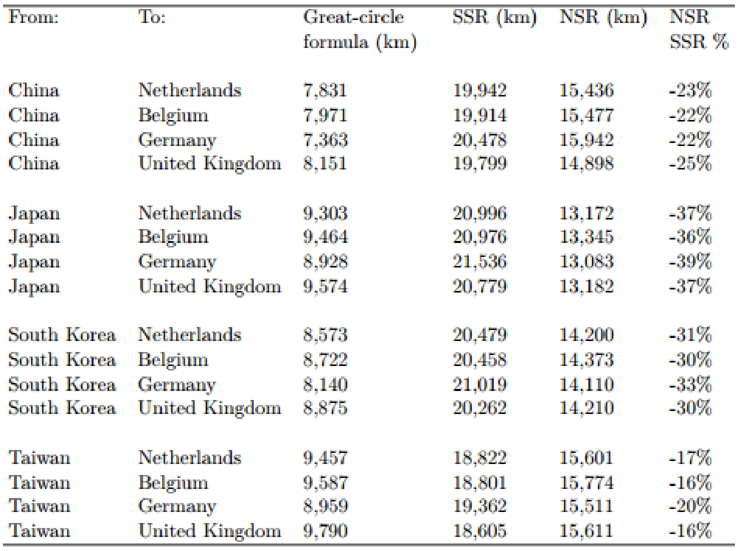
23% when using wind energy. The far more usable natural gas option however, still nets a 14% reduction in total emissions produced in the process (Veziroglu & Macario, 2011). These fuel cells could be used to deliver extra energy, but in the near future it will become possible to rely on fuel cells even for propulsion. The ship will then no longer need a regular engine but can make the switch to this environmentally friendly way of producing energy. However, fuel cells are very costly in regular use and are not yet as durable as a normal engine, so need replacement and maintenance more often (Wang, Chen, Mishler, Cho, & Adroher, 2011).

There are certainly options if a shipping line wants to decrease its carbon footprint by changing the fuel used. Significant benefits can be made by choosing liquefied biogas, bio-ethanol or a hydrogen fuel cell. However, costs still play a role and in that aspect, the heavy fuel oils still have a big advantage, especially over the innovative fuel cells.

2.3 Arctic routes

Paradoxically, the greenhouse effect and subsequently rising temperatures have caused a new route for deep sea shipping to appear. The rising global temperature means that the arctic seas north of Russia are become ice- free for a longer period each year. Because of this, the Northern Sea Route, or NSR, formally a national used route to supply remote towns in Russia, is become more attractive for international shipping (Stephenson, Brigham, & Smith, 2014).

The NSR is a very attractive option to connect north-east Asia and north-west Europe, because it is shorter than the sea rout through the Suez Canal (Southern Sea Route or SSR). As seen in the figure below, the distances differ quite significantly in favour of the NSR, up to 39% decrease in distance is huge (Francois & Rojas-Romagosa, 2014).



From:	To:	Great-circle formula (km)	SSR (km)	NSR (km)	NSR SSR %
China	Netherlands	7,831	19,942	15,436	-23%
China	Belgium	7,971	19,914	15,477	-22%
China	Germany	7,363	20,478	15,942	-22%
China	United Kingdom	8,151	19,799	14,898	-25%
Japan	Netherlands	9,303	20,996	13,172	-37%
Japan	Belgium	9,464	20,976	13,345	-36%
Japan	Germany	8,928	21,536	13,083	-39%
Japan	United Kingdom	9,574	20,779	13,182	-37%
South Korea	Netherlands	8,573	20,479	14,200	-31%
South Korea	Belgium	8,722	20,458	14,373	-30%
South Korea	Germany	8,140	21,019	14,110	-33%
South Korea	United Kingdom	8,875	20,262	14,210	-30%
Taiwan	Netherlands	9,457	18,822	15,601	-17%
Taiwan	Belgium	9,587	18,801	15,774	-16%
Taiwan	Germany	8,959	19,362	15,511	-20%
Taiwan	United Kingdom	9,790	18,605	15,611	-16%

Figure 2. Distances from East Asia to Western Europe. NSR and SSR compared (Francois & Rojas-Romagosa, 2014).

Normally a distance reduction would result in the same amount of fuel saved, but along the NSR the conditions are very different than on other shipping routes. Most importantly, the NSR is still closed during the winter months, and even in spring and autumn only specialised ships can use it. This means that only the summer voyages of a ship can be done through the NSR, so that reduces the actual overall effect a lot. The exact expectation is that until approximately 2027 the NSR will only be useable by standard ships in the months July, August and September (Stephenson, Brigham, & Smith, 2014). This decreases the impact of the NSR to one fourth of its distance reduction percentage.

Apart from this problem, the shipping lines wishing to operate via the NSR face other problems. One of those is uncertainty: while the NSR is generally useable during summer, weather conditions can still be harsh and sometimes the water can still freeze solid. Making an expensive icebreaker necessary to complete the trip (Smith & Stephenson, 2013). Another point of interest is the speed with which vessels sail on the NSR, because of weather conditions and uncertainty regarding ice, the speed on the NSR is relatively low, even during summer. An example is the journey of the Nordic Odyssey from Murmansk to China in July 2012, its average speed on the NSR was only 9,7 knots. Similar summer voyages also note average speeds of around 10-11 knots (Stephenson, Brigham, & Smith, 2014). For reference, in their 2012 research about different forms of slow steaming, Maloney et. al. define 21 knots as slow steaming, 17 knots as extra slow steaming and 15 knots as super slow steaming (Maloni, Paul, & Gligor, 2013). This very slow speed will also have an impact on the performance along the NSR.

So, although the NSR has some great benefits in terms of distance reduction, it cannot be assumed that the percentages lost in distance will mean the exact same percentages lost in fuel consumption and subsequent emissions. After taking into account that the NSR can be used only 25% of the time by regular ships, who then sail at a disadvantageous speed, the gains are only average.

2.4 Slow steaming

In the recent economic crisis, the shipping industry was faced by big problems. High fuel prices, low freight rates and overcapacity, the latter two because of a significant decrease in demand. These problems led shipping lines to explore every option possible to lower their costs, and this made them also more critically examine ship speed. Slow steaming was appealing at the time because it diminished the effect of the three problems mentioned above. By letting a ship sail slower, the fuel costs of the trip were found to decrease, making overall operations cheaper. A very interesting piece of information in times of crisis, but slow steaming has another benefit. When sailing on a schedule, as most shipping lines do, a slower sailing speed means that more ships are needed to uphold the same level of service on a route. The latter means that some of the abundant ships, due to overcapacity, can be used on the slow steaming routes (Yin, Fan, Yang, & Li, 2014).

Although slow steaming was implemented as a countermeasure to a crisis, it has been kept in use until the present date. Mainly because it is cheaper then sailing at full speed, but also because it has a positive impact on the shipping sector's carbon footprint. After all, when the amount of fuel that is used per trip is decreased, the total emissions will follow (Psaraftis & Kontovas, 2015). Full speed steaming is often described as sailing at 25 knots, while regular slow steaming sails at 21 knots. However, even slower forms of steaming exist and results of emission reductions per trip are huge. In 2013, Maloni, Paul and Grigor found a 43% reduction of Co2 emissions when using a speed of 15 knots, "extra slow steaming" as they call it (Maloni, Paul, & Gligor, 2013). As is shown by Woo and Moon in their article about slow steaming in 2014, when looking at the emissions per trip, every decrease in knots means an extra decrease in emissions (Woo & Moon, 2014).

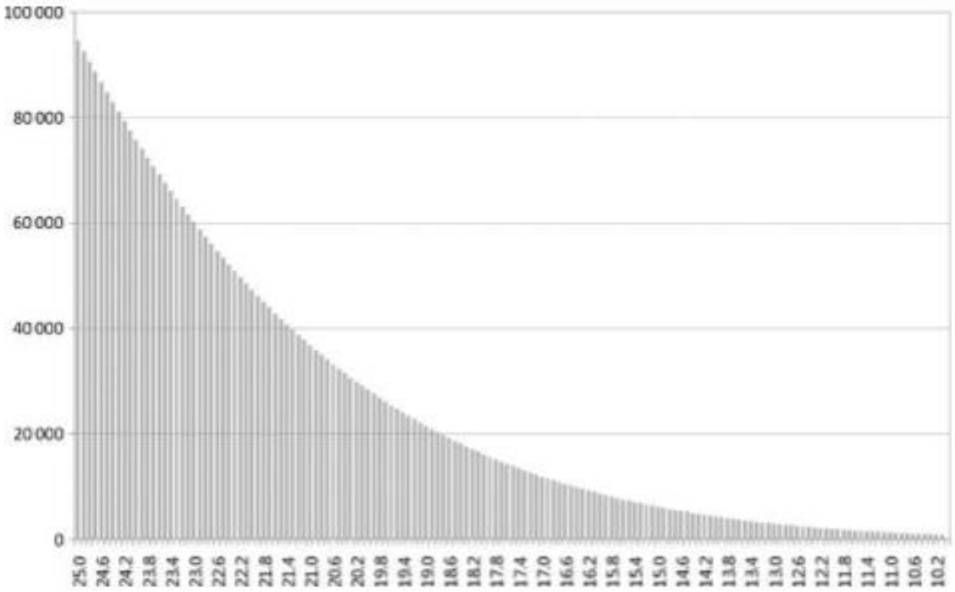


Figure 3 The effect of a speed reduction (in knots) on Co2 emissions per trip (Woo & Moon, 2014).

Figure 3 is however an oversimplification, because shipping lines do not make just one trip per period, they are aiming at a certain service level, visiting ports multiple times per period. The fact that slow steaming means a ship will take longer to complete its journey implies that its total amount of cargo carried per year will decrease. The latter because of the decrease in trips per year. This can be illustrated best by the maximum transport performance formula: Fs = capeff * To(Th+Ts). Here, Fs is the maximum transport performance, capeff is the ship's effective capacity, To is the operational time period, and Th and Ts are the time spend in harbour and sailing respectively (Meyer, Stahlbock, & Voss, Slow steaming in container shipping., 2012). The simple implication of this formula from Meyer, Stahlbock and Voss is that on slower sailing speeds, more ships will be needed per fixed period. These extra ships will produce emissions and decrease the overall impact of slow steaming. Woo and Moon write that because of this effect, sailing at speeds below 14 knots will have no or negative effects on the carbon footprint of the route per fixed time period (Woo & Moon, 2014).

Furthermore, slow steaming means a decrease in service to customers, as their products take longer to be delivered. They will face extra costs because of this and may demand compensation if the speed is very slow (Maloni, Paul, & Gligor, 2013). When looking from an environmental point of view, the problem with this is that some of the shipping line's customers will have to change to another form of transport because of the slower delivery times. These other forms of transport are trains, trucks and airplanes. Since they all produce more emissions per tonne transported, more than two times as much by rail for instance (Dekker, Bloemhof, & Mallidis, 2012), this will have a negative impact on the total emissions. Psarafatis and Kontovas are convinced that shifts like these will be made by very expensive types of cargo as long as a decrease in speed is not accompanied by a decrease in the freight rate (Psaraftis & Kontovas, 2010).

Energy use / Emissions g/t/km	**PS-type container vessel (11,000 TEU)**	**S-type container vessel (6,600 TEU)**	**Rail-Electric**	**Rail-Diesel**	**Heavy Truck**	**Boeing 747-400**
kWh/t/km	0.014	0.018	0.043	0.067	0.18	2.00
CO_2	7.48	8.36	18	17	50	552
SO_x	0.19	0.21	0.44	0.35	0.31	5.69
NO_x	0.12	0.162	0.10	0.00005	0.00006	0.17
PM	0.008	0.009	n/a	0.008	0.005	n/a

Figure 4 Energy use of different modalities per tonne kilometre. Note especially the differences in Co2 emissions between the container vessels and other modes (Dekker, Bloemhof & Mallidis, 2012).

Essentially, slow steaming can be very beneficial in terms of emission reduction, as long as there are not too many other ships needed to maintain the service level. Also, to prevent a shift in modalities that is increasing the carbon footprint of worldwide trade, if not of ocean shipping, an accompanying decrease in freight rates is necessary.

2.5 In-port emission reduction

While the main part of a ship's journey is spent on sea, a significant amount of time is also spent in ports, either waiting to enter, being handled by a terminal, or waiting for the latter. This amounts up to an average of 17% of the total voyage time spent in or nearby a port (Midoro, Musso, & Parola, 2005). And although the engine does not have to deliver full power, the ship still consumes fuel and thus produces emissions. When a port authority decides to lower the total emissions of the port, this is usually implemented by two main actions.

First, it is common to install a speed limit in a region around the port. Often implemented to preserve the local air quality, the speed limit is usually enforced from 10 to 40 nautical miles from the port's entrance (Chang & Wang, 2012). The speed that is set as the limit varies, but the consensus is that this speed should be very slow, around 12 knots. This is shown to have a significant impact: the 12 knots scenario, implemented in a zone of 12 NM from the port, was shown to have an effect of 10% to 20% in terms of emission reduction. The variation is seen between ports with low berthing times and slower ports, where the higher berthing times meant less gain from the slow steaming zone (Zis, North, Angeloudis, Ochieng, & Bell, 2014). Similar results were found by Chang and Wang in their 2012 case study focussing on Taiwan. They found that a reduction to 12 knots was optimal and would reduce emissions around the port with an average of 15% (Chang & Wang, 2012).

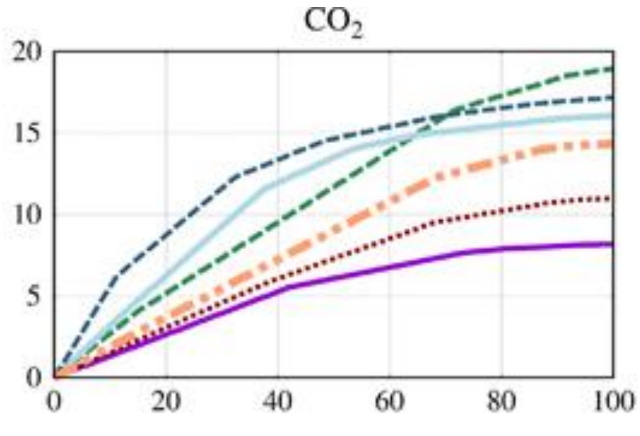


Figure 5 Co2 emission reductions in percentages. The horizontal axis represents the percentage of ships that follow the speed rules. The different lines represent geographical regions, with the North Sea region being the orange line, reaching just about 15% at 100% participation (Zis, North, Angeloudis, Ochieng & Bell, 2014).

The majority of in- and near- port emissions however, are produced when the ship is berthing, either being handled at the terminal or waiting for the latter. While the ship is stationary, the engine is still producing hoteling emissions. Certain auxiliary systems, like cooling supplies, or keeping temperature of the fuel under control are still needed at berth. There is an alternative to the engine of the ship however, using cold ironing, where the port provides electricity to the ship, will reduce emissions. Cold ironing is a power supply network that is suitable for every ship to plug in to. This requires some investments from the port, the terminals and the shipping lines, but it certainly will reduce emissions. This is because the electricity is often generated by a more climate friendly fuel than is used by the ship (Zis, North, Angeloudis, Ochieng, & Bell, 2014).

The benefits of this in terms of emission reductions are huge: berthing emissions could be decreased with as much as 57% according to Chang and Wang (Chang & Wang, 2012). Zis et. al. found a similar result where the benefits ranged from 40% to 70%, depending on the region and its quality of ports (Zis, North, Angeloudis, Ochieng, & Bell, 2014).

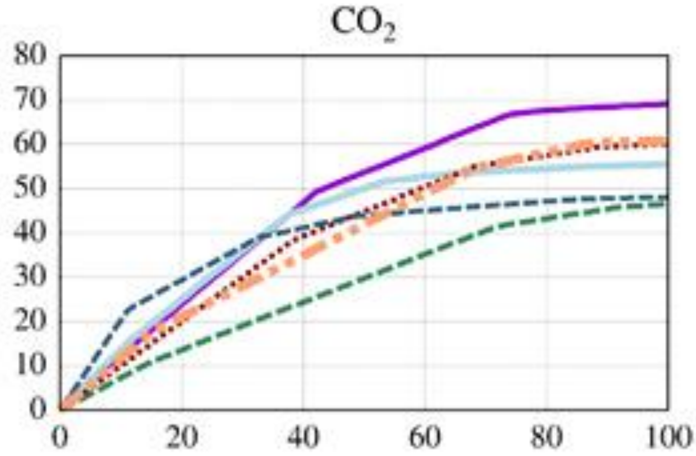


Figure 6 Percentage of CO2 reduction because of cold ironing (vertical axis) on percentage of ships participating (horizontal axis). The North Sea is represented by the orange line that hits 60% at 100% participation(Zis, North, Angeloudis, Ochien & Bell, 2014).

This means that in-port measures can also have a significant effect on shipping emissions, although the investments needed for cold ironing are high, it is very worthwhile. Implementing mandatory slow steaming near ports is a cheaper option, but also has positive effects.

3 Technological Measures

Technological measures are the measures that require technical changes, the way a ship is designed could be changed to decrease its carbon footprint and those measures will be discussed here. First comes hull design, greatly effecting the resistance of the ship, second are the new ways to clean a ship, also effecting the resistance to be faced. Third is the propeller and the options available to upgrade, clean or fine-tune it, making it more effective and last is engine design, presenting ways to design an engine that has a smaller carbon footprint.

3.1 Hull design

The improvement of the design of the hull of a ship also has potential to reduce fuel consumption and thus emissions. It has always been a big question for ship builders how the hull should be made. And in recent times, the potential benefits in terms of a reduction in fuel consumption have become more and more important. The latter mainly because of the increasing fuel price from the past years, but the environment is also catching the eye of ship owners and builders.

When we look at hull design, the most important focus is the front of the hull, as that is facing the most resistance. There are a few ways of designing the front of the hull, which all aim to be as hydrodynamic as possible. The latter means that the ship has minimal resistance from the water, so the same speed can be achieved with lower engine power and thus lower fuel consumption. The standard approach to designing the front of the hull is derived from the principle that the ship should be as smooth as possible, almost like a knife cutting the water. It is however also possible to design the hull differently. The effects of different hull designs on fuel consumption were assessed by Harries, Abt, Heimann and Hochkirch (Harries, Abt, Heimann, & Hochkirch, 2006) and their results are very interesting from an environmental point of view. They were able to find a hull design that was more hydrodynamic than the standard hull designs.

This design differs from the rest because it is not smooth at all, it has more curves in the front of the hull than necessary. Figure 7 gives the standard hull design and the new one, where we clearly see the attempted smoothness in the standard design and the extra curves in the new design (Harries, Abt, Heimann, & Hochkirch, 2006).

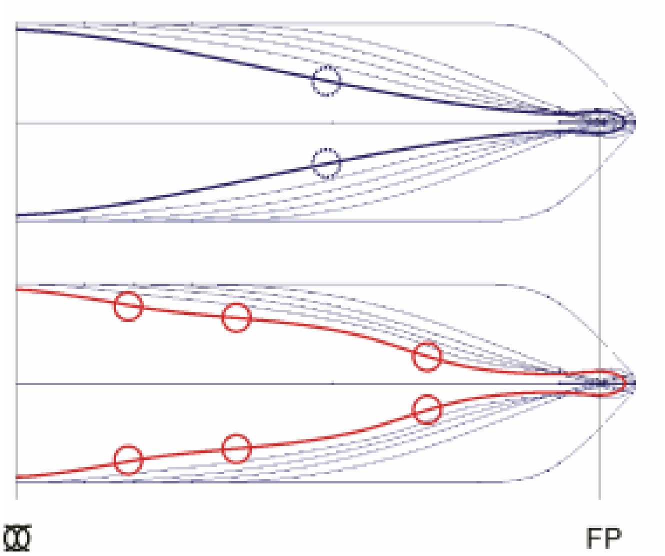


Figure 7 Standard (in blue) and innovative (in red) hull designs (Harries, Abt, Heimann & Hochkirch, 2006).

The new, or innovative, design actually turns out to perform better than the standard design. It lowered the water resistance, which means the engine needs to deliver less power for the same speed. This is very beneficial from an environmental point of view. The new design also delivered the same stability as the standard hulls did and the effects of the draft of the ship were pretty small. The latter means that it does not matter that much if the ship is full or empty, the new hull design makes the ship more hydrodynamic (Harries, Abt, Heimann, & Hochkirch, 2006).

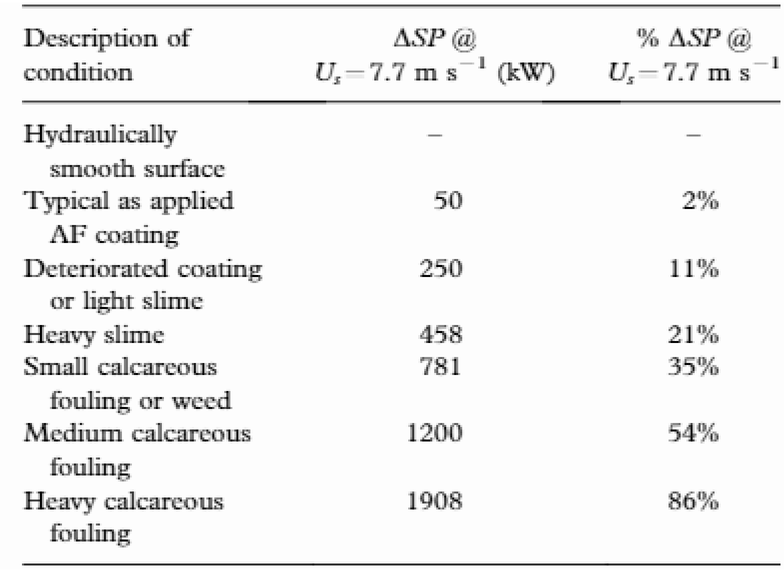
Now that it is clear that hull design can be beneficial for the environment, it is important to know how much potential benefit there is to reap from innovations like the one above. In his study to find out the potential for reducing emissions in international shipping, P Crist has taken a look at a couple hull design options. He found that the optimal hull design could give a fuel efficiency gain of up to 9%. However, next to the optimal design case described above, Crist also takes into account the length to breadth ration, stating that this also has a huge impact on hydrodynamics. His suggestion is that the length of the ship be taken into account when looking at the hull design (Crist, 2009).

The way the hull is designed can have impact on emissions by the ship, therefore it is interesting to compare the innovative hull design with other measures to reduce emissions.

3.2 Hull cleaning and coating

Once lowered under water, the hull of a ship faces a constant problem. Within the first hour, there is a tiny layer of organic carbon residues formed on the underwater parts of the ship. This layer makes is possible for small organisms to attach themselves to the ship as well, and in the first week there will be a colony of bacteria and other micro-organisms attached to the ship. This colony will then attract other organisms such as larvae to the ship. And in a small month, the original hull will be covered in a slimy substance called biofouling. One mayor problem caused by biofouling is corrosion. The biofouling reduces the amount of oxygen that can reach the surface of the hull, which has negative effects in terms of life expectancy (Chambers, Stokes, Walsh, & Wood, 2006).

Biofouling does also have negative impacts on the fuel consumption of a ship however. The slimy layers of micro-organisms and bacteria change the structure of the hull, making it less hydrodynamic. This changes the resistance the ship faces from the water and makes that the engine has to deliver significantly more power for the same speed. In his research from 2007, M.P. Schultz has compared hull material in different stages of biofouling. He found that biofouling could increase the total resistance of the ship with up to 80% in the worst case scenario or with 11% when some cleaning is done. The coating however is also responsible for 2% extra resistance, as it is not as smooth as the original hull itself (Schultz, Effects of coating roughness and biofouling on ship resistance and powering. , 2007).



Description of condition	ΔSP @ $U_s = 7.7$ m s^{-1} (kW)	% ΔSP @ $U_s = 7.7$ m s^{-1}
Hydraulically smooth surface	–	–
Typical as applied AF coating	50	2%
Deteriorated coating or light slime	250	11%
Heavy slime	458	21%
Small calcareous fouling or weed	781	35%
Medium calcareous fouling	1200	54%
Heavy calcareous fouling	1908	86%

Figure 8 Change in Required Shaft Power (Shultz, 2007).

Figure 8 shows the change in power delivery needed at 15 knots. This data from Schultz is very interesting as this is relatable to the fuel usage and thus total emissions. Here, we see almost the same structure as with the resistance: under heavy fouling, the ship will need 86% more power to sail the same speed. A huge impact. The deteriorated coating scenario is however far more likely to appear. Here, a certain level of maintenance has been upheld and a coating has been used. There is still a negative impact of 11% compared to a smooth hull and a 9 percentage point negative impact compared to a clean anti fouling coating (Schultz, Effects of coating roughness and biofouling on ship resistance and powering. , 2007).

In his research from 2009 Crist also acknowledges the importance of a clean hull, stating that it would be possible to make a 5% fuel efficiency gain by using the best availably coating and that regular cleaning will result in another 3% to be gained (Crist, 2009).

It is clear now that having a clean hull is very beneficial to fuel consumption. The question remains how to do this. With today's coating cleaning will still be needed from time to time, which is expensive. A very interesting development is presented in a more recent paper by Schultz. Here, he and his co-authors broach the subject of proactive hull cleaning by "small, autonomous underwater vehicles" (Schultz, Bendick, Holm, & Hertel, 2011). This would make regular cleaning more cost effective and can be used to keep biofouling at a minimum if used every few weeks.

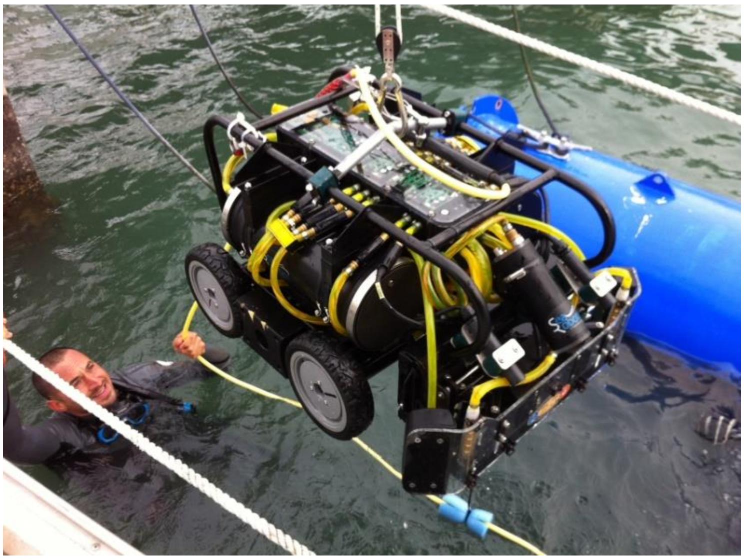


Figure 9 An underwater cleaning robot or Hull BUGS (searobotics, 2015).

Since the publishing date of the paper, these kind of robots have been tested and are now in the beginning stage of being implemented in the industry (Maxonmotor, 2012) (SeaRobotics, 2015). It is therefore not unreasonable to assume the further implementation of these kind of robots in the shipping industry. Hopefully, with this kind of new technologies and the most up-to-date coatings, the shipping industry will have a cost effective means of fuel consumption reduction.

3.3 Propeller Cleaning & Polishing

The propeller is the ships sole way of dispatching energy to move forward, through its rotation the engine is enabled to deliver power to the ship. The propeller is however susceptible to the same fouling problems that are faced by the hull. Without maintenance the optimal way of rotation will soon be impossible because of this fouling. However, even with basic maintenance the impact will be felt. Corrosion will have its impact on the life expectancy and the added friction and resistance will increase fuel consumption (Xiao, Huang, & Fei, 2016).

This problem can be solved pretty straight forwardly by polishing the propeller. This is beneficial because a super smooth surface is less attractive for the organisms that cause biofouling. Polishing can be done in the dry docks. Cleaning, another option, can be performed under water through similar technological developments as are used to clean the hull of the ship. The fact that this measure can be done underwater makes it cheaper and possible to be used more often, thus improving efficiency (von Lukas, Quarles, Kaklis, & Dolereit, 2015).

Propeller cleaning and polishing itself will have significant benefits, especially considering the fact that it will not be necessary to take a ship out of service to do it. The estimated benefits range from 3% (Sherbaz & Duan, 2012) up to 9% (Crist, 2009) in fuel reduction. It is however also possible to do certain upgrades to the propeller and its surroundings. Optimal alignment, optimal skeg design (an extended part of the ship's hull, almost reaching the propeller), optimizing the propeller wings or installing a nozzle around the propeller will each improve fuel efficiency with two to five percent. The downside of these measures are that they cannot be implemented while the ship is in service and that their payback time is of medium length (Crist, 2009).

3.4 Engine design

The engine of the ship is designed to perform as efficiently as possible. The problem here is that we have recently seen a change in the way ships are operated: speed reduction. This reduces fuel costs per trip, and thus emissions. It does however mean that the ships with older engines, a large part of the current world cargo fleet, have an engine that is used in a way it was not designed for (Hochkirch & Bertram, 2010). The so-called operating profile (the estimation of the actions of the ship like voyage length, ship length, but also speed) is however crucial in designing an engine that will perform optimally. By adapting the design of new engines to current trends in shipping, there can be a lot of gains made (Banks, et al., 2013). By implementing this new way of designing an engine, or the re-tuning of older engines, efficiency gains in terms of fuel consumption can add up to 3.5 percentage points (Crist, 2009).

Another problem is the waste heath that is produced by marine engines. On a first glance, that fact that an engine becomes hot is not a problem, but it is actually reducing the efficiency and thus increasing fuel consumption. Cooling the engine is an option, but the heath produced can also be used to produce electricity. This method of heath recovery generates energy that can be used for all kinds of appliances on the ship, and is a certain way of saving energy (Osses & Bucknall, 2014). When done optimally, it is guaranteed to decrease fuel consumption with 5 percentage points (Crist, 2009). Combined, this could decrease fuel consumption by 8.5 percent.

3.5 Sub-conclusion

From the research presented above, it has become clear that there are many possibilities to reduce the carbon footprint of the shipping industry. The biggest reduction seem to be made possible by the so-called strategical measures: slow steaming, in-port emission reductions, the use of the arctic sea routes and the changing of fuel type. The technological measures, like weather routing, optimizing hull design, hull cleaning and coating and propeller polishing give smaller, although still substantial, benefits. The next step in this research is to set up a model to calculate Co2 emissions and test all the measures in multiple case studies.

4 Analysis

To really compare the different technological and operational measures, it is best to perform a couple of case studies. The measures will all be tested on different shipping routes that are likely to be in the network of a global container shipping line. It is key to note however, that the arctic shipping route, as a measure, can only be used on the Europe-Far East route. After all, a route like Far East- Australasia, has no arctic detour available. The routes chosen are Europe- Far East, Far East- Australasia and the shorter routes intra-Asia, Asian Short Sea Shipping and European Short Sea Shipping. They have been chosen to provide a mix between longer and shorter routes, so that the measures will be tested in different conditions. It is assumed that the ships are sailing within a schedule, where the shipping line has committed itself to a weekly service. Further, the simplification is made that the ships do not stop in between the port of origin and the port of destination. Albeit unrealistic, allowing stops in between would influence the analysis and shift the focus to the service times in the various local ports. Said service or berth time is estimated at a standard time of 25 hours total. This number has been taken after looking at recent data for the ports of Rotterdam (Cargosmart, 2014), Antwerp (Portstrategy, 2015) and Hong Kong (mardep.gov.hk, 2016).

4.1 Methodology

To calculate the effects on Co2 emission of the various measures, a couple of formula's have been used. The main formula is derived from the modelling work of Woo and Moon in 2014 (Woo & Moon, 2014), though it should be noted that this is only a simplification of a small part of their model.

$$TYE = (VET * TPV) * \#Vessels \; (1)$$

Formula 1 is the basic formula to compute the total Co2 emissions per year of the given route and schedule. TYE stands for Total Yearly Emissions, VET means Vessel Emissions per roundtrip, TPV stands the amount of Trips per Vessel and the number of vessels is the total number of ships needed to be able to maintain the given service level.

$$VET = (2 * KM * DWT) * CTkm + (2 * PT * PE)(2)$$

Formula 2 explains how the vessel emissions per roundtrip are obtained. Here KM stands for the length of a single trip, DWT is deadweight tonnage and CTkm is the amount of Co2 emitted per tonne kilometre. PT stands for port time and PE for in-port emissions.

$$TPV = (365 * 24)/(ToS + TiP)(3)$$

Formula 3 is a simple computation, to calculate the trips per vessel, the number of hours per year are divided by ToS, the time spent on sea and TiP, the time spent in port.

$$\#Vessels = \frac{Servicelevel}{TPV}(4)$$

Formula 4 explains that the total amount of vessels needed per year is calculated by dividing the service level by the TPV. Here, the service level means the number of calls that are to be made at a port per year.

With these formulas a model has been made in excel which calculates the Co2 output per year on a given loop. However, it is also very interesting to look at this from the shipping line's point of view, they will be very concerned about the costs of the yearly loop. Costs are made up of the costs of one ship, including the price, staffing and port dues, and the costs of fuel. The latter can be obtained by multiplying the fuel consumption per kilometre with the total distance and the fuel price per litre. The former is derived from the literature. An estimation of the costs has been added to the model, so it is possible to rank measures according to effectiveness and efficiency.

4.2 Europe- Far East

The first route to analyse is the most famous one. In this case study, the major ports of Shanghai and Rotterdam will be linked by ship along the commonly known route through the Suez canal. According to the website searates.com, the distance between those ports is an estimated 19,379 kilometres (searates.com, 2016). This route is known for the use of huge ships. Therefore, the ship's tonnage is chosen according to one of those huge ship types that are currently in operation on this route. Maersk's triple-e class is capable of carrying up to

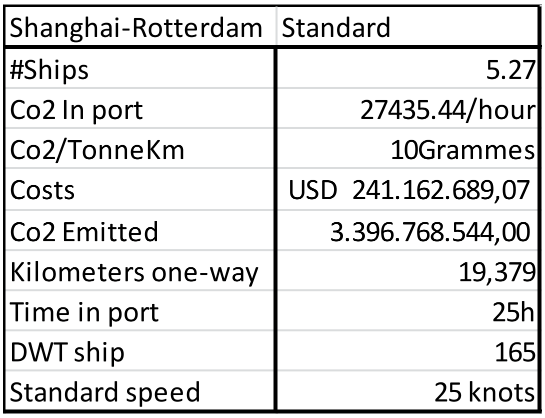
18000 TEU of containers and has a deadweight of 165,000 tonnes (Maersk, 2014). Most ships that sail on this route will be of the Suez-max type, with a deadweight tonnage between 100,000 and 200,000 (maritime-connector.com, 2015). It seems that the triple-e class vessel's weight is a reasonable representation of this category, with its deadweight tonnage falling roughly in the middle of the spectrum.

Now that we know the weight of the ship and the length of the route, it is important to understand how many Co2 emissions are produced by the average containership of this category. According to a study in 2009 by Psaraftis and Kontovas, a vessel larger than 4400 TEU produces on average 10,8 grams of Co2 per tonne kilometre. It is important to note that they found smaller results per tonne kilometre for the bigger ships, but the slope started to flatten near the biggest category (Psaraftis & Kontovas, 2009). Their findings are supported by the European Environment Agency, who find approximately 12 grams per tonne kilometre as an average for the entire shipping sector (European Environment Agency, 2015). In 2014, the International Chamber of Shipping classified large containerships as only producing 3 grams of Co2 per tonne kilometre (International Chamber of Shipping, 2014). These results have to be taken with a grain of salt however, because they assume that all large containerships are very recently built, which is not the case. They are also trying to prove the energy efficiency of shipping over other forms of transport. Thus, it seems reasonably sure that a ship in the Suez max class will be producing about 10 grams per tonne kilometre. This means that the journey of 19,379 kilometres, with the ship of 165,000 tonnes will lead to 31,975,350.00 kilograms of Co2 emitted.

It is however far more useful to look at the impact of emission reduction on liner networks. Meaning that the shipping line has committed itself to call at Rotterdam once per week from Shanghai. On a normal speed of 25 knots, this would take 17.4 days. The ship will then spend 25 hours in Rotterdam, and make its way back to Shanghai where it will have to berth for another 25 hours before it can make its way to Rotterdam once more. A cycle thus costs 37 days. Given a year of 365 days, a ship can make 9.87 roundtrips per year. Since the service level is 52 roundtrips, the number of ships needed is 5.27. The total emissions from one trip equal two times the journey emissions, as stated above, plus the emissions generated in the ports. In 2014 the International Shipping Forum estimated that 18 million tonnes of Co2 are produced by ships while they are in port, large containerships being among the worst polluters (International Transport Forum, 2014). Since the estimate of global emissions from international shipping was 843 million tonnes of Co2 (Psaraftis & Kontovas, 2009), the in port emissions account for 2,1 percent of total shipping pollution.

In this case, that will lead to a total of 1,371,771.91 Kg of Co2 emitted in port, or 27,435.44 Kg Co2 per hour. Thus, total roundtrip emissions equals 65,322,472.00 Kg Co2. Now that we know the number of trips each vessel makes per year, how many vessels are needed and how much they emit per trip, we can estimate the total emissions by using formula one. Here, that would result in total yearly emissions of 3,396,768,544 Kg of Co2 per year.

The costs of the ship consist of 4 million dollars per year and the price of the ship (Hofstra University, 2016). The latter is estimated to be around 160 million dollars for the largest containership category (Maersk, 2014), this will be spread out over a depreciation period of 30 years. This gives 4 + (160/30) = 9.3 million dollars per year. The costs for fuel are approximately 270 dollars per tonne (shipbunker.com, 2016), the fuel consumption ranges from 370 tonnes per day on 25 knots to 100 tonnes per day on 15 knots (Hofstra University, 2016). Total costs for the standard yearly loop are then 241,162,689.07 USD.



Shanghai-Rotterdam	Standard
#Ships	5.27
Co2 In port	27435.44/hour
Co2/TonneKm	10Grammes
Costs	USD 241.162.689,07
Co2 Emitted	3.396.768.544,00
Kilometers one-way	19,379
Time in port	25h
DWT ship	165
Standard speed	25 knots

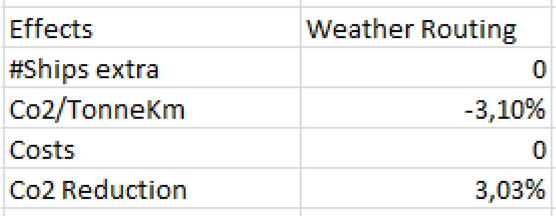
Figure 10 Shanghai-Rotterdam Standard

4.2.1 Operational Measures

Operational measures will be the first to be assessed. They consist of weather routing, the arctic route, slow steaming, fuel choice and in-port emission reductions.

Weather routing

The first measure to analyse in this scenario is weather routing. As stated before, this measure consists of new and somewhat expensive software that will help the crew to assess the weather better and adjust the course of the vessel. The new software system can reduce fuel consumption during travelling with 3.1 percent (Shao, Zhou, & Thong, 2012). The costs will be high, but safety will increase and the chance of delays and the fuel use will decrease. The savings are computed by taking 3.1 percent of the emissions produced at sea. On this route, weather routing accounts for a decrease of 103,088,528.4 Kg Co2 per year. A total gain of 3,03 %. This measure has only the costs of the software as a negative, but a state of the art weather routing system will equal its costs by preventing safety issues and the loss of containers in storms.



Effects	Weather Routing
#Ships extra	0
Co2/TonneKm	-3,10%
Costs	0
Co2 Reduction	3,03%

Figure 11 Weather Routing, effects

Changing of fuel type

One can also decrease his carbon footprint by changing the type of fuel that is used. Since fuel cells are currently in a state of fast innovation, it is interesting to look at the most promising new designs. A fuel cell will decrease the emissions at sea a lot, but will also need to be replaced more often, a fuel cell will need major maintenance or replacement after 5000 hours of use (Wang, Chen, Mishler, Cho, & Adroher, 2011). While replacing a regular engine could mean that the ship is out of service for weeks (Turan, Ölçer, Lazakis, Rigo, & Caprace, 2009), a fuel cell is far more suited for this and will take only a fraction of that time. It is however as of yet uncertain how long this will take, so here an estimate of 50 extra hours in the port is taken. This seems very optimistic, but the fuel cell industry is aiming at making this process as fast as possible.

This would then mean that every 5000 hours a ship needs to stay in the port for an extra 50 hours, this is costly but more important for the analysis here, it is also emitting extra Co2. The total sailing time per ship per trip is currently 2*418.55 = 837.1. This means that a prolonged stop will be needed every sixth trip (5000/873,1 = 5,73). Total trip time is then brought to 904 hours, lowering the total amount of trips per ship per year to 9.68 and bringing the number of ships needed up to 5.37. Emissions per trip will increase with 24,909,184.68 Kg from the extra time in port. This measure is thus costly in terms of extra Co2 emitted, but the benefits are thought to be substantial. In the positive scenario a fuel cell can decrease at-sea Co2 pollution by 14%. Generating a total reduction of 440,651,911.32 Kg Co2, after deducting the extra emissions from the delays in port. So in terms of Co2 reduction this measure is feasible: it nets 12.97% reduction of Co2.

The costs will however be high: both for the extra maintenance/replacement of fuel cells and because of the fact that the power delivered by a fuel cell is still twice as expensive as power delivered by a normal diesel engine (Wang, Chen, Mishler, Cho, & Adroher, 2011). This would increase the yearly total costs by 83% or 200,539,833.67 USD, an extraordinary cost increase.

Effects	Fuel Cells
#Ships extra	0,1
Co2/TonneKm	-14,00%
Costs Increase	83%
Co2 Reduction	12,97%

Figure 12 Fuel Cells, effects

The Arctic route

Another option is the arctic route, or the Northern Sea Route. The NSR is significantly shorter, but can only be used in the tree summer months. Even then a very low speed is usually maintained because of the weather and sometimes even in summer the services of an icebreaker are needed (Francois & Rojas-Romagosa, 2014). The slow speed may seem advantageous in terms of slow steaming, but this must be considered as a total speed, also caused by periods of waiting out storms, or hard winds. Making emission reduction because of the slower speed far from certain, for reasons of simplicity these reductions and their gains in fuel costs have been excluded from the analysis. The NSR will decrease the distance between Shanghai and Rotterdam with 23% (Francois & Rojas-Romagosa, 2014), this means that the journey will be only 14,921.83 kilometres. However due to the conditions, the very low speed of 11 knots, or 20.4 km/h will be the norm (Stephenson, Brigham, & Smith, 2014). The journey would take 731.46 hours which is significantly longer than the 418.55 hours the southern route would take with a normal speed. This means that for the same service level, more ships would be needed. A roundtrip would now 63 days, meaning that one ship will be able to perform 5,78 roundtrips per year and there would be 8,99 ships needed to service Rotterdam once per week. This means that 3.69 new ships will have to be acquired in this scenario. After incorporating the new speed, and the new length of the trip, the model gives an output of 764,850,372.00 Kg of Co2 saved.

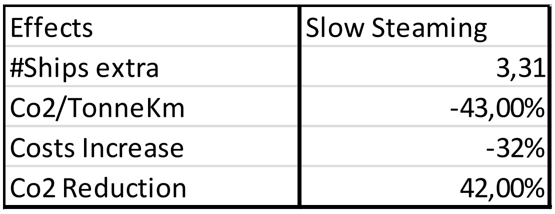
Yearly, this would mean a saving of 22.52%, however we know that this route can only be used in the tree summer months. Being available only one fourth of the year still nets a total of 191,212,593 Kg Co2 saved, a total of 5.63%. Total extra costs will equal 42,669,379.08 USD for the three summer months from the costs of the extra ships needed and the extra fuel costs due to the longer trip, an increase of 18%.

Effects	NSR
#Ships extra	0,92
Co2/TonneKm	0,00%
Costs Increase	18%
Co2 Reduction	5,63%

Figure 13 The Arctic Route, effects

Slow Steaming

The fourth option is slow steaming, as we have noted before there is already an enormous amount of study done to assess the effects of slow steaming on Co2 emissions, per trip but also taking into account service levels on a loop. Nevertheless, the most popular form of slow steaming will be tested here so that we are able to compare it to the other measures. This most popular form of slow steaming is what Maloni, Paul and Gligor named ‘Extra Slow Steaming’ (Maloni, Paul, & Gligor, 2013). It is performed at a speed of 15 knots and was chosen to represent slow steaming based on the mentioned paper by Maloni, Paul and Gligor. In another important paper, Woo and Moon state that the effects of lowering speed keep being favourable in terms of Co2 emissions, until speed is decreased to 14 knots, where they found that emission levels were no longer falling (Woo & Moon, 2014). Having thus chosen a speed of 15 knots, we must now assess how much the Emissions per tonne kilometre would decrease. Maloni and Gligor estimate the decrease in Co2 emissions to be 43% (Maloni, Paul, & Gligor, 2013), Woo and Moon predict even higher numbers (Woo & Moon, 2014). Here however, the relatively moderate 43% reduction in Co2 emitted on sea will be used. The model then estimates a total saving of 1,429,937,652 Kg Co2 per year, a staggering 42% reduction. This comes at a cost however: Trips per vessel fall from 9.87 to 6.06 and thus the number of ships needed rises from 5.27 to 8.58. And while those extra ships do not directly impact the Co2 emissions of the Shanghai-Rotterdam service, they do influence costs, the ships need to be bought or leased, maintained and staffed. Woo and Moon showed however, that even with those costs incorporated, slow steaming is still profitable up to a decrease to 15 knots. The model gives the same output as Woo and Moon found in their research, extra slow steaming is even profitable for the shipping line. It saves 76,552,262.32 USD or 32% of the total costs.



Effects	Slow Steaming
#Ships extra	3,31
Co2/TonneKm	-43,00%
Costs Increase	-32%
Co2 Reduction	42,00%

Figure 14 Slow Steaming, effects

In-Port Emission Reduction

Fifth is the option to reduce in port emissions. One of the two possibilities consists of a speed limit near ports, effectively forcing slow steaming on all ships entering or leaving. This is not considered here, as slow steaming on its own has already been evaluated. The other possibility focusses on ships at berth and is very interesting. Cold ironing can provide the ship with energy that is generated on the shore. Because cold iron energy can be produced in a cleaner way, the reductions will be big. The reduction in terms of emissions are estimated to be between 40 and 70% (Zis, North, Angeloudis, Ochieng, & Bell, 2014), this estimate is strengthened by other research that found an average reduction of 57% in terms of Co2 emitted (Chang & Wang, 2012). We will take the cautious approach and go with a 40% reduction of Co2 emissions while in port. This will bring the Co2 emitted per hour in the port down from 27,435.44 Kg to 16,461.26 Kg Co2. This will decrease the yearly output with 28,532,868 Kg Co2. A reduction of 0.84%. The benefits may seem relatively small, but the costs of a cold ironing network in the port will at least be partly financed by the other actors, such as the port authority and terminal operators. These costs can be shared and are not estimated to be very high. This measure does not increase the other costs, since there is no loss of time, so the costs of ships and fuel do not rise. Overall, a simple way of reducing some of the carbon footprint.

Effects	In-Port Reductions
#Ships extra	0
Co2 In port	-40%
Co2/TonneKm	0,00%
Costs Increase	0%
Co2 Reduction	0,84%

Figure 15 In-Port Reductions, effects

4.2.2 Technological Measures

In the following part, the impact of technological measures on the Shanghai-Rotterdam yearly loop will be assessed. These measures consist of hull design, hull cleaning, propeller cleaning and coating and engine design. Some of these measures are easy to implement and will only take some extra time, while others can only be implemented on new ships, so again the costs will have to be taken into mind.

Hull Design

The first technological measure is hull design. Ongoing innovations and research make it possible to save on fuel and thus emissions when designing a new hull. The obvious downside is that it is only possible to implement these innovations in new ships. Effectively stating that, to get the full benefits of this measure, the whole fleet will have to be replaced. This is not realistic, but it is still interesting to see what the gains would be in terms of Co2 reduction on a single yearly loop. With the estimate of saving set at 9% as done by Christ in his research (Crist, 2009), the total savings would be 299,289,276 Kg Co2 per year, which is 8.81%. The number of trips per vessel and thus the total number of vessels needed remains the same, however they all need to be newly acquired because older ships do not have the advantage of the newly designed hull. The costs of this will be huge: the currently used ships will have to be sold, and the selling price will be low compared to the buying price because they are no longer new.

Effects	Hull Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	Unrealisticly High
Co2 Reduction	8,81%

Figure 16 Hull Design, effects

Hull Cleaning & Coating

The second technological measure is hull cleaning and coating. This focusses on smoothening the surface of the hull, by using the newest coating and by regular cleaning. This would result in less resistance for the ship, decreasing the amount of fuel used and the amount of Co2 emitted. Claims range from an 11% reduction (Schultz, Bendick, Holm, & Hertel, 2011), to a 9% reduction (Crist, 2009). And in this case, we use the lowest estimate again, setting at-sea emission reductions from hull cleaning and coating to 9 percent.

Underwater hull cleaning, making use of robots instead of divers will be able to clean the hull relatively fast, estimates range from 300 up to 2000 square meters per hour (GAC, 2016), and here the relatively low rate of 1000 sqm/h is chosen. An 18000TEU containership will have about 25400 square meters of hull to clean (GAC, 2016), this means that cleaning will take 25.4 hours. However, not all the cleaning can be done while berthing and there will still be significant delays. Cleaning will further be needed many times per year to really impact fuel consumption (Schultz, Bendick, Holm, & Hertel, 2011). We thus estimate that every time in port, an underwater hull cleaning will be performed, which will be done in the berthing time, but will still delay the ship for another 5 hours in port. A coating is a onetime measure, it will need to be done in a dock, but since all containerships have a coating (Moser, et al., 2016), it will not mean extra delays. After taking the extra delays into account, the total number of trips per ship will decline and the number of ships needed will increase.

The extra time in port costs 14,266,428 Kg Co2, the benefits of this measure however overcome this. A total gain of 285,022,847 Kg of Co2 is made, which is a total reduction of 8.39%. Costs will consist of the increase in vessels, accounting for 2,718,533.47 USD or 1%, the cleaning costs will total 76,200 USD per cleaning (3 dollars per square meter cleaned (GAC, 2016)), of which we estimate there to be two per roundtrip. Meaning the total cleaning costs will be 7,924,800. Total costs increase will then be 10,643,333.47 USD, or 4.4%.

Effects	Hull Cleaning & Coating
#Ships extra	0,06
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	4,40%
Co2 Reduction	8,39%

Figure 17 Hull Cleaning & Coating, effects

Propeller Cleaning & Polishing

The third measure is cleaning or polishing the propeller. Estimated benefits range from 3 to 9% in the reduction of Co2 emissions. The costs in terms of Co2 will also be small as the cleaning of the propeller only is a very fast procedure, the screw of a cruise ship, for instance can be cleaned in 40 minutes by one diver (Hydrex, 2012). Since the propeller of an 18000 TEU containership is approximately three times bigger than that of the cruise ship in the case study, we will estimate the needed time at 120 minutes. In the 25 hour berthing time, there will be more than enough opportunities to clean the propeller without causing extra delays. Therefore, this measure will come at little to no costs in terms of Co2 emissions, and the monetary costs will only be that of the service provided, since we do not lose time and need no extra ships. In this case, the lowest estimates of the gain are used again: three percent of the ships on sea emissions will be eliminated by frequent propeller cleaning. This means a total reduction of 99,763,092 Kg of Co2, or 2,94%. A small benefit, but it also comes at small costs: the costs for cleaning will be a total of 624,000 USD or 0.25%.

Effects	Propeller Cleaning
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,00%
Costs Increase	0,25%
Co2 Reduction	2,94%

Figure 18 Propeller Cleaning, effects

Engine Design

The fourth and last technological measure is engine design. By designing a new engine and using the latest technologies, a total of 8,5% fuel reduction can be obtained. Like the case of a new hull design, it only makes sense to use this measure when one chooses to make use of new ships. The costs of those new ships will be huge, but the benefits in terms of Co2 reduction might make this worthwhile. If not from the shipping lines' point of view, then at least from a global point of view. The new ships will pollute 8,5% less while on sea, decreasing the loop's yearly output of Co2 with 282,662,094 Kg Co2, a total reduction of 8,32%. This is of course a huge decrease in Co2, but it remains unrealistic that a shipping line will acquire new vessels purely to decrease the Co2 output.

Effects	Engine Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-8,50%
Costs Increase	Unrealisticly high
Co2 Reduction	8,32%

Figure 19 Engine Design, effects

4.2.3 Route Conclusion

On this route, it is clear that slow steaming is by far the most effective way to reduce Co2 emissions. It is also the least costly way to do this, so overall the clear winner. It is followed by the fuel cell option, but since those costs are huge, it is not an efficient option. Efficient and effective options consist further of Weather routing, In-Port Reductions, Hull cleaning and Coating and Propeller Cleaning. The arctic route is an effective measure, but since it will increase costs by a lot more percentage points than it decreases emissions, it is not efficient. Both design options are deemed unrealistic because they would need a complete new fleet acquired.

Measure	Co2 Savings		Costs Increase		Comments
Operational	KG	%	USD	%	
Weather Routing	103,088,528.40	3.03%	0	0.0%	(costs unsure, but likely to be outweighed by benefits)
Fuel Cells	440,651,911.32	12.97%	200,539,833.67	83.0%	
Arctic Route	191,212,593.00	5.63%	42,669,379.08	17.69%	
Slow Steaming	1,429,937,652.00	42.00%	-76,552,262.32	-32.0%	
In-Port Reduction	28,532,868.00	0.84%	Close to zero		(Costs largely taken by other actors)
Technological					
Hull Design	299,289,276.00	8.81%	Unrealisticly high		(Due to having to buy all the ships brand new)
Hull Cleaning&Coating	285,022,847.00	8.39%	10,643,333.47	4.40%	
Propeller Cleaning	99,763,092.00	2.94%	624,000.00	0.25%	
Engine Design	282,662,094.00	8.32%	Unrealisticly high		(Due to having to buy all the ships brand new)

Figure 20 Results Rotterdam-Shanghai

4.3 Far East- Australasia

This route will be studied using the ports of Shanghai and Melbourne, two ports that are separated by 9,617 Km (searates.com, 2016), using the most direct sailing route. The waiting time in port, the size of the ship and all other variables will remain the same as used in the former route.

Shanghai-Melbourne	Standard
#Ships	2.76
Co2 In port	27435.44/hour
Co2/TonneKm	10Grammes
Costs	USD 126.526.301,63
Co2 Emitted	1.721.609.344,00
Kilometers one-way	9,617
Time in port	25h
DWT ship	165
Standard speed	25 knots

Figure 21 Shanghai-Melbourne, standard

After using the formula's, this leads to a total yearly emittance of 1,721,609,344.00 Kg of Co2 and total costs of 126,526,301.63 Dollars. Because the route is much shorter than the Europe-Far East route, these numbers are very low in comparison.

4.3.1 Operational Measures

The operational measures will again consist of weather routing, fuel type, in-port reduction and slow steaming. The arctic route is not available here, there is no arctic shortcut possible, and is thus excluded as an option. The relevant tables for the measures can be found in the appendix.

Weather routing

Again, weather routing reduces Co2 emitted per tonne kilometre by 3.1 percent and has very low costs due to the decrease in losses and damage by storms. With all other variables remaining unchanged, this leads to a decrease in Co2 output of 51,158,593.20 Kg Co2 per year. This is a decrease of 2.97%, with negligible costs.

Changing of Fuel Type

The change to fuel cells has the same effects as before: an average delay of 8.73 hours per trip in the port, a decrease of 14% in the Co2 emitted per tonne kilometre and a huge increase of costs due to the higher costs of power and the maintenance needed. There is a reduction of 11.97% (206,129,623.32 Kg Co2) of yearly emissions, but the costs are huge with an increase of 109,266,187.88 USD or 86.36%.

Slow steaming

Again, the speed of 15 knots is taken as slow steaming. We see that slow steaming is saving both Co2 and money with a respective 709,619,196.00 Kg a year and 41,986,032.50 USD.

In-Port emission reduction

Cold ironing still reduces in-port emissions with 40% and is almost free because of the low costs, which are shared between many different actors. On this route, it nets a decrease in Co2 emitted of 1.66% or 28,532,857.60 Kg Co2 per year.

4.3.2 Technological Measures

All the technological measures, hull design, hull cleaning and coating, propeller cleaning and engine design, will be tested on the current route. The relevant tables for the measures can be found in the appendix.

Hull Design

As before, hull design decreases Co2 output at sea by 9%, it can however only be implemented when buying a totally new fleet. We see that the total gain would be 8.63% or 148,524,948 Kg Co2 per year, but the scenario remains unrealistic.

Hull Cleaning and Coating

Using the same cleaning rate, meaning we lose 5 hours during every port call and also taking the same costs, 3 dollars per square meter, the following results will be obtained by the cleaning and coating of the hull. Total costs consist of the costs from the extra ships needed and the costs of cleaning, and mount up to a total of 10,619,656.64 USD. And while we still see a significant decrease in Co2 emitted, the costs increase by a higher percentage. This is unlike the latter route, where costs increased by only 4.4%.

Propeller Cleaning

When keeping the costs and time of cleaning constant, and also keeping the estimated reduction of Co2 per tonne kilometre at 3 percent, the following results are presented by using the formula’s. We see a gain of 2.88% in Co2 emitted, the costs have remained the same, 3 dollars per square meter of 624000 USD per year, but they now make a bigger, although still minor impact, at 0.49% cost increase. This is still a very cheap way to reduce a little bit of Co2.

Engine Design

Again, we assume the same costs and benefits as in the previous route, applying the formula gives us the following results. With a reduction 140,273562 Kg of Co2 per year, this measure scores relatively high. The costs of actually replacing the fleet will still be too high to be considered however.

4.3.3 Route Conclusion

This route has weather routing, slow steaming, in-port reduction and propeller cleaning as effective and efficient measures. Compared with the former route, hull cleaning and coating is no longer efficient. Other changes are small however.

Measure	Co2 Savings		Costs Increase		Comments
Operational	KG	%	USD	%	
Weather Routing	51,158,593.20	2.97%	0	0.0%	(costs unsure, but likely to be outweighed by benefits)
Fuel Cells	206,129,623.32	11.97%	109,266,187.88	86.63%	
Arctic Route	Unavailable	U	Unavailable	U	(No arctic shortcut possible)
Slow Steaming	709,619,196.00	41.22%	-41,986,032.50	-33.17%	
In-Port Reduction	28,532,857.60	1.66%	Close to zero		(Costs largely taken by other actors)
Technological					
Hull Design	148,524,948.00	8.63%	Unrealisticly high		(Due to having to buy all the ships brand new)
Hull Cleaning&Coating	134,249,544.00	7.80%	10,619,656.64	8.40	
Propeller Cleaning	49,569,062.40	2.88%	624,000.00	0.49%	
Engine Design	140,273,562.00	8.15%	Unrealisticly high		(Due to having to buy all the ships brand new)

Figure 22 Overview Shanghai-Melbourne

4.4 Intra-Asia

Another interesting trade route is entirely located in Asia. The trip from the port of Singapore to Shanghai mounts up to a total of 4003.80 Kilometres (searates.com, 2016). Compared to the previously analysed routes this is only a short distance. Singapore is a transhipment hub and thus it is very likely that a shipping line would also include it in its network. Again, the standard speed, waiting time in port, Co2 emission per tonne kilometre and the deadweight tonnage are the same.

Shanghai-Singapore	Standard
#Ships	1.32
Co2 In port	27435.44/hour
Co2/TonneKm	10Grammes
Costs	USD 60.609.791,69
Co2 Emitted	758.384.224,00
Kilometers one-way	4.003,80
Time in port	25h
DWT ship	165.000,00
Standard speed	25 knots

Figure 23 Shanghai-Singapore, standard

On this route that means a total yearly emittance of 758,384,224.00 Kg Co2. It is interesting to note that the trip is so short that the number of ships needed has fallen steeply.

4.4.1 Operational Measures

All the operational measures will be tested on this route, however the arctic route must be excluded. Again, there is no artic shortcut available. The relevant tables for the measures can be found in the appendix.

Weather routing

Weather routings decrease in Co2 per tonne kilometre of 3.1 percent nets us a 21,298,614.48 Kg Co2 decrease in yearly emissions, or 2.81% of the total. The costs will be so small that they are outweighed by benefits like the decrease of damage and loss from storms.

Fuel type

In this scenario, the change to fuel cells gives the following results. Total Co2 is reduced with 71,278,106.52Kg per year and costs have increased with a staggering 56,783,374.06 USD. The latter is mainly attributed to the doubling of the fuel price while using fuel cells.

Slow steaming

On this route, the lower speed of 15 knots nets the shipping line the following benefits. Slow steaming decreases yearly Co2 output with 295,432,394.40 Kg, or 38.96% and the costs are lowered with 36% or 32,098,923.21 USD.

In-Port Reduction

Using a cold ironing network will also benefit the shipping line in terms of Co2 reduction. Co2 emissions are reduced with 3.76% or 28,532,857.60Kg per year. Since the costs are still shared with many other actors, they are set as zero again.

4.4.2 Technological Measures

The results of the technological measures, hull design, hull cleaning & coating, propeller cleaning & coating and engine design, will be discussed below. The relevant tables for the measures can be found in the appendix.

Hull Design

A newly designed hull would decrease Co2 by 8.15% or 61,834,687.20Kg Co2 per year. Costs however would be outrageous because of the new to buy fleet.

Hull Cleaning and Coating

Hull cleaning and coating is saving the shipping line a lot of Co2 emissions, 47,568,258.40 Kg per year, but is increasing costs with a high percentage. A total of 10,643,333.47 USD is added per year, mainly because of the high cleaning costs. Costs for extra ships will be relatively low.

Propeller Cleaning

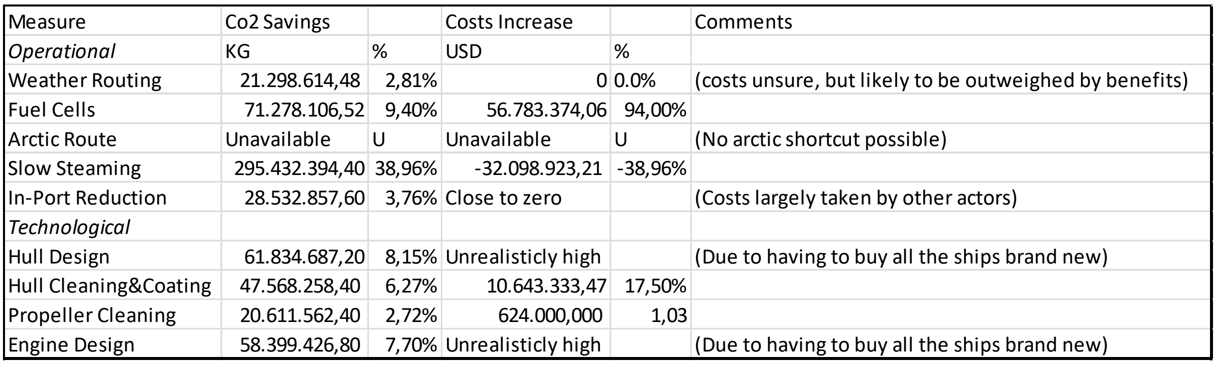
Propeller cleaning decreases the yearly emissions with only 2.72%, 20,611,562.40Kg Co2. The costs however are only those of the cleaning operation, at 624,000 USD only 1.03% on this route.

Engine Design

Designing and using a new engine would result in a decrease of 58,399,426.80Kg Co2 or 7.7% per year on this route. The nature of this measure however means that the whole fleet would have to be replaced by new ships. An unrealistically costly option.

4.4.3 Route Conclusion

This route has weather routing, slow steaming, in-port reduction and propeller cleaning as effective and efficient measures. Changes with the previous routes are small, although we see that Hull Cleaning and Coating is in this case only effective.



Measure	Co2 Savings		Costs Increase		Comments
Operational	KG	%	USD	%	
Weather Routing	21.298.614,48	2,81%	0	0.0%	(costs unsure, but likely to be outweighed by benefits)
Fuel Cells	71.278.106,52	9,40%	56.783.374,06	94,00%	
Arctic Route	Unavailable	U	Unavailable	U	(No arctic shortcut possible)
Slow Steaming	295.432.394,40	38,96%	-32.098.923,21	-38,96%	
In-Port Reduction	28.532.857,60	3,76%	Close to zero		(Costs largely taken by other actors)
Technological					
Hull Design	61.834.687,20	8,15%	Unrealisticly high		(Due to having to buy all the ships brand new)
Hull Cleaning&Coating	47.568.258,40	6,27%	10.643.333,47	17,50%	
Propeller Cleaning	20.611.562,40	2,72%	624.000,000	1,03	
Engine Design	58.399.426,80	7,70%	Unrealisticly high		(Due to having to buy all the ships brand new)

Figure 24 Shanghai-Singapore Overview

4.5 Asian Short Sea Shipping

After the evaluation of three routes with the largest class of ships, it will be interesting to add a small differentiation in the next route. The selected ports are Shanghai and Busan (South-Korea), both are among the busiest container ports in the world, visited by the biggest ships. The current route of 853 kilometres however is assumed to be traversed with a much smaller vessel; a so called feeder. Here, a feeder of approximately 3000 TEU is selected, a vessel that is comparable in size with an older containership class, the Panamax vessels (vesseltracking.net, 2016). A vessel of this class would have a DWT of approximately 65,000 Kg and has only 60% of the underwater surface of the ship used on the other routes (maritime-connector.com, 2015). Due to the smaller amount of containers to be on or off-loaded, we assume the time in port to fall drastically to 20 hours. The total handling time will probably decrease even more, but in-port time also consists of waiting for other ships to be handled. As can be seen below, this route is the first where one vessel would be more than enough to perform the weekly service. Co2 emissions in port have been decreased according to the decrease in vessel size. Total yearly costs are also set to decrease to 60% of the costs of the bigger vessel.

Shanghai-Busan	Standard
#Ships	0,46
Co2 In port	16461,26Kg/hour
Co2/TonneKm	10Grammes
Costs	USD 19.187.994,91
Co2 Emitted	91.902.220,80
Kilometers one-way	853,00
Time in port	20h
DWT ship	65.000,00
Standard speed	25 knots

Figure 25 Shanghai-Busan, standard

4.5.1 Operational Measures

Weather routing, the changing of fuel type, slow steaming and in-port reduction are all tested on this route. The arctic route is not analysed for obvious reasons: it is unavailable as a shortcut here. The relevant tables for the measures can be found in the appendix.

Weather Routing

Weather routing reduces Co2 emissions with a total of 1,787,546.80 Kg per year and is still considered to gain back what it costs because of less losses and dangers. The measure only gains 1.9% but is also very cheap, again a suitable option.

Changing of Fuel Type

Effects	Fuel Cells
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-14,00%
Costs Increase	129,00%
Co2 Reduction	-7,48

Figure 26 Fuel Cells, effects

The fuel cells, with all the extra time in port they generate, are not an effective measure for Co2 reduction on this route. For the first time, one of the measures is not only inefficient, but also ineffective. This means that it should be avoided on this route.

Slow Steaming

Slow steaming is again reducing Co2 emissions, by 24,759,004Kg or 26.8% per year, and costs by 9,884,338.15 USD per year. Co2 reduction has fallen in percentage points compared to the other routes though.

In-Port Reduction

Using a cold ironing network decreases the yearly emissions with 14.90% or 13,695,768.32Kg of Co2. Again, the costs are estimated as zero, making In-Port Reduction by cold ironing a very good option on this route.

4.5.2 Technological Measures

All technological measures will be tested on this route, starting with hull design and ending with engine design. The relevant tables for the measures can be found in the appendix.

Hull Design

Although the costs will be terrible, hull design decreases Co2 emissions by 5,189,652 Kg per year. A total Co2 reduction of 5.65 per cent, making this measure effective but not efficient.

Hull Cleaning and Coating

Since the current ship has only 60% of the surface of the ship used in the previous scenario's, the price of cleaning will be lower. The cleanable surface will be 15,240 Square meter, which will take 15.24 hours at the lowest cleaning rate. This means no more extra delays in port, it is deemed reasonable that this cleaning will be done within the current berthing time of 20 hours. Costs will equal 4,754,880 USD at 3 USD per square meter and two cleanings per round trip. Total Co2 reduction equals 5,189,652 Kg per year, or 5.65 per cent, costs however increase by a staggering 24.70%.

Propeller Cleaning

The standard costs for propeller cleaning for the bigger ship, 624,000 USD per year are also assumed to decrease according to the decrease in size when comparing the big vessel to the current one. They are then estimated at 374,400 USD per year. Cleaning will still be done within current berthing times. The savings of Co2 emitted mount up to 1,729,884 Kg per year, or 1.88%. This makes propeller cleaning effective but not efficient, because of costs that increase with 1.95%.

Engine Design

Replacing all engines by newly designed ones will decrease emissions by 4,901,338 Kg CO2 per year, 5.33%, but the costs are still deemed too high for a shipping line to consider this option.

4.5.3 Route Conclusion

Measure	Co2 Savings		Costs Increase		Comments
Operational	KG	%	USD	%	
Weather Routing	1.787.546,80	1,95%	0	0.0%	(costs unsure, but likely to be outweighed by benefits)
Fuel Cells	-6.872.715,18	-7,48%	-24.772.297,34	129,00%	
Arctic Route	Unavailable	U	Unavailable	U	(No arctic shortcut possible)
Slow Steaming	24.795.004,00	26,98%	-9.884.338,15	-52,00%	
In-Port Reduction	13.695.768,32	14,90%	Close to zero		(Costs largely taken by other actors)
Technological					
Hull Design	5.189.652,00	5,65%	Unrealisticly high		(Due to having to buy all the ships brand new)
Hull Cleaning&Coating	5.189.652,00	5,65%	4.754.880,00	24,70%	
Propeller Cleaning	1.729.884,00	1,88%	374.400,00	1,95%	
Engine Design	4.901.338,00	5,33%	Unrealisticly high		(Due to having to buy all the ships brand new)

Figure 27 Shanghai-Busan, overview

The most interesting change is that this is the first route where a measure is ineffective. The fuel cells option is not viable for a route of this size since it increases waiting time and thus pollutions in port more than it decreases pollution on sea.

4.6 European Short Sea Shipping

The last route chosen is also the shortest one. Here, a feeder vessel like the one used in the previous route is chosen to connect the port of Rotterdam with the port of Felixstowe. A journey of only 267.59 kilometres (searates.com, 2016).

Rotterdam-Felixstowe	Standard
#Ships	0,31
Co2 In port	16461,26Kg/hour
Co2/TonneKm	10Grammes
Costs	USD 12.873.861,07
Co2 Emitted	52.328.504,80
Kilometers one-way	267,59
Time in port	20h
DWT ship	65.000,00
Standard speed	25 knots

Figure 28 Rotterdam-Felixstowe, standard

4.6.1 Operational Measures

Weather Routing, change of fuel type, slow steaming and in-port emission reductions have been assessed for the European short sea shipping route. The arctic route was not available here. The relevant tables for the measures can be found in the appendix.

Weather Routing

Weather routing has a negative impact on Co2 emissions of 1.07%, or 560,761.60 Kg per year. As usual the costs are estimated to be zero, resulting in a useful measure.

Changing Fuel type

Fuel Cells are again not effective, they would increase Co2 output with 12,413,035.42 Kg or 23.72% per year and costs with 19,298,999.06 USD. This makes the measure ineffective and inefficient, the same result as in the previous short shipping route.

Slow Steaming

Slow steaming reduces yearly Co2 emissions with 7,778,306.12 Kg and also decreases costs by 7,436,776.58 USD. A Co2 reduction of 14.86% and a cost reduction of 57.77%, effective and efficient once more.

In-port emission reduction

The cold ironing network can reduce Co2 with 26.17% or 13,695,768.32Kg of Co2, a huge reduction at a low price. After all, cold ironing facilities will also be a shared costs between many other actors in this scenario.

4.6.2 Technological Measures

All technological measures were available as options on this route and their results can be found below. The relevant tables for the measures can be found in the appendix.

Hull Design

Hull design is effective in reducing Co2 emissions, with 1,628,017.56 Kg or 3.11% per year, but costs will be staggering. This measure is effective but inefficient.

Hull Cleaning and Coating

Here, hull cleaning and coating decreases Co2 emissions with 1,628,017.56 Kg, or 3.11% per year. Costs increase wit 4,754,880 USD, or 36.39%. An effective but inefficient measure on this route.

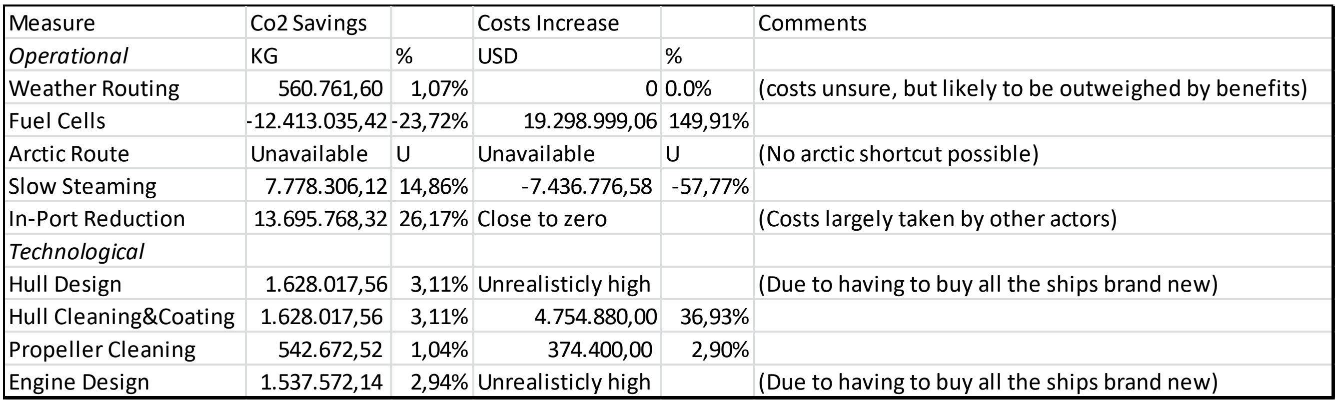
Propeller Cleaning

Propeller cleaning decreases Co2 output with 542,672.52 Kg or 1.04% per year, but costs increase with the cleaning rate of 374,400 USD per year, 2.90%. Making this measure effective but inefficient.

Engine Design

A fleet outfitted with newly designed engines would reduce Co2 emissions with 1,537,572.14 Kg per year in this case. This would mean a 2.94% reduction in Co2 emissions, the high costs however make sure Engine Design is not efficient.

4.6.3 Route Conclusion



Measure	Co2 Savings		Costs Increase		Comments
Operational	KG	%	USD	%	
Weather Routing	560.761,60	1,07%	0	0.0%	(costs unsure, but likely to be outweighed by benefits)
Fuel Cells	-12.413.035,42	-23,72%	19.298.999,06	149,91%	
Arctic Route	Unavailable	U	Unavailable	U	(No arctic shortcut possible)
Slow Steaming	7.778.306,12	14,86%	-7.436.776,58	-57,77%	
In-Port Reduction	13.695.768,32	26,17%	Close to zero		(Costs largely taken by other actors)
Technological					
Hull Design	1.628.017,56	3,11%	Unrealisticly high		(Due to having to buy all the ships brand new)
Hull Cleaning&Coating	1.628.017,56	3,11%	4.754.880,00	36,93%	
Propeller Cleaning	542.672,52	1,04%	374.400,00	2,90%	
Engine Design	1.537.572,14	2,94%	Unrealisticly high		(Due to having to buy all the ships brand new)

Figure 29 Rotterdam-Felixstowe, overview

This route has only weather routing, slow steaming and in-port reductions as effective and efficient measures. It shows broadly the same signs as the Asian Short Sea shipping route when we compare them to the longer routes.

5 Results

The previous analysis with its five different case studies has resulted in a lot of data for the different measures. Here, the results of the total analysis will be presented, rather than the partial results that have already been presented above. This will allow for an overall comparison.

5.1 Effectiveness

First, it is important to note that all measures are effective in reducing Co2 emissions in all case studies, except for the Fuel Cell measure. The exact results per measure for each route can be found in figure 73 from the appendix. Once the sailing distance drops significantly, this measure is no longer effective, compared over all routes it has the smallest rate of effectiveness. Slow steaming is the clear winner, being the best individual measure in all but one case study and leaving other measures far behind in average effectiveness. In-Port reduction also scores significantly higher than the others, gaining from its large impact on short routes. Fuel Cells score by far the lowest in terms of effectiveness.

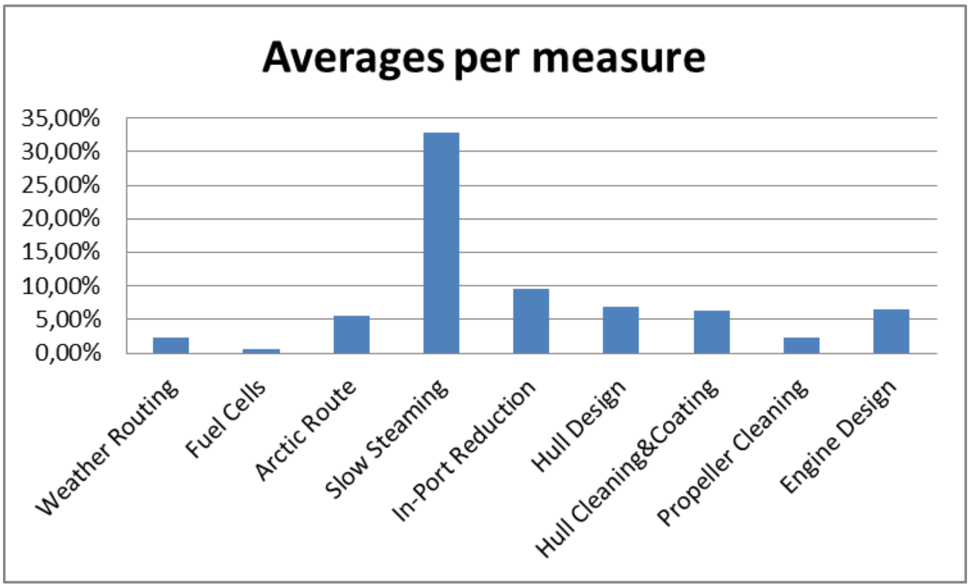


Figure 30 Average overall effectiveness per measure

Figure 30 is made by taking the effectiveness in percentage points per measure for all the routes and computing its average.

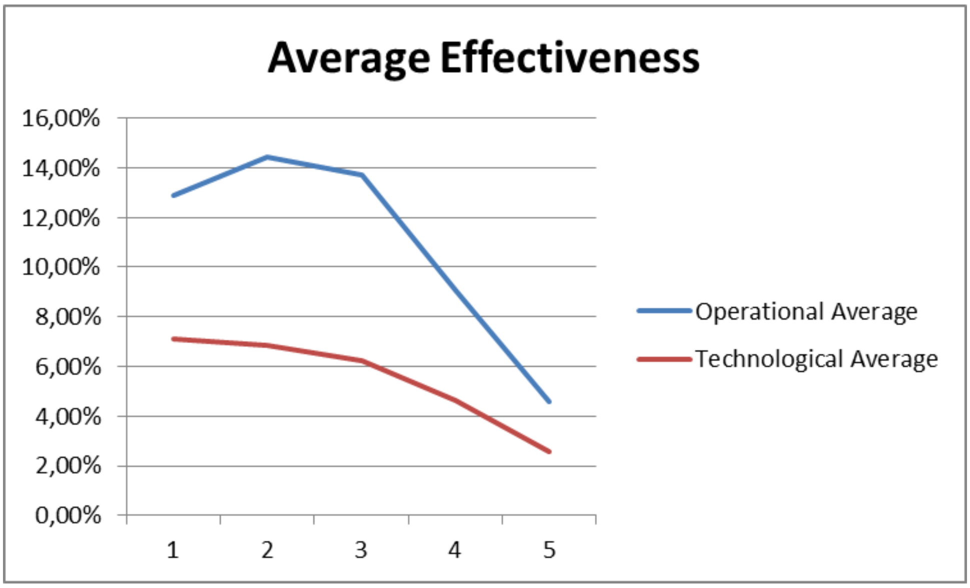


Figure 31 Average Effectiveness per types of measures in percentages per case study.

The graph above shows the average effectiveness. We see that both types of measures decrease in effectiveness as the sailing distances decrease with every different case study. In the beginning the difference is big, but in the two shortest scenario's the results are becoming more and more alike.

5.2 Efficiency

Now it is clear which measures are the most effective, but the aspect of costs also plays a big role in the decision making of ship owners. It is therefore that costs have been a part of the analysis. The goal of this inclusion is to determine whether or not a measure is efficient. Efficiency means that a measure is effective without costing too much money. In this research a measure is seen as efficient if it reduces Co2 emissions by more percentage points than it increases the costs.

Efficient or Not	EU-Far East	Far East- Australasia	Intra Asia	Short Sea	Short Sea Europe	**Average**
Measure						
Operational						
Weather Routing	1	1	1	1	1	**1**
Fuel Cells	0	0	0	0	0	**0**
Arctic Route	0	U	U	U	U	**0**
Slow Steaming	1	1	1	1	1	**1**
In-Port Reduction	1	1	1	1	1	**1**
Operational Average	**0,6**	**0,75**	**0,75**	**0,75**	**0,75**	**0.6**
Technological						
Hull Design	0	0	0	0	0	**0**
Hull Cleaning&Coating	1	0	0	0	0	**0**
Propeller Cleaning	1	1	1	0	0	**1**
Engine Design	0	0	0	0	0	**0**
Technological Average	**0,5**	**0,25**	**0,25**	**0**	**0**	**0,25**

Figure 32 Efficient (1) or not (0)

Figure 33 is obtained by comparing figures 73 and 74 (Appendix), if the percentage of Co2 reduction is higher than that of cost increase, the measure is efficient. Averages are the efficient measures/routes divided by the total measures/routes. The outcome is clear, almost all operational measures are efficient, apart from Fuel Cells and the Arctic route. The technological measures see a rapid fall in total efficiency when the sailing distances decline, but operational measures have a rather stable total efficiency.

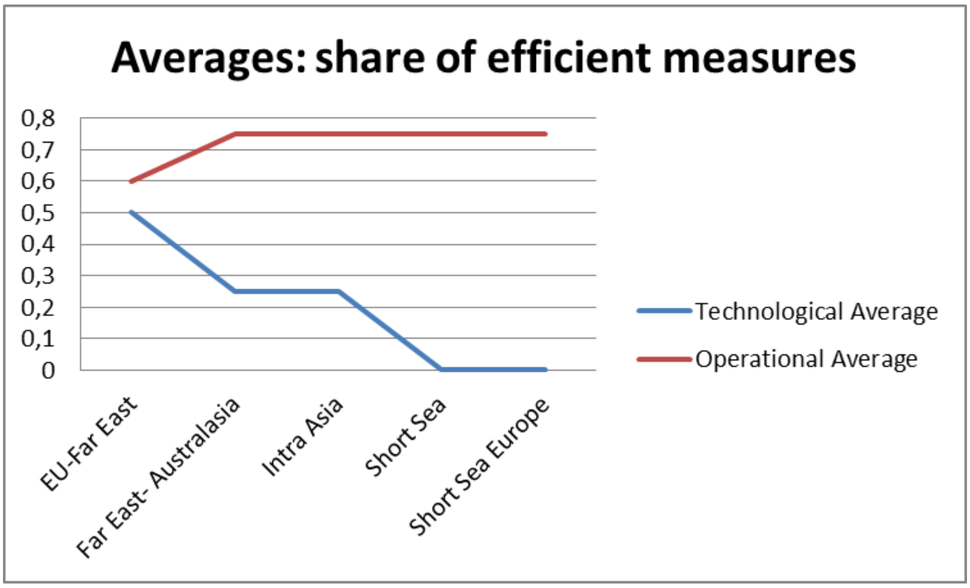


Figure 33 Technological and Operational Measures: share of efficient measures

The latter is to be explained in part by slow steaming, it is not only efficient but beneficial in both Co2 reduction and the cost side of the equation. Other benefits for operational measures are the costs for weather routing and in-port reduction, they have been estimated as zero. Technological measures have amongst them two measures that can never be efficient, hull design and engine design require a new fleet to be built at tremendous costs. Therefore, their cost increase has been estimated as 100%.

When we look into the efficiency of the separate measures more in depth, we get the following numbers.

Rate of Efficiency Measure	EU-Far East	Far East- Australasia	Intra Asia	Short Sea	Short Sea Europe	**Average**
Weather Routing	3,03%	2,97%	2,81%	1,95%	1,07%	**2,37%**
Fuel Cells	-70,03%	-74,66%	-84,60%	-136,48%	-173,63%	**-107,88%**
Arctic Route	-12,06%	U	U	U	U	**-12,06%**
Slow Steaming	74,00%	74,39%	77,92%	78,98%	72,63%	**75,58%**
In-Port Reduction	0,84%	1,66%	3,76%	14,90%	26,17%	**9,47%**
Hull Design	-91,19%	-91,37%	-91,85%	-94,35%	-96,89%	**-93,13%**
Hull Cleaning&Coating	3,99%	-0,60%	-11,23%	-19,05%	-33,82%	**-12,14%**
Propeller Cleaning	2,69%	2,39%	1,69%	-0,07%	-1,86%	**0,97%**
Engine Design	-91,68%	-91,85%	-92,30%	-94,67%	-97,06%	**-93,51%**

Figure 34 Rate of efficiency: Co2 reduction minus cost increase in percentage points

There are a total of four measures that are efficient overall, weather routing, slow steaming, in-port reduction and propeller cleaning. Slow steaming is much more beneficial than the others, as can be seen in figure 35.

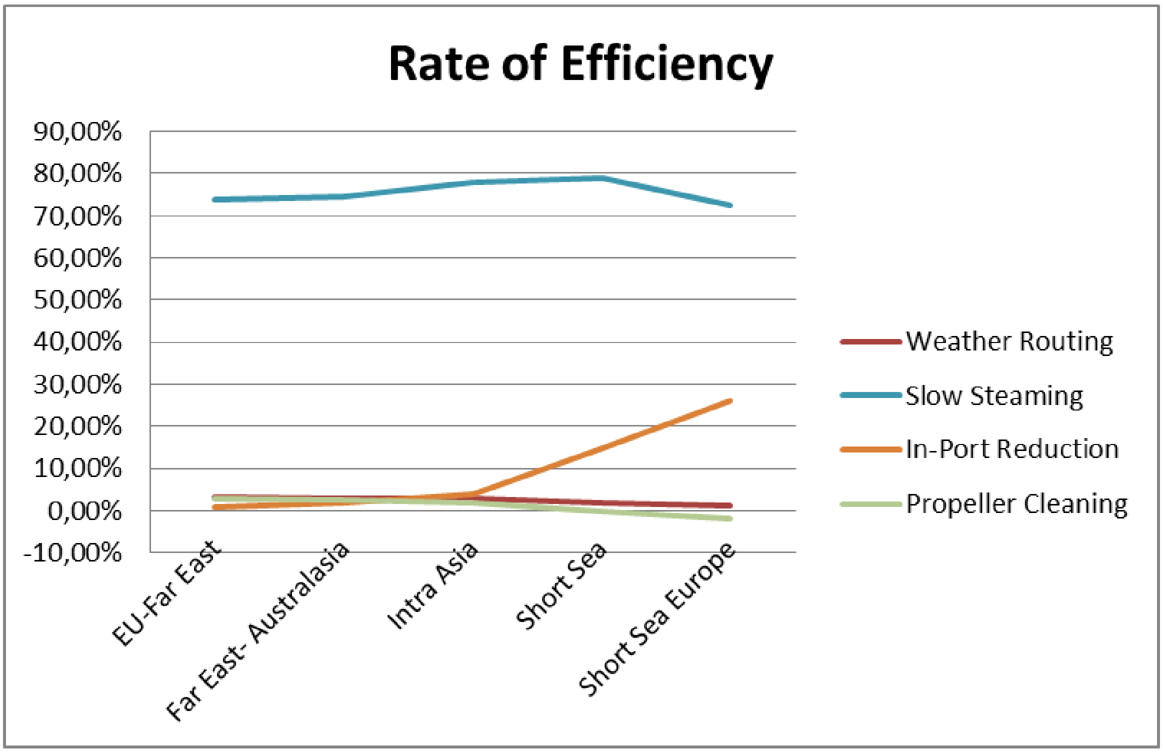


Figure 35 Rate of Efficiency for the four efficient measures

This figure is a very clear indication that slow steaming is the most beneficial for both environment and shipping line. Weather routing and propeller cleaning show roughly the same movements, decreasing with voyage length, while in-port reduction shows the exact opposite. This means that on very short routes, it is important to visit a port with good facilities- including in-port reduction’s cold ironing- as in port emissions and costs make up a larger share in the total.

5.3 Co2 reduction and cost increase per measure

Next, the measures will be reviewed individually, comparing Co2 reduction and costs over the different routes. Since the Arctic Sea Route has only been tested on one route, it is excluded here.

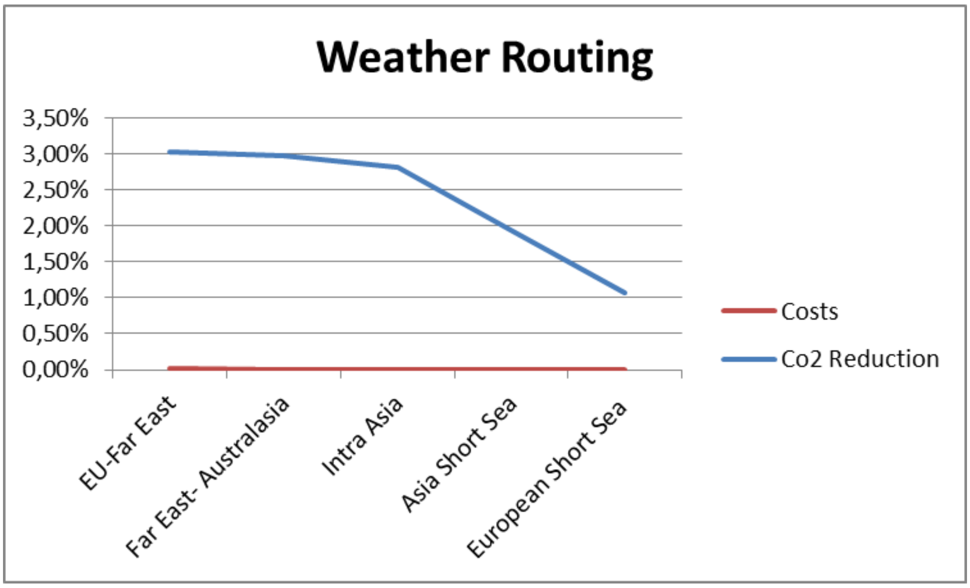


Figure 36 Weather Routing: costs and Co2 reductions in percentages

Weather routing is a measure that reduces Co2 emissions while at sea, so it is logical that the effectiveness decreases with the length of the voyage. Costs are assumed to be overcome by benefits like safety and a decrease of containers lost in storms. This measure should be implemented, longer routes having priority over shorter ones.

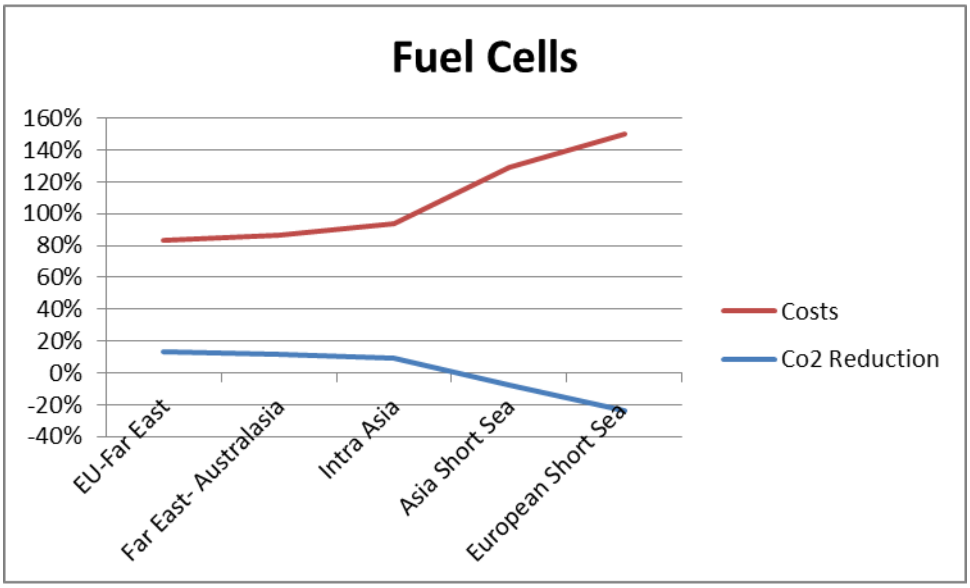


Figure 37 Fuel Cells: Co2 reductions and costs in percentages

Fuel Cells are also reducing Co2 output at sea, but they delay the ship in port, meaning the in-port emissions increase. As the distances to be sailed decrease, the extra in-port emissions become larger than the gains made at sea. The costs percentage increases as the travel distance decreases, the standard costs of the route become smaller and smaller so the relative impact of the costs of fuel cells increases. This measures is, with the current high cost level not yet ready for implementation.

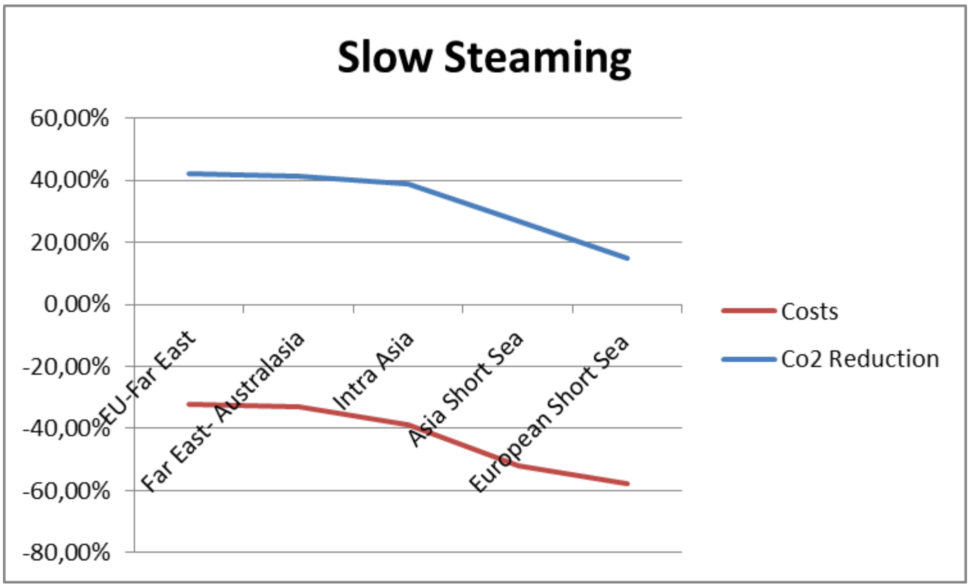


Figure 38 Slow Steaming: Co2 reductions and costs in percentages

The Co2 reduction effectiveness of slow steaming decreases with the voyage length, but the cost impact shows the exact opposite. With decreasing length of voyage, slow steaming becomes more effective at reducing costs. Slow steaming should be implemented, but long routes have priority over shorter ones. Also, one has to look at the risk of losing freight to truck, train or plane on the short routes.

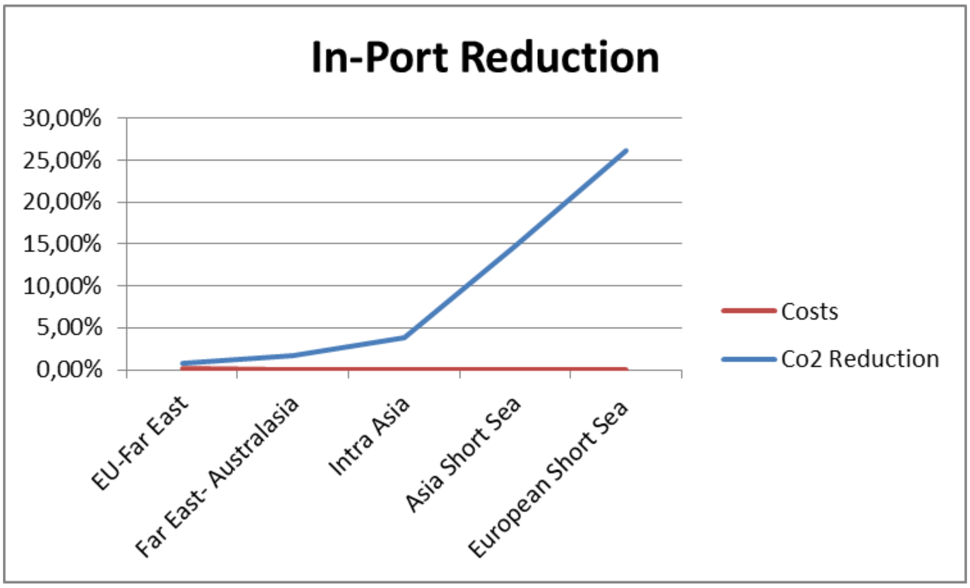


Figure 39 In-Port Reduction: Co2 reduction and costs in percentages

In-Port reduction has stable costs of zero, and the effectiveness in reducing emissions increases as voyage length decreases. This is logical because with decreasing voyage length, in-port emissions become a larger part of total emissions per trip. In-Port Reduction, or cold ironing in this case, can and should be implemented on all routes. On short routes the impact will be higher, so these should be prioritised.

Hull design’s costs are set at 100% because it is not realistic to replace the entire fleet for small gains in Co2 reduction. Should one want to replace a fleet, it is best to replace that fleet that is used for the longest voyages. As with other measures that reduce emissions at sea, Hull design’s impact decreases with the decrease of voyage length. Unless when new ships need to be bought to increase or replace capacity, hull design is too expensive to implement. As can be seen in figure 75 of the appendix, if one chooses to replace the fleet, it should be done first on the longest routes.

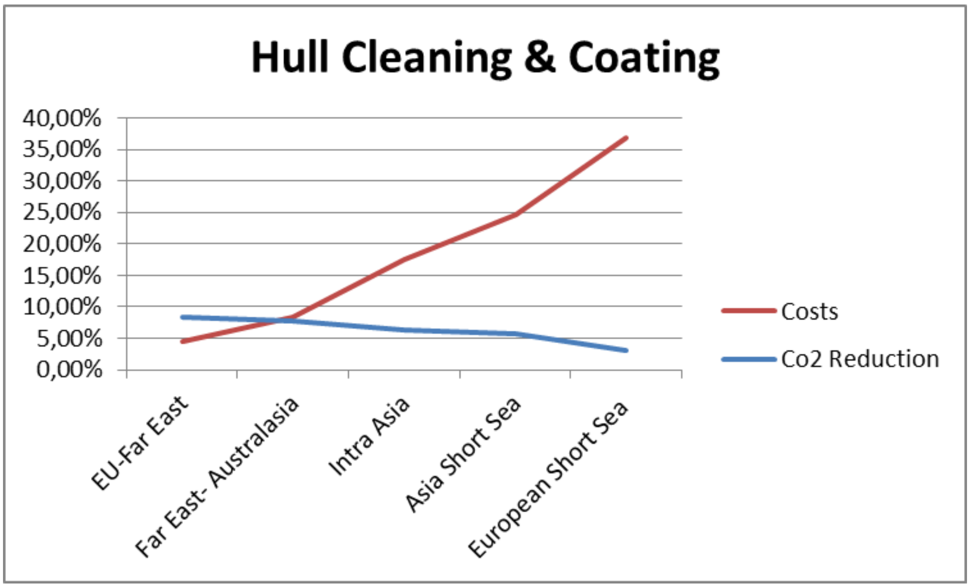


Figure 40 Hull Cleaning & Coating: Co2 reductions and costs in percentages

Hull cleaning and coating is an interesting case. It has slowly decreasing effectiveness in Co2 reduction as voyage distance falls and its total costs are largely fixed. The latter means that the relative costs increase with the fall in voyage distances. A measure like this one is to be used only on very long routes. This measure should be implemented on the longest routes in the network, but for smaller routes it is still too expensive.

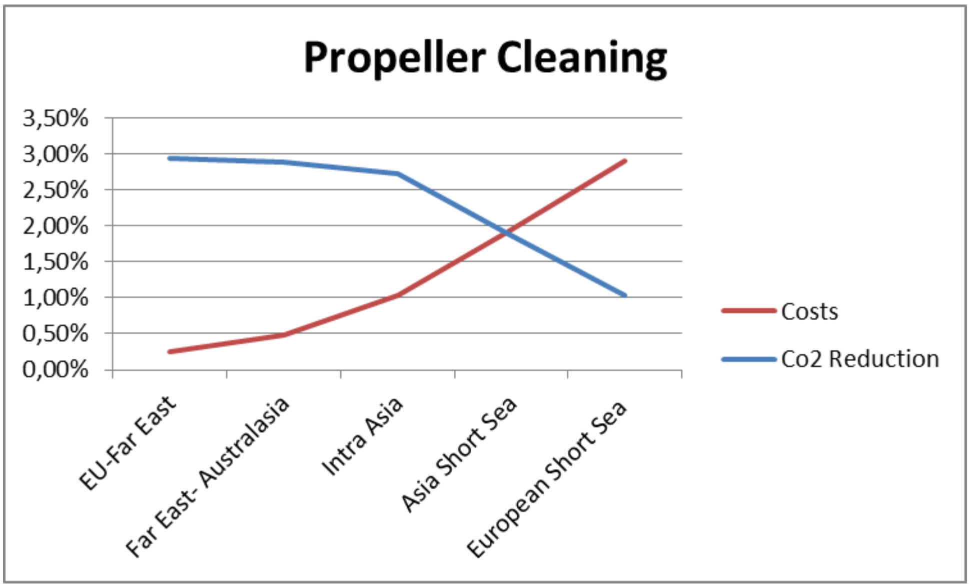


Figure 41 Propeller Cleaning: Co2 reductions and costs in percentages

Propeller cleaning shows the same pattern as Hull Cleaning and Coating, but here the measure is effective in the three longest routes. This measure is suitable for implementation in all but the shortest routes.

Engine design shows the same pattern as hull design (see figure 76 of the appendix). Tremendous costs and small Co2 reductions that decrease with voyage length. Much the same as with hull design, engine design is not effective enough to be the only factor in the replacement decision.

6 Conclusion

Are operational measures to reduce the carbon footprint of global shipping outperformed by technological ones? This research question was the motivation behind the analysis presented above. It can be answered quite simply: no. The most effective technological measures are plagued by huge implementation costs and those technological measures that are efficient are less effective than most operational measures. This does not mean that technological innovations in shipping are useless. When shipping lines do decide to buy new vessels, the impact of a new hull and/or engine design will be significant, and on longer routes the cleaning and coating of hull and propeller will certainly pay off.

Slow steaming is by far the most effective measure presented here. Not only in reducing emissions, but also in reducing costs. None of the other measures could live up to this. It is important to note however that the effectiveness in terms of emission reduction decreases with the decrease of voyage length. While the effectiveness of reducing costs shows the opposite pattern. Since we know that slow steaming might push some freight away to more polluting forms of transport, this might be a danger to the global Co2 reduction. After all, on short trips, trains, trucks or planes are more likely to replace shipping.

On the shorter routes, in-port reduction can keep up with slow steaming in terms of emission reduction. The decrease in voyage length makes the emissions in port have a larger share in total trip emissions. Allowing in-port reduction to keep up with and even surpass slow steaming on the European Short Sea route. This means that the infrastructure of a port, most importantly the possibility of cold ironing, becomes more important when the distance to be sailed decreases. Certainly an indication that the offering of services like cold ironing by smaller ports should be stimulated. Most other measures do only impact the emissions produced at sea and they should always first be implemented on those routes that have the longest distances to sail.

So when one is facing a long distance to sail, both operational and technological measures should be considered. Both offer suitable options to decrease emissions. However, on a short distance, technological measures are barely effective. In those cases, operational measures should be the number one focus. Most measures decrease pollution while the ship is sailing, while some decrease it in-port (cold ironing in this thesis). Generally speaking, in-port measures are favourable on routes where a large percentage of time is spent in a port. This means very short routes, or long routes with many stops. The general loading and unloading time of a ship and the ports should also be taken into consideration. At-sea measures should be used in opposite scenario's: they need long sailing times to be effective.

While technological measures are currently lagging behind operational ones, they should not be disregarded. Further innovation in underwater robotics can reduce the costs of underwater cleaning, as needed for hull cleaning and propeller cleaning. The ongoing innovations regarding the hull and engine of the ship might not make it worthwhile to replace an entire fleet, but it will make new ships more energy efficient. Hopefully leading to a greener worldwide container fleet.

The fact that this thesis tests the usefulness of several measures and compares them to each other is making it somewhat unique. There is a lot of literature that theoretically compares different measures, and there is much written in terms of case studies for individual measures. The combination of those two factors makes this research a useful contribution to the literature. Furthermore, this research can be useful for several specific parties. First of all, shipping lines are presented with options to decrease Co2 emissions. They can also find out what this will cost them and what measures they should implement per type of route. Secondly, the great effectiveness of engine- and hull design are a confirmation that new ships are better for the environment, useful information for shipbuilders. Thirdly, the innovators that are improving fuel cells are presented with evidence for its effectiveness, hopefully a powerful lobby material to ensure investments for further research and improvements. Fourth and last are governments or port authorities. These institutions are focussing heavily on climate change and can conclude from this research that in-port innovations like a cold ironing network are not only to be implemented in the biggest ports. These measures make a severe impact on the carbon footprint of short sea shipping and should thus also be implemented in smaller ports. Governments are also presented an overview of the best measures to decrease the carbon footprint of shipping overall. So should the time arise to impose measures on the sector by force, the outcome of this research can be helpful to decide what measures to choose.

7 Shortcomings

This research is certainly not without flaw. For reasons of simplicity, there have been many assumptions made and there have also been some exclusions.

First, the assumptions made will be stated. The estimation of emissions in port was made by assuming the percentage of total emissions that are produced in ports is equal for every vessel. There were not enough sources to safely state a number per class of ship, so this generalisation had to be used. The costs of certain measures were not readily available or did vary too much between different sources. Measures like hull design, engine design, weather routing and in-port reduction suffered from this. In the first two cases, it was only sure that the costs would be extremely high, the latter two could only be said to be very small. Further, the estimation of efficiency per measure was based on the assumption that a decrease in emissions of one percentage point was of the same value as a decrease in costs of one percentage point. This simplification overlooks the value that is attributed to Co2 by shipping lines and society and is probably not equal to the value attributed to costs. Another shortcoming is the fact that all the different case studies or routes are direct routes, with stops only at the beginning and ending points. This is far from common on all but the shortest routes in the shipping industry. This assumption was made for reasons of simplicity and to limit the influence of the many differences between ports in geographical regions.

Secondly, some measures have been excluded. The possibility of a change in fuel type is only represented by the innovative fuel cell option. And the in-port reduction option only brought cold ironing to the research. To limit the number of measures that had to be tested, other options like a change to biofuels or a slow steaming program near and in ports have been excluded. This has led to only one measure effecting emissions produced in the ports, making the results regarding in-port measures weaker than necessary.

Thirdly, in the calculation of the costs and emissions itself this research is also not perfect. It was decided not to round up the number of ships used, leading to cases where a route is traversed by 5.12 or 0.46 ships. This is impossible, both number should be rounded up, and this makes the calculated costs weaker than needed. The choice was made however to be able to address the small changes, an increase of 0.11 ships would matter not in the previous examples. But if the same route was done with a higher frequency it suddenly could matter. The costs and emissions in port of the smaller class of vessel have been estimated by decreasing the costs and in-port emissions of the large vessel with the same rate as the size of the vessel. This is of course very arbitrary but it serves to deliver the general point of this research.

Hopefully these shortcomings can be a guideline to further research, for which recommendations are presented below.

8 Recommendations for further research

Here, a few recommendations for further research will be presented. The shortcomings presented above are a good starting point, but some will be presented in more detail. Other recommendations do not stem from the shortcomings, but from new insights.

The assumptions made regarding the costs of In-Port Reduction, Weather Routing, Engine Design and Hull Design are enough to classify the respective measure as either very cheap or tremendously expensive. They do however not reflect reality a hundred percent. It would be interesting to look at the efficiency of new hulls and engines when assuming that the old fleet can be sold at a decent price. Or to have a look at how the costs of a cold ironing network are distributed between the different actors, if the shipping line needs to pay for the investment to be able to use it, efficiency might fall.

Another point of interest for further research is the impact on the service level of these measures. Measures that include an extra delay in port or that decrease voyage speed, decrease the speed of deliverance. Since the latter is important to the shipping line's customers, this could have certain effects like a shift towards rail, road or air transport. To really understand the global impact of the measures, it is vital to know when this shift occurs and how many cargo will be shifted to which modality.

When looking at how a measure performs, the efficiency is a key component. Here, the latter is stated to be the case when Co2 decreases by more percentage points than costs increase. This means that Co2 and costs are valued roughly the same, but this might not be truly the case. Indeed, it would be beneficial to know what a certain amount of Co2 emissions costs in USD. This could also be done from different perspectives, the global perspective might value Co2 reduction more than a company.

The emission reduction measures in this research have been selected with in mind the most standard shipping routes, like Shanghai-Rotterdam. The changes found when the shortest routes were added indicate that those deserve their own research. It would be interesting to select measures for short sea shipping only. Further, different locations could also be investigated separately, as this research leaves out differences in climate, local regulation and the service level in ports. Last, the Northern Sea Route has been used here as an alternative for the route Shanghai-Rotterdam, and it was proven effective though in-efficient. Ongoing climate change will probably mean that the NSR can be used longer and longer every year, so an in depth analysis of the costs and benefits is certainly needed.

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Appendix

In the appendix, the reader can review tables and figures that have been omitted from the main body of the thesis.

1 Far East- Australasia

Effects	Weather Routing
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,10%
Costs Increase	0,00%
Co2 Reduction	2,97%

Figure 42 Far East- Australasia, effects of Weather Routing

Effects	Fuel Cells
#Ships extra	0,11
Co2 In port	0%
Co2/TonneKm	-14,00%
Costs Increase	86,36%
Co2 Reduction	11,97%

Figure 43 Far East- Australasia, effects of Fuel Cells

Effects	Slow Steaming
#Ships extra	1,65
Co2 In port	0%
Co2/TonneKm	-43,00%
Costs Increase	-33,17%
Co2 Reduction	41,22%

Figure 44 Far East-Australasia, effects of Slow Steaming

Effects	In-Port Reduction
#Ships extra	0
Co2 In port	-40%
Co2/TonneKm	0,00%
Costs Increase	0,00%
Co2 Reduction	1,66%

Figure 45 Far East-Australasia, effects of In-Port Reduction

Effects	Hull Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	Unrealistically High
Co2 Reduction	8,63%

Figure 46 Far East-Australasia, effects of Hull Design

Effects	Hull Cleaning and Coating
#Ships extra	0,6
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	8,40%
Co2 Reduction	7,80%

Figure 47 Far East-Australasia, effects of Hull Cleaning & Coating

Effects	Propeller Cleaning and Polishing
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,00%
Costs Increase	0,49%
Co2 Reduction	2,88%

Figure 48 Far East-Australasia, effects of Propeller Cleaning

Effects	Engine Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-8,50%
Costs Increase	Unrealistically High
Co2 Reduction	8,15%

Figure 49 Far East-Australasia, effects of Engine Design

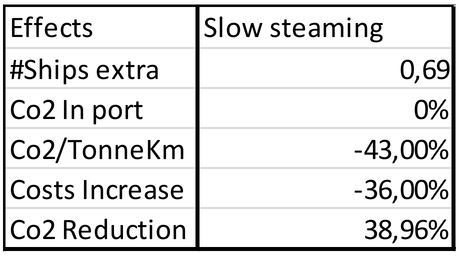
2 Intra-Asia

Effects	Weather Routing
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,10%
Costs Increase	0,00%
Co2 Reduction	2,81%

Figure 50 Intra-Asia, effects of Weather Routing

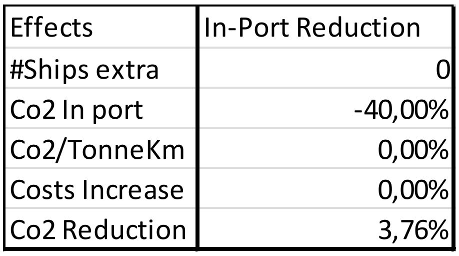
Effects	Fuel Cells
#Ships extra	0,11
Co2 In port	0%
Co2/TonneKm	-14,00%
Costs Increase	94,00%
Co2 Reduction	9,40%

Figure 51 Intra-Asia effects of Fuel Cells



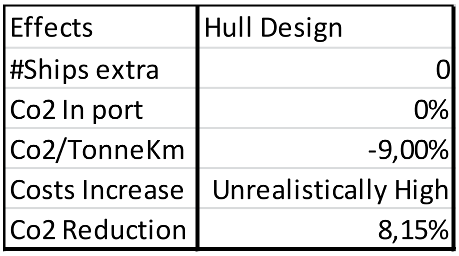
Effects	Slow steaming
#Ships extra	0,69
Co2 In port	0%
Co2/TonneKm	-43,00%
Costs Increase	-36,00%
Co2 Reduction	38,96%

Figure 52 Intra-Asia, effects of Slow Steaming



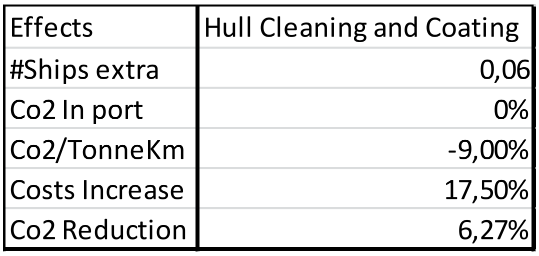
Effects	In-Port Reduction
#Ships extra	0
Co2 In port	-40,00%
Co2/TonneKm	0,00%
Costs Increase	0,00%
Co2 Reduction	3,76%

Figure 53 Intra-Asia, effects of In-Port Reduction



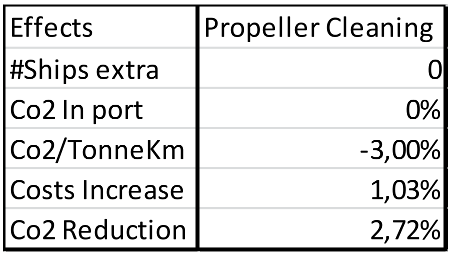
Effects	Hull Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	Unrealistically High
Co2 Reduction	8,15%

Figure 54 Intra-Asia, effects of Hull Design



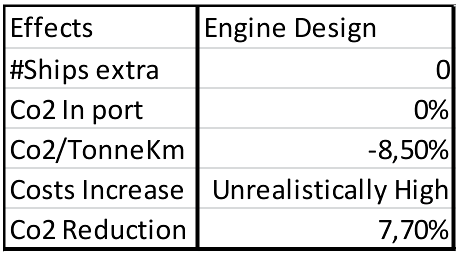
Effects	Hull Cleaning and Coating
#Ships extra	0,06
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	17,50%
Co2 Reduction	6,27%

Figure 55 Intra-Asia, effects of Hull Cleaning & Coating



Effects	Propeller Cleaning
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,00%
Costs Increase	1,03%
Co2 Reduction	2,72%

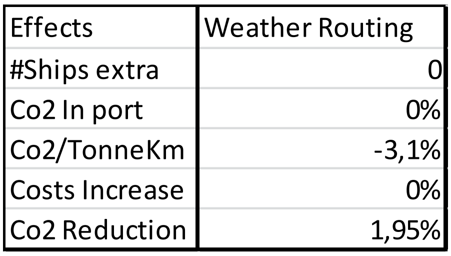
Figure 56 Intra-Asia, effects of Propeller Cleaning



Effects	Engine Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-8,50%
Costs Increase	Unrealistically High
Co2 Reduction	7,70%

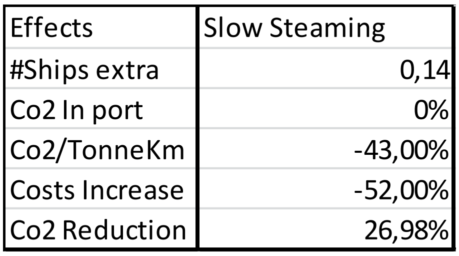
Figure 57 Intra-Asia, effects of Engine Design

3 Asian Short Sea shipping



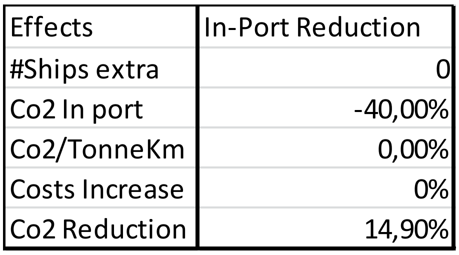
Effects	Weather Routing
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,1%
Costs Increase	0%
Co2 Reduction	1,95%

Figure 58 Asian Short Sea, effects of Weather Routing



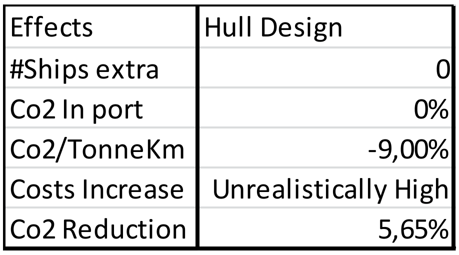
Effects	Slow Steaming
#Ships extra	0,14
Co2 In port	0%
Co2/TonneKm	-43,00%
Costs Increase	-52,00%
Co2 Reduction	26,98%

Figure 59 Asian Short Sea, effects of Slow Steaming



Effects	In-Port Reduction
#Ships extra	0
Co2 In port	-40,00%
Co2/TonneKm	0,00%
Costs Increase	0%
Co2 Reduction	14,90%

Figure 60 Asian Short Sea, effects of In-Port Reduction



Effects	Hull Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	Unrealistically High
Co2 Reduction	5,65%

Figure 61 Asia Short Sea, effects of Hull Design

Effects	Hull Cleaning and Coating
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	24,70%
Co2 Reduction	5,65%

Figure 62 Asian Short Sea, effects of Hull Cleaning & Coating

Effects	Propeller Cleaning
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,00%
Costs Increase	1,95%
Co2 Reduction	1,88%

Figure 63 Asian Short Sea, effects of Propeller Cleaning

Effects	Engine Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-8,50%
Costs Increase	Unrealistically High
Co2 Reduction	5,33%

Figure 64 Asian Short Sea, effects of Engine Design

4 European Short Sea Shipping

Effects	Weather Routing
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,10%
Costs Increase	0,00%
Co2 Reduction	1,07%

Figure 65 European Short Sea, effects of Weather Routing

Effects	Fuel Cells
#Ships extra	0,1
Co2 In port	0%
Co2/TonneKm	-14,00%
Costs Increase	149,91%
Co2 Reduction	-23,72%

Figure 66 European Short Sea, effects of Fuel Cells

Effects	Slow steaming
#Ships extra	0,04
Co2 In port	0%
Co2/TonneKm	-43,00%
Costs Increase	-57,77%
Co2 Reduction	14,86%

Figure 67 European Short Sea, effects of Slow Steaming

Effects	In-Port Reduction
#Ships extra	0
Co2 In port	-40,00%
Co2/TonneKm	0,00%
Costs Increase	0,00%
Co2 Reduction	26,17%

Figure 68 European Short Sea, effects of In-Port Reduction

Effects	Hull Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	Unrealistically High
Co2 Reduction	3,11%

Figure 69 European Short Sea, effects of Hull Design

Effects	Hull Cleaning and Coating
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-9,00%
Costs Increase	36,39%
Co2 Reduction	3,11%

Figure 70 European Short Sea, effects of Hull Cleaning & Coating

Effects	Propeller Cleaning
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-3,00%
Costs Increase	2,90%
Co2 Reduction	1,04%

Figure 71 European Short Sea, effects of Propeller Cleaning

Effects	Engine Design
#Ships extra	0
Co2 In port	0%
Co2/TonneKm	-8,50%
Costs Increase	Unrealistically High
Co2 Reduction	2,94%

Figure 72 European Short Sea, effects of Engine Design

5 Results

Co2 Reductions	EU-Far East	Far East- Australasia	Intra Asia	Asia Short Sea	European Short Sea	**Average**
Measure						
Operational						
Weather Routing	3,03%	2,97%	2,81%	1,95%	1,07%	**2.37%**
Fuel Cells	12,97%	11,97%	9,40%	-7,48%	-23,72%	**0.63%**
Arctic Route	5,63%	U	U	U	U	**5.63%**
Slow Steaming	42,00%	41,22%	38,96%	26,98%	14,86%	**32.80%**
In-Port Reduction	0,84%	1,66%	3,76%	14,90%	26,17%	**9.47%**
Operational Average	**13%**	**14,46%**	**13,73%**	**9,09%**	**4,60%**	**10.95%**
Technological						
Hull Design	8,81%	8,63%	8,15%	5,65%	3,11%	**6.87%**
Hull Cleaning&Coating	8,39%	7,80%	6,27%	5,65%	3,11%	**6.24%**
Propeller Cleaning	2,94%	2,88%	2,72%	1,88%	1,04%	**2.29%**
Engine Design	8,32%	8,15%	7,70%	5,33%	2,94%	**6.49%**
Technological Average	**7,12%**	**6,87%**	**6,21%**	**4,63%**	**2,55%**	**5.48%**

Figure 73 Overview of effectiveness per measure

Cost increase	EU-Far East	Far East- Australasia	Intra Asia	Short Sea	Short Sea Europe	**Average**
Measure						
Operational						
Weather Routing	0,11%	0,01%	0,00%	0,00%	0,00%	**0.0%**
Fuel Cells	83%	86,63%	94,00%	129,00%	149,91%	**108.51%**
Arctic Route	17,69%	U	U	U	U	**17.69%**
Slow Steaming	-32,00%	-33,17%	-38,96%	-52,00%	-57,77%	**-42.78%**
In-Port Reduction	0%	0,00%	0,00%	0,00%	0,00%	**0.0%**
Operational Average	**14%**	**13,37%**	**13,76%**	**19,25%**	**23,04%**	**16.63**
Technological						
Hull Design	100%	100%	100%	100%	100%	**100%**
Hull Cleaning&Coating	4,40%	8,40%	17,50%	24,70%	36,93%	**18.39%**
Propeller Cleaning	0,25%	0,49%	1,03%	1,95%	2,90%	**1.32%**
Engine Design	100%	100%	100%	100%	100%	**100%**
Technological Average	**51,16%**	**52,22%**	**54,63%**	**56,66%**	**59,96%**	**54.93%**

Figure 74 Cost increase in percentages

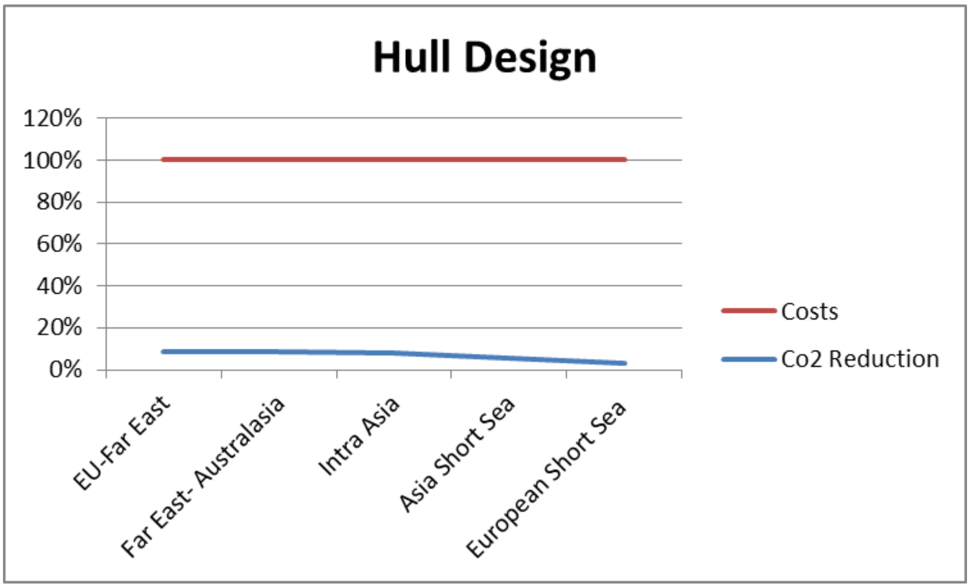


Figure 75 Hull Design: Co2 reduction and costs in percentages

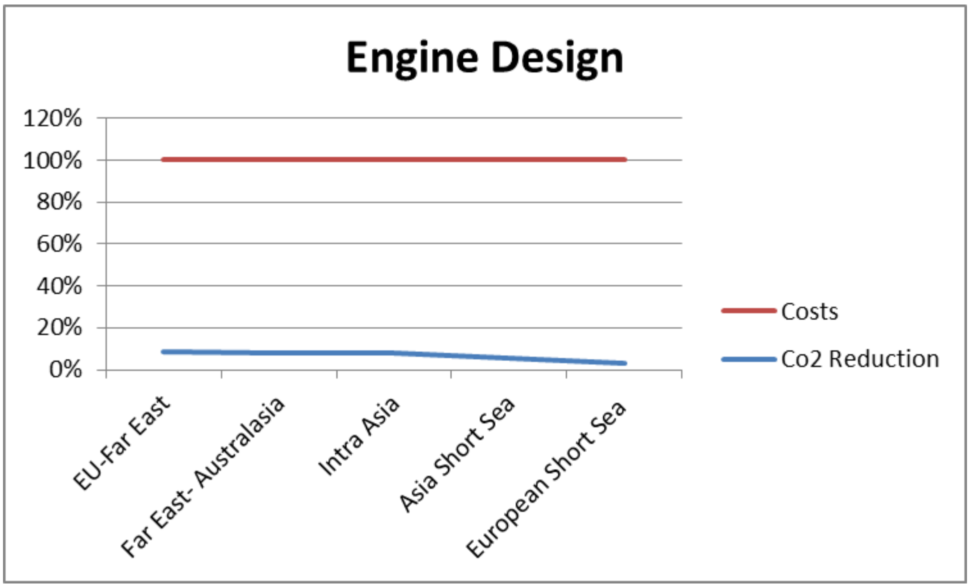


Figure 76 Engine Design: Co2 reduction and costs in percentages