No ocean for old ships

Robust design for a sustainable future of shipping

Jeroen Pruijn

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Inhoud

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The good, the bad and the ugly

Between 23 and 29 March 2021, the Suez Canal was blocked by the container ship Ever Given. This incident demonstrated the importance of shipping in our daily lives. A great many news outlets had headlines claiming that barbecues and sex toys would not be delivered on time, in an effort to convey the impact of this blockade to the general public. In fact, the former is traditionally sold more often in spring, when the weather improves, and the latter is intended for the peak in sales in the run-up to Mother's Day. However, that is only part of the story of shipping. Due to an increase in welfare and technological development, the dependence of Western societies on the worldwide production of specific products has increased. So, when the container ship Ever Given blocked the Suez Canal for a week, this shocked our society in several ways. The disruption in our transport system had serious consequences, and although the headlines were mainly focused on juicy products, the impact is still noticeable to this day. Several goods became rarer and therefore more expensive and harder to come by.

Before continuing, it should be explained that within this lecture shipping will refer to the transport by ships, and not the transport of goods by other means. At the time of writing, the production of most goods is quickly reducing the shortage, but shipping is not able to handle the transport of this temporary extra production. As a result, transport prices are rising and maintaining the higher prices caused by the shortages. Furthermore, the severe disruption in the production of computer chips, due to COVID and the blockade, has not yet been solved. These chips are used in all kinds of devices like computers, game consoles, cars, heavy equipment, and crucial medical equipment. This shortage is expected to last well into 2023 and most likely beyond. Depriving many not only of luxury but also of relevant care.

Thus, shipping plays a crucial role in all of our lives. Almost everything we own was at some point transported by a ship, either as a final product or for example as a raw material. Yet we seldom give it a thought. Shipping happens out of our sight and works without any issues. At least it seems that way. But there are issues and these are affecting our lives, not only in a positive way. I will explain below what these issues are, after describing the driving forces for shipping.

The good

Why did we choose to produce our products on the other side of the world? To understand this, it is important to know a little bit about macroeconomics: the economic relations at the country level. In the early 19th century Ricardo already stated the principle of comparative advantage (Ricardo, 1817).

Comparative Advantage

In an imaginary world with two countries, Woodland and Sheepland, only two products are produced, hulls and sails. With the available labour Woodland can produce at most 90 hulls or 80 sails. Combinations are possible as well. For example, if labour is divided equally, Woodland can produce 45 hulls and 40 sails. Similarly, Sheepland, a larger country, can produce 100 hulls or 120 sails. If both countries were to divide production equally, they would end up producing 95 hulls (45+50) and 100 sails (40+60). Ricardo proved that if hulls and sails have equal value, the highest global production would be achieved if both countries were to produce only that good which they are better at producing (have a comparative advantage), so only hulls in Woodland and only sails in Sheepland. In that case, 90 hulls and 120 sails would be produced, 210 products in total. This means an increase of 15 products in total compared to the half/half situation. This is a key reason for specialisation and the existence of international shipping.

Over the last two hundred years, this theory has been criticised and improved, but its basis remains relevant today. Our society depends on international trade in goods because, even when including transportation costs, it is often cheaper to produce something elsewhere. For this to be successful the transport needs to be very cheap, and that is where shipping comes in. International shipping is cheap: we can transport a pair of shoes from a factory in China to a warehouse in the Netherlands for about 10 cents. Transport of sunglasses will cost about 1 or 2 cents only.

Why is shipping so cheap? In order to offer these very low rates, the maritime industry makes excellent use of something called economies of scale. Simply said, the costs per product are lower if you transport them in larger quantities. This can be explained by comparing a truck with the container ship Emma Maersk (Maersk Shipping, n.d.). The truck can transport two containers, and the Emma Maersk 14,770. The truck has a crew of one, while the ship has a crew of thirteen. This means that with the truck one container pays for half the truck driver's wages, while on the ship this is about one-thousandth of the wages of a crewman. Both have an average speed of about 50 kilometres per hour. However, the truck uses about thirty litres of fuel per hour, or 15 litres per container per hour, while the ship uses only 1 litre per container per hour. This makes for a significant fuel saving and impact reduction, which is partly due to a more effective propulsion train, but also to the difference in extra weight between the truck and the ship. The truck and chassis weigh about the same as one loaded container, or 50% extra weight per container. The Emma Maersk is much heavier, weighing about 2,500 loaded containers, but this is only 17% extra weight per container. All these benefits reduce the costs of transport per container.

The bad

So large is cheap? Yes and no. Large ships offer cheap transport, but ships are expensive to build, normally costing between 10 million and 120 million euros. However, as can be seen in Figure 1, prices can vary significantly over time for the same ship. Recovering the costs of these investments requires ships with a long lifespan, often well over 25 years. Furthermore, it takes quite some time to build such large ships. On average, the time between signing the contract and the delivery of the vessel is about three years. A consequence of these long construction times is that shipping capacity cannot be instantly increased. A good example of this is the period between 2005 and 2010. In 2005 the economy was booming, resulting in more and more trade. Freight rates increased and more ships were ordered to deal with the increase in demand. As this drove up the prices of new ships, new yards were created and in 2007 the construction of the largest yard in the world started. Delivery time was now five years or more, and prices for vessels were three times as high as in 2000. In 2008 the order books for ships were fuller than ever, well exceeding what would be needed in the future (see Figure 2). At the end of that year, the banking crisis started. This was also the moment the new largest yard started production. In 2009 the crisis was in full swing and although several orders were cancelled, still the number of ships on order was equal to about 15% of the fleet. In 2010 the largest yard declared bankruptcy, and shipping was in a big crisis, with too many ships for very little cargo. This crisis would last a long time, as the ordered ships continued to be delivered till well into 2013, maintaining and even increasing the oversupply of ships. This was the worst cycle in shipping, but not the first and definitely not the last.

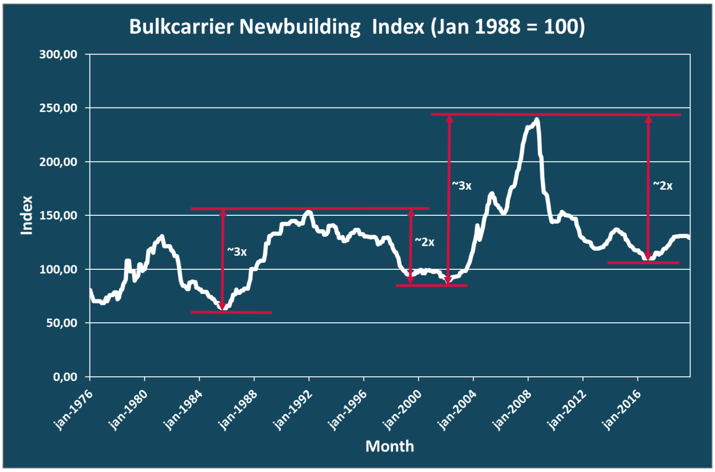

Figure 1: Relative ship price movement (Based on data from Clarksons (n.d.))

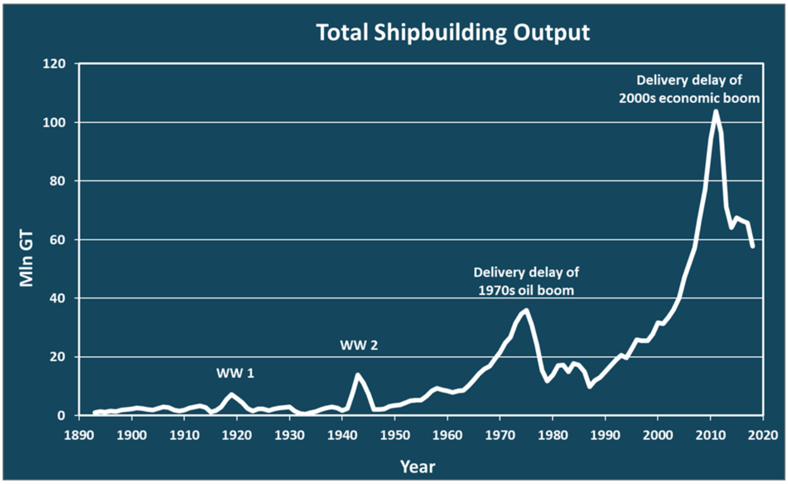

Figure 2: Shipping output (Based on Lloyd's Register data (n.d.))

Economists call this cyclical variation in over- and under-supply the pork cycle. It can be found in many markets where there is a time delay in adjustments between supply and demand, and it is the first bad side of shipping. Another bad side is the fact that all this transportation is causing emissions of CO_2 and other greenhouse gases (GHG). In principle, GHG is necessary to make life possible on earth. Without it, it would simply be too cold. However, due to the burning of carbon captured in the earth (coal, oil, gas), we are disturbing the balance and accelerating climate change.

Shipping primarily uses fossil fuels, and this of course has an impact on emissions. As can be seen in figure 3, transport is responsible for 22% of all CO_2 emissions. With 1,058 million metric tons (mt) of CO_2 in 2018 , shipping is a serious contributor, with roughly the

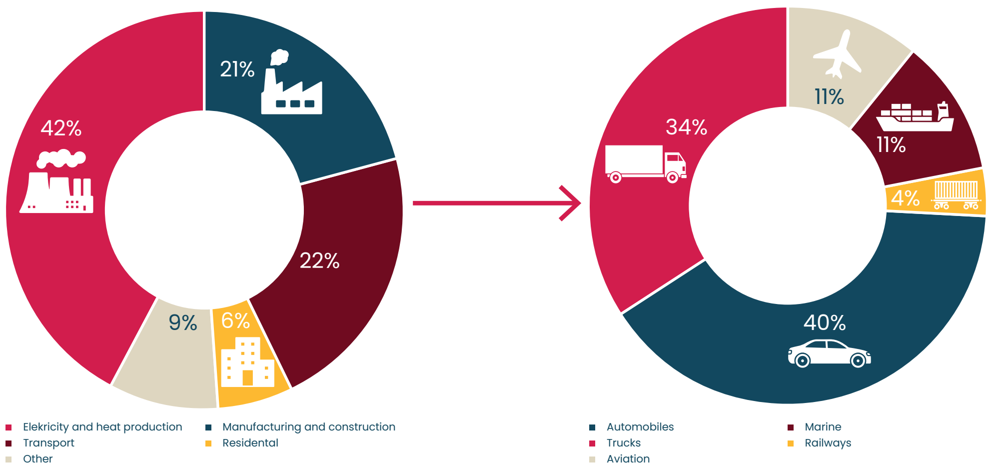

Figure 3: CO_2 emissions from shipping (Based on data from IPCC (2014))

same volume of emissions as the country of Germany as a whole (IMO, 2021). On the other hand, it provides only 11% of the CO_2 emission from transport, while it provides for about 80-90% of the tonne-kilometres (ton*km) of transport work. This is in part because the transport includes not only finished goods but also intermediate products. In some cases, this could be considered excessive, for example, when the process of turning a tree into a magazine on the coffee table includes four or five crossings of the Atlantic Ocean, all in order to save a couple of cents in the production process. On the other hand, trucks produce about 34% of the emissions and provide about 7-10% of the transport work, which when considered per ton*km, is a much larger impact. So, all in all, the GHG emissions of shipping are bad, but not yet ugly.

The ugly

The ugliest part of shipping consists of two aspects not yet addressed. As recent news shows, port cities (and especially Rotterdam) have the worst air quality of all cities, and this is often linked to shipping (e.g., Werft (2022) and Rotterdam (n.d.)). Bad air quality is responsible for a shortening of life expectations by three (in Europe) to nine (in India) years (Schuttenhelm, 2022). It has a similar impact as smoking and can cause lung cancer and cardiovascular diseases. The emissions are also linked to increases in dementia as well as to rises in premature birth and autism.

As can be seen in Figure 4, the emissions of shipping vary per type of emissions. Especially the more local emissions like NO_x, PM and SO_x are relatively high. These affect all of us in Rotterdam, as well as the people living in other ports or along important shipping lanes. Besides the emissions from engines, there is also pollution when venting cargo holds. Venting is necessary to evaporate any leftover liquid cargo in the ship, as not all cargo can be removed during unloading. A thin film remains, and this evaporates or is washed away, depending on the cargo. Those cargos that are evaporated can be relatively harmless, like alcohols, or highly carcinogenic like benzene. This is officially not allowed in rural areas, however, monitoring this is very difficult.

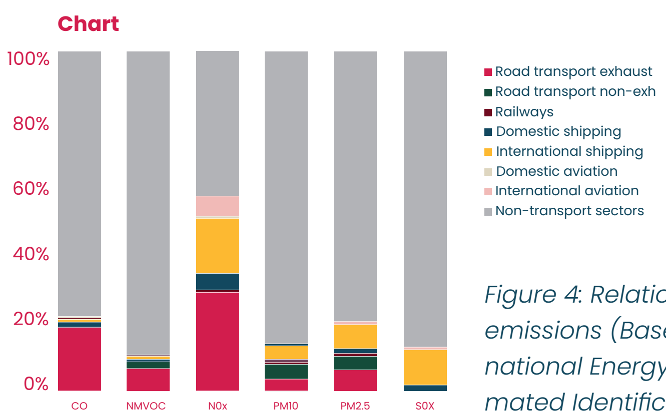

Figure 4: Relation between shipping and emissions (Based on data from the International Energy Agency (IEA) and Automated Identification System (AIS) data)

Finally, and probably the most well-known through the photo series from 1989 by Sebastião Salgado, there is the issue of the scrapping of ships. In his photographs, Salgado shows the shipbreaking workers of Bangladesh working on the beaches, without protective clothing and without regard for the environment. Ships are demolished there, and in India and Pakistan, by grounding them on the beach during a high tide. Next, the gravity method is used. This means simply that a section of steel weighing up to 20,000 kg is cut loose from the ship and falls to the beach (under the influence of gravity). It is not uncommon for workers to be crushed by such a block when it falls unexpectedly or outside the planned area (see also Image 1).

Image 1: Shipbreakers in Chittagong, Bangladesh

These blocks are pulled up the beach by winches to be cut down further, usually in plates for reuse or in smaller blocks or strips for melting and recycling. Once the front of the ship is removed, the ship is pulled further onto the beach at the next high tide, using the same winches as for the blocks. In between the materials from the ships are removed for recycling and reuse. As the beach is sandy and unstable, this is difficult. Also, any liquids leaked from the ship will seep into the sand and pollute the area. Furthermore, any rubbish, including heavy chemicals, lying around is flushed away with the next high tide.

At the moment the economic incentive is too big to change the ways of the industry. A ship "recycled" in India will not cost the owners anything but earn them money. The materials, and especially steel, are sold for more money than the labour costs. Even for a small ship, this can amount to 2 million U.S. dollars, or in general about 20% of the newbuilding price. To recycle a ship, without contaminating the environment, ensuring the health and safety of workers and taking care of proper disposal of waste is much more expensive. An owner selecting a capable yard in Europe would receive only a fraction of this if anything at all.

A part of the risk and costs could be addressed in the design of ships. But this is a long-term solution. As mentioned, ships become very old, and thirty years ago recycling was not an issue yet, so ships were not designed with recycling in mind. Also, many substances, such as asbestos, were not yet known to be hazardous to our health and were used widely in ships as well. These issues are perhaps best illustrated by the renovation of the SS Rotterdam, which went from an initial estimate of 24 million to 250 million U.S. dollars over a period of sixteen years. Inexperience, unforeseen issues, widespread hazardous materials, and a lack of data on the design all contributed to this disaster (Schellens, 2015). But isn't the final result a beauty?

With improper recycling providing significant financial benefits, the issue may need to be addressed by legislation. However, it is also very difficult to address these issues with legislation, as shipping operates globally and ships can be registered in any country, even those that have no access to the oceans. Once registered to the ship must abide by the rules of that country. However, it is not uncommon for ships to change their country, called changing flag, several times during their lifetime. This means that for instance the EU legislation for recycling can be easily avoided by changing the flag of the vessel early enough to not fall under its jurisdiction. This issue is not new, and to deal with it, international treaties are required. A well-known treaty accepted globally was the Safety Convention for the Life at Sea (SOLAS), which was accepted for the first time in 1914, shortly after the Titanic disaster. Several more treaties were created this way. In 1946 the UN created the International Maritime Organisation (IMO) to support the creation of international standards and legislation for ships.

Within the IMO a treaty is proposed in the general assembly, which consists of almost all the countries in the world. Once the idea is accepted, a working group will develop the content and present an update for each general assembly. Once all members are satisfied, the new rules are accepted. The rules are at that moment not yet the law, as sufficient member states will first need to ratify the rules. This means that they embed the rules in their national legislation. How many countries need to sign for rules to be ratified, is part of these new rules and a subject of negotiations. In the case of ship recycling, there is a set of rules to promote the green recycling of ships. These are called the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (Hong Kong Convention). In March 2000 this process was started, and in July 2003 this resulted in a set of voluntary guidelines on ship recycling. These were followed two years later by the start of the development of legally binding principles. These were accepted in 2009 during a special convention in Hong Kong (giving the name to the legislation). To be ratified at least fifteen states representing, at least 40% of the world fleet (based on the flag of the ship, not the location of the company) needs to sign and implement this treaty. At this moment that is not yet the case.

Is IMO always so slow? No, once legislation is created and ratified, adjustments and extensions to these rules and legislation do not need to go through the same time-consuming process. In that case, a majority vote of the general assembly is sufficient, although IMO does try to achieve the consensus of its 175 member states. This way, especially in the last twenty years, many updates and amendments were created and came into force. In fact, the amount of new legislation in the past twenty years exceeds that of the previous eighty years of international shipping legislation. On top of that, several amendments do not only address ships built after that date, which was the common approach up until relatively recently, but it often also affects ships already in operation. This improves the rate of change towards sustainability, but also increases the complexity and uncertainty for ship owners, as they do not know how to prepare for unknown future legislation.

My professorship is about addressing the ugly parts of shipping, emissions, dismantling and material waste, as these directly impact the environment. The key question is: how do we make shipping more sustainable and ready for the future?

2

The missing

As a first step towards answering the question: 'How to make shipping more sustainable and ready for the future?', the components of sustainability in shipping will be identified. This will, in the next chapter, be followed by my vision on the actions that are required.

My scheme for sustainability

Sustainability has many definitions and perspectives. Too many to discuss in depth in this chapter. I accept that, and will not focus on an exact definition, but only on a scheme I use to address sustainability in shipping. The focus is on how to achieve sustainability in shipping, leaving out, for clarity, other aspects. It may be beneficial outside shipping as well, but this is not the intention here. The model that I propose to investigate sustainability in a maritime context consists of five elements (see Figure 5):

1. General sustainability aspects: what are the impacts, and what drives them?
2. Power & energy (systems): what are the options to reduce the operational impact?
3. Resources & materials: what are the options to reduce the creation impact?
4. Digital and data systems: how to make well-informed decisions?
5. Non-technical measures: how can sustainability in shipping be encouraged?

I've designed the scheme as a classical temple, as sustainability is achieved through adaptations in the two columns of 'Power & Energy' and 'Resources & Materials'. While accurate insights (Data) and supporting measures form the foundation for the move to sustainability. In the next subsections, these elements will be investigated in more detail, incorporating several pieces of research to achieve a solid knowledge base.

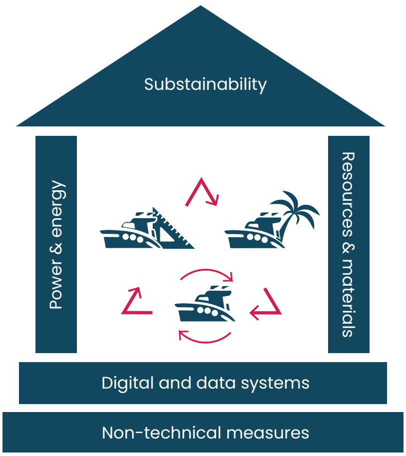

Figure 5: Temple of sustainability, an approach to sustainability in shipping

Sustainability

Sustainability is a broad term which covers many aspects, but at its core concerns the reduction of negative impacts on the environment. The environment is broad and includes human society, flora and fauna, and limited resources for instance. It is crucial when analysing the environmental impact of a product or service, to categorize its effects throughout its total lifespan. Furthermore, it is important to value the different effects in the expected outcome and gain. When applied to ships, there are several major impacts to be considered.

Focussing on the material-related impact, which is more than the substandard recycling. Each phase in the lifetime of a vessel has its specific impacts to be considered. The first step is the production of the ship. Considering that 80-85% of the weight of a ship is made up of steel, that is the first aspect to consider. During production, only virgin steel is allowed to be used. The production of this steel requires a lot of energy as well as ores, as only about 20-30% of the input is scrap steel. Steel is completely molten in this process instead of being reused. When parts are cut from a plate, some material is always left over. 3-5% of that steel is scrapped directly as the result of plate-cutting inefficiencies. Furthermore, the majority of waste generated during production consists of packaging (plastic foil, wood, Styrofoam), used for the transportation of up to 40,000 parts that go into a vessel. Finally, there is the use of energy and water during production. As welding requires a high current to melt the material locally, yards use a significant amount of energy. Water is often used in the cleaning of steel structures and to cool the plates during cutting (Elingsen et al, 2002, GAUSS, 2002, Kameyame et al, 2005).

While the production takes up to three years between contract and delivery, the ship is operated for twenty to fifty years. During this operational phase, the emissions of the engine discussed above, form a major part of its impact. Energy systems of vessels generate over 80% of the total impact during the lifecycle of the vessel, mainly through energy consumption and the fuel used. Besides energy, wastes generated by the vessel and crew have an impact, and the introduction of new species into an environment should be considered an unsustainable impact.

At the end of its economic lifetime, the vessel is recycled. As discussed in the first chapter, improper material recycling and the use of hazardous materials have a large impact on the environment. Energy does not play a major role in this phase. On the positive side, much of the steel used is still very valuable at the end of its lifetime, and almost all steel is recycled or even re-used. Due to this reuse, the combined impact of production and recycling is only 10-12% of the total impact and concerns materials primarily. As stated above 80% of the impact during operations comes from energy. The remaining 8% is divided over a large number of smaller items, which sometimes can be addressed together with the two major contributors, but will not be discussed in detail here.

Although all statements above are supported by research (Cozijnsen, 2019, Elingsen et al, 2002, GAUSS, 2002, Kameyame et al, 2005), significant variations are to be found when comparing these. Assessing the reduction of the impact on the environment is crucial to selecting the right innovations and actions. However, despite the research and insights mentioned above, there are significant variations in the comparisons. Although the assessment method is sound, during application choices have to be made on the scope of emissions to be included, the valuation of different impacts (you might reduce one exhaust gas at the cost of another) and the lack of available data from reliable sources. This means estimations have to be made, leading to different insights. This is something to keep in mind when considering sustainability as a goal.

Finally, as became clear from the ship recycling discussion, sustainability is not always the most profitable option available. Also, with most of the shipping activities taking place far away from public awareness, social pressure is limited. So, just as is the case for ship recycling, legislation may be required for other impacts as well, not necessarily forbidding certain acts, but often as a nudge in the right direction. For example, California introduced tax legislation on the carbon footprint in 2013. As a result, producers selling in California are actively looking for ways to decrease their footprint, especially those producers located on the other side of the globe, who found themselves at a disadvantage compared to local companies. As a result, these have implemented green shipping options in their supply chain (ACEEE, n.d.).

However, these initiatives are not limited to governments alone. Wind farm owners, for example, are also looking to lower the impact of installation and maintenance, as it runs counter to the green energy they sell. As a result, electric support vessels are now used for the maintenance of wind farms. Thus, new business networks and cooperations might be able to create a suitable and profitable situation for sustainability. All these elements support the adoption of new low-impact technologies and materials in shipping (Blenkey, 2021, Memija, 2022).

Power and energy systems

As described in the previous section, the energy use during the lifetime of a vessel is a very large contributor to its impact. This is a good reason to start by looking at the energy aspect. Power and energy systems are both systems related to the operations of the ship. This includes the kitchen equipment, the cranes and especially the propulsion system. Even the hull is a part of this, as its shape influences the power required to achieve the desired speed. All of these systems influence each other and form an intricate network, where the energy demand is supplied by the onboard energy systems, such as generators and engines. Any change to this complex system, for example in order to become more sustainable, has an impact on the other elements, if not on all of them. This complex balance is at the core of ship design and the design process. In design, options are compared based on the requests from the owner as well as the requirement of legislation and regulation. The result is a balanced compromise between contradicting desires, for example between speed and cargo volume. You can increase the cargo volume by increasing the fullness of the hull, but this will entail a cost in terms of extra wave resistance. As a result, all other things being equal, the speed will be lower.

When there is a need to reduce the impact of the power and energy systems, a ship owner has two options open to him: increasing efficiency and changing to a cleaner fuel. To start with the first, an increase in efficiency results in a reduction in energy demand. The number of possible options in this respect seems almost endless. Of course, improving the engine performance or reducing the resistance of the hull come to mind, but many other exotic forms have been developed and tested: kites to help propel the ship, air bubbles along the hull to reduce resistance, whale-tail-inspired propulsion to increase efficiency, submarines to reduce the wave resistance component, capturing the exhaust gasses or using favourable weather routing.
Broadly speaking these options can be divided into five categories (Bouman, 2017).

1. The first option is to increase the efficiency of the hull and propellor. This can be achieved by improving the flow towards the propellor, making the hull smoother, with a narrower shape, and by reducing waves with a bulbous bow, a whale tail as mentioned before, and many other techniques.
2. The second option is to use power assistance, primarily aimed at reducing the demand on the engine for propulsion. This could be a sail, a kite, solar panels, but also batteries that store excess energy and give it back when needed (this is called peak shaving).
3. The next option is to look directly at the exhaust of the engines. A lot of energy is lost in the form of heat, and if this energy is recovered and used, a separate heater is not required.
4. Next to this, it is an option to wash or clean exhaust emissions, as the catalyser in a car does, removing the worst from the exhaust before emitting it. This does come at the cost of extra energy because the resistance in the exhaust is also increased.
5. Finally, there are less technical options, such as operational improvements, which boils down to doing things differently to save energy. The weather routing as mentioned before is an example of this. By sailing a different route, energy is saved. Of course, slowing down is another good example. In general, all operational options save energy and reduce fuel costs for the owner. And as these do not require any investments, it is actually often a win-win situation. However, in many cases contract stipulations, safety requirements and common practices prevent the implementation of such options. For example, sometimes speeds are fixed in the contract, or waiting brings extra cost, causing owners to make haste unnecessarily, to maximise their income.

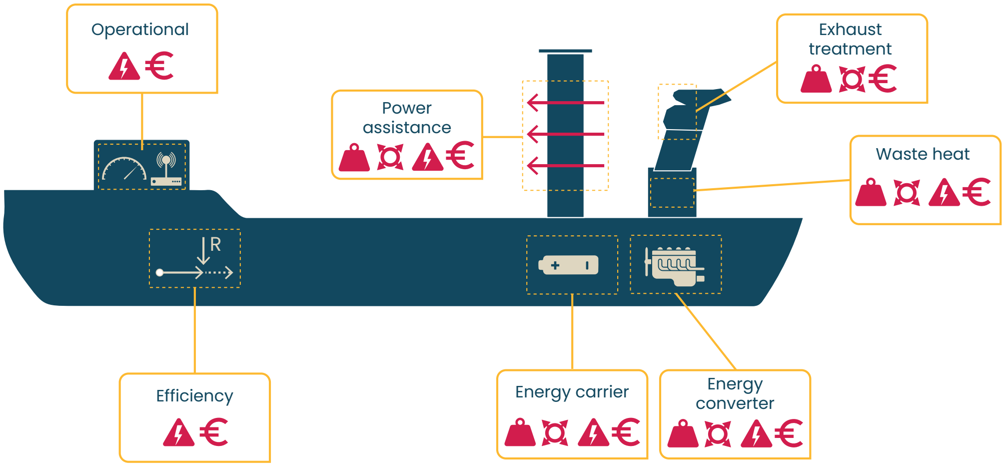

Figure 6: Power and energy improvements for ships

I have only selected these five options, but there are many more options available to the ship owner. Although all these options will help in reducing the impact, most researchers put their combined impact at a maximum of 30-40% of the total fuel consumption, and thus of the total emissions. IMO has set a goal for 2030 to reduce the GHG emissions of ships by 40% per ship compared to 2008. This should be achievable but finding the right buttons to press for your ship can be like finding a needle in a haystack (IMO, 2021).

Furthermore, the target of IMO for 2050 is a reduction of 70-85%, and preferably near-zero emissions. To achieve this, a sixth option to reduce the impact of the power and energy systems is required: changing to a cleaner fuel (all presented in Figure 6). The energy carrier (the fuel) will need to change, and as a result of that, the engine might also need to be changed. In the literature, seven options are often mentioned: biodiesel, LNG, hydrogen, batteries, alcohols, ammonia and, more recently, nuclear power (Bouman, 2017, IMO, 2021, Rehmatlulla, 2016). However, when one goes into detail and accepts other unlikely options such as iron powder, the number of options increases to around 25. This does not include the source, which can often be biological (e.g., tree stumps) or based on green electricity. Also, the energy converter (the engine) is often offered in different types and choices. As a result, it is not an exaggeration to say that at this moment, over a hundred powering options can be considered for the maritime sector. New options are suggested regularly, so this number will only increase further. This complicates selecting the right option to address the problems, especially the issue of exhaust gas impact.

With the urgency to reduce emissions and the large number of options available to contribute, it might be surprising to hear that less than 1% of the vessels (911 out of 103,358 (Clarkson, 2022)) are actually able to sail on alternative fuels, that only 6% of the vessels have a form of exhaust gas treatment, and that only about 5% have installed an energy-saving device (ESD) (Clarkson, 2022). 2030 is not that far away. Why are these numbers not much higher already?

The reason for this low adaption rate is that all new fuels have lower performance when it comes to energy per volume or energy per weight. In short, the same amount of fuel brings less energy, and thus a vessel will need to bring more of it to complete the same trip. The example given in Figure 7 shows three relevant fuels compared side by side: diesel, methanol (an alcohol) and ammonia. Without going into all the details of the fuel, the first point is that the energy in the top part is the same, but methanol and ammonia require much more volume, just for the fuel. Secondly, the safety requirements for methanol and ammonia are different (both are toxic in gas form), and extra insulation is required, which increases the size of the space occupied by the tank. Ammonia, like LNG, is a gas and requires pressurized tanks to be stored. This severely increases the volume required as you store a round tank in a rectangular box (top right). Finally in the bottom part, also due to safety legislation and the impact when the fuel is leaked into the ocean, the location where you can store the fuel in the ship is indicated. Methanol has a slight advantage as it dissolves in water and is not considered toxic, so it can be stored next to the hull. In the case of ammonia, it is an option to put the tanks on deck. But many ships need their deck space for cargo, so this is not always the desired option.

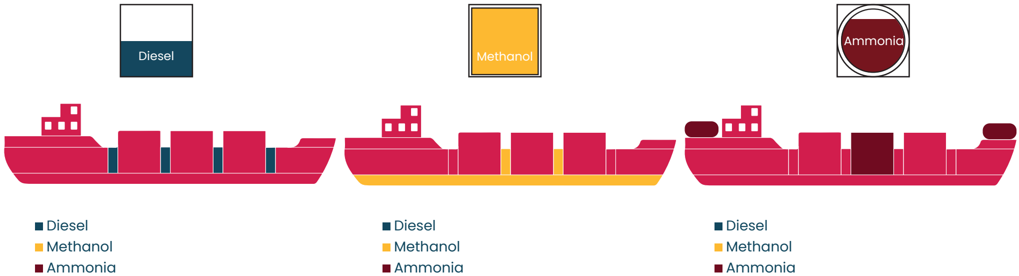

Figure 7: Impact of energy density on fuel storage in a vessel

The issues described hold true for all one hundred-plus new fuel and engine considerations and do not yet include how a different fuel impacts the other systems on board. New piping, and alarms, but also a different weight distribution, with a different hull shape as a result might be needed. In short, a completely new balance and compromise of all requirements might have to be found. As a result, it is expected that different vessel types and sizes will lead to different fuel preferences.

So far only the vessel was considered. But requiring ports to offer many different fuels for bunkering is quite uneconomical from the perspective of fuel production and supply, and is not likely to be sustained. So, in the end, the general expectation is that we will have one or at most a few new fuels for shipping. Which ones these will be is still the subject of extensive practical and scientific debate, especially as many techniques are new, unproven and most likely open to further developments. Also, many fuels and techniques lack proper safety regulations, because the risks and impacts are not yet fully understood. Due to all these different uncertainties, ship owners are dragging their feet, in the hope that clarity will come in the near future.

Resources and materials

As outlined in the introduction, ship recycling is in most cases far from sustainable. Most recycling activity is happening under bad circumstances on the beaches of the Asian subcontinent. The EU has already introduced regulations ahead of those proposed by the IMO, but banning the demolition of ships under unsuitable circumstances is difficult. Key recycling countries need the raw materials and are afraid to lose market share to each other if they act first. Also, there is simply not enough green recycling capacity to fulfil these requirements at the moment. 40% of the fleet falls under EU regulation. Yet, 90% of the recycling is done in the Asian subcontinent, by yards not accepted by EU regulation. Extra capacity is badly needed, or ships will be leaving the EU flags well before demolition, to circumvent the regulation.

EU legislation might boost green ship recycling in Europe. Initiatives are under development for efficient and green recycling yards, but their development is still in the early stages, and they have not yet led to concrete and successful results. To make recycling feasible, legislation alone is not enough. There also needs to be a demand for recycled steel. Normally 90% of the ship is recycled, and the largest part of this, 85% of the ship's weight, is steel. Currently, as mentioned earlier, the legislation for shipbuilding requires virgin materials from accepted steel mills. The majority of steel mills produce steel using about 10-15% high-quality recycled materials, and 85-90% fresh iron from iron ore and cokes. Recently, under the pressure of public opinion, steel mills are shifting to less energy-intensive production methods. An additional benefit is that these methods require up to 65% recycled steel. If all EU smelters make this switch, it would significantly increase the demand for recycled steel, which in turn would increase the demand for ship recycling in the EU, and create an opportunity for the new green recycling yards.

In the current market, steel is steel. In other industries, designers have become increasingly concerned about the impact of their products, and they use the Life Cycle Analysis (LCA) to validate the choices of materials and operations to create the product. Such an analysis looks not only at the processes within the company but also at the sources of the materials, the use of the object and how it is recycled in the end. The superyacht industry is already working on a similar approach for their yachts under the umbrella of the Yacht Environmental Transparency Index (YETI). This index would increase the value of steel created by processes with less impact and could result in a differentiation of products by impact in the steel market. A further impulse for steel mills to convert to greener production methods.

To reduce the impact of materials, steel is a good start, and various forces are working in line to better close the loop. However, ships contain many more materials and even significant amounts of rare earth minerals in their equipment. Effective recovery of these elements could further support recycling and reuse over time. Although opportunities for more sustainable use of materials are on the horizon, the maritime sector is only taking its first steps in that direction. There is a big gap in this area at the moment and closing it will not likely happen in the near future.

Digital and data systems

A lack of data leads to assumptions. As a result, an action may seem a good idea, but in practice, it is not. Thus, data is the key to properly identifying both the actual situation and the impact a change will have. The field of digital and data systems is developing rapidly. Storage capacity has increased exponentially since the dawn of computers around the Second World War. As a result, we are able to measure and store more information at lower costs than before. Shipping companies are continuously expanding the information they gather from their equipment. This can be on a very detailed level with sensors in the compression chambers of the engine measuring pressure and temperature, but also at a more abstract level, for example with an Automatic Identification System (AIS) recording all the ship's positions in time with high accuracy. Measurements are taken between two seconds and three minutes, depending on the vessel's speed.

But to be useful, storing data is not enough. It needs to be converted into information we can use. This includes cleaning and structuring the data. However, there is so much data today that humans cannot hope to make sense of it on their own. A relatively new field of data analysis, big data science, has been developed to deal with this, though it is not yet very well grounded in the maritime sector. Currently, a lector at NHL Stenden University of Applied Sciences, Herbert Koelman, is leading a large research project aimed at using this data to improve the design rules for vessels. Also, the firms offering weather routing and digital twins for your vessel are working on this with varying degrees of success. The digital twins should be able to optimise the operations in real-time based on live input from the vessels.

Together with open data such as AIS and the EU fuel monitoring data, these are the insights that could help improve or at least validate the sustainability of the maritime sector. Data thus supports our developments and also innovations towards sustainability. As a result, data represents value and more often than not, it is seen as commercially sensitive. That means that data is closely guarded and not shared in any form. This lack of availability is slowing down developments and innovations. Not only on the data science side but also with respect to sustainability. Without the right amount of reliable data, assumptions will be made and the wrong decision taken for the right reason. Or even worse, we can fail to take any decision and remain in the current situation.

My professorship doesn't have a focus on data science, but I cannot ignore it. In the future everybody in the maritime sector will have to deal with all kinds of data: at an office to make sense of the maintenance planning, on board the ship to see if the warning is a sensor malfunction or an actual issue, as brokers and cargo shippers to optimise your logistics and at customs to indicate which containers will most likely contain drugs. Similarly, I will use data to better establish the potential increase in the sustainability of innovations for the maritime sector.

Non-technical measures

Non-technical measures primarily refer to policies. In many other industries, public awareness can also be relevant as a pressure to change. Policies normally tend to prescribe a certain limit or direction. Yet another factor could be subsidies. The Dutch government signed the Green Deal for shipping aimed at supporting the transition toward green shipping, and the EU has launched its 'Fit for 55' package consisting of both legislation and support. Previous research amply demonstrates that pilot projects are key in a transformation, as they not only demonstrate the potential, but deliver an important basis for the supporting infrastructure (such as fuel bunkering, but also shipbuilding knowledge) to be available to others, significantly lowering follow-up project costs.

Also, new business models, such as companies offering operational performance improvements by analysing ship's data, but also platforms increasing the efficiency of brokers by increasing their reach could be seen as new business opportunities in the sector in part driven by sustainability.

Although these last two aspects are welcome, it is the first aspect that is giving the sector and the ship owners nightmares. Not because they do not want to comply or become more sustainable, but because they are faced with unprecedented uncertainty. Any ship ordered today could become economically obsolete within ten years due to new legislation requiring large investments in a refit. Or recycling could become impossible, converting the end-of-life premium into a cost, which would turn any profitable business case upside down.

The changes in legislation permeate all other factors and especially the power and energy pillar as fuels considered green today, could become an issue tomorrow. This has, to some extent, already happened with LNG, which was first seen as a good way to reduce CO_2 emissions and as a cleaner fuel, but which is now often seen as worse than diesel due to the methane slip. LNG is largely made out of methane gas and methane is also a GHG, but with an impact that is about 25 times higher than CO_2. So, any unburned LNG in the exhaust is a big issue. Even if 20% CO_2 is saved, 1% unburned methane would offset this benefit.

As a result, shipowners are afraid to order new vessels, and orders for ships are far behind normal. Of course, the crisis and the oversupply of 2009 play a role here as well, but many owners indicate that they prefer to invest in a vessel of five to ten years old, which most likely will not be around anymore in 2050, than risk being stuck with a vessel that cannot operate and thus has no value somewhere in the next ten to fifteen years. As a result of these delays, shipyards may go bankrupt, decreasing the building capacity, and finally, the pork cycle as described earlier will have a very severe swing in the up and a downturn in the near future.

With the elements of sustainability clear, another overarching issue has emerged. To address the exhaust emissions of the power and energy systems, as well as the improvement of the recycling and reuse in shipping, policies have already been and continue to be developed. However, our knowledge and data to support this are lagging behind this movement. As a result, the requirements for a ship have become increasingly uncertain. The past practice of ordering a ship for the market of today and hoping for the best has become too risky. We need to look at our ships in a different way, which includes their future and the uncertainties that this future beholds. If ships can be adapted more easily, recycling and changing equipment to reduce emissions will become cheaper, mitigating part of these risks. Thus, new design considerations and approaches must deal with the uncertainty and support the reduction of toxic exhaust and recycling principles for the sector. This is what my research is about, and this will be introduced in the next chapter.

3

For a few dollars more

As mentioned in the previous chapters, ships are very expensive equipment and have to last quite a long time. I believe that for only a minimal increase in costs, you can address the uncertainty and greatly improve the overall sustainability of shipping. Before explaining my solution, design, and its role in the life of the ships, needs to be better understood. Designing ships is a complex and highly specialised task because realizing a buildable design is what can be called a wicked problem (Andrews, 2011). For a wicked problem, the qualities of one possible solution are only clear in the end, so it requires major effort and a lot of trial and error (or experience) to even find one such solution. To be able to make use of such experience, ships are commonly designed by shipyards or specialised design offices instead of ship owners. This solution reduces the impact of the wicked problem but also has some important drawbacks.

Influence of the design phase

When a shipyard designs a ship with the intention to get the job to build it, they tend to keep the design effort as low as possible. This basic design or contract design is made before the contract for the building is signed. The designing shipyard cannot expect the offer with the design to be accepted. Investing in such a predesign is, therefore, a big risk to the shipyard. If the offer is not granted to the shipyard, the costs of this design need to be earned back in other projects for other vessels. So if they want to prolong their business, shipyards need to keep it simple. All money spent on design is considered a risk.

In addition to this, the competition in shipbuilding is very tough. The chances of losing out on a contract are huge. And this risk is still rising, with more yards opening up each year. Ship owners can thus choose from many yards. Europe, for example, has over 300 shipyards and there is continued growth in other parts of the world. So, if a shipyard steps into a tender for a new ship design, the risk of not getting the money spent on the preparation of the offer back is considerable. With these odds in mind, shipyards hold back on luminous, well-thought-out designs.

The fact that the design of each ship is unique contributes to this financial squeeze. Ships are rarely produced multiple times from the same design. Manufacturing, as well as design, are single acts. This is quite extraordinary compared to other transport products like cars or planes. Those are produced at least in batches or even massproduced, so the turnover of the design costs is far less per build. The grounds for this are found in the lack of dominant players in both the producers' and owners' markets. Each design reflects the views of the future owner who will shop around to find the best-suited design for his vision. Using the same design over and over again is therefore not common. So, the design costs that are made have to be taxed to that one ship and the yard has very little room to spread the design costs. Combined with the almost cutthroat competition in shipbuilding shipyards cannot afford to go all out in their basic design.

Sadly enough, this phase of basic design is the most decisive of all design phases when it comes to making a successful ship. According to several analyses, basic designs determine 70-90% of the total cost of the ship in the end. Furthermore, the decisions made in this phase can cause major cost increases when they turn out to be a mistake. The basic design forms the backbone of a ship in all phases of its production and existence. Later phases in the design process, like the engineering phase, where all details are created and producibility is validated, add to the quality of the end product, but have limited impact on the success of the ship, only on that of the yard. All design phases together impact many aspects of shipping including circularity and sustainability, and as mentioned earlier economics.

As can be seen in Figure 8, design not only impacts production and use but also the potential to recycle the product and refit a ship. So, design is highly decisive for the sustainability of a ship. A thorough design with good solutions for the total life cycle of a ship is beneficial to people, the planet and profit. Expressed in another way, a design mistake that impacts operations is multiplied by that operational life of twenty to fifty years. Thus, a ship with a hampered power system will require more maintenance and will be operational for a shorter time. And if this concerns a ship that is vital to our society, for instance, a navy ship that guards our safety, this puts us all at risk. Similarly, a ship that is constructed with environmentally unfriendly materials will place a burden on the people that have to demolish it as well as on the environment when it is scrapped. So, a design goes far beyond the actual occupation and needs of the shipyard. Many more aspects need to be considered in design optimization.

With growing problems in shortage of materials and the required reduction in fossil energy consumption, the need to invest in proper sustainable ship design increases rapidly. However, with the increase in uncertainty about the future of shipping, companies are afraid to buy ships. Investing in the current technology, which is at the moment the cheapest option, might result in restrictions because of sustainability policies, which will diminish profit. Investing in newer technology that answers the sustainability targets, or will do so in the future, means spending more money with an extra commercial burden now, and no certainty that this will be beneficial in the future. As a result, shipping companies hold back on their orders for new ships. In turn, yards struggle in dealing with a reduction in orders.

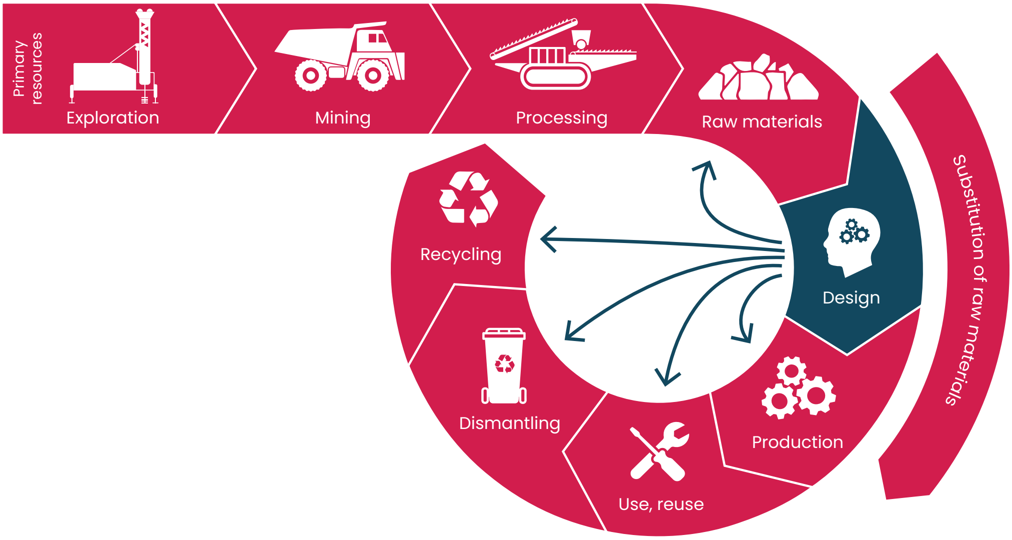

Figure 8: Influence of design on the impact of a vessel

Luckily some options combine current and future-proof technologies, and at the same time keep the risk for investors quite low. In these designs, the flexibility to swap to an alternative is incorporated. This means that flexibility is purposely incorporated into the design to be better prepared for variations in tasks or regulations. Although not yet available for the shipping sector, it would be an ideal solution for the issues that were identified. For instance, by allowing the adaptation to new fuels when that technology is fully developed. This requires a more extensive design phase, but will not be much more expensive, although requiring some more commitment from owners than before. As a large portion of the future success is determined by the choices from the pre-contract design, they will need to be willing to invest in this contract. The commitment is small, as a ship costs millions of dollars and switching to this approach will not raise the design costs far beyond the current 1% of the total vessel costs. In that way, shipping will be able to survive for only a few dollars more.

Robust ship design

An increase in the design effort will undoubtedly improve the performance of the vessel. However, it will not address the increase in uncertainty by itself. As described in the previous chapter, this uncertainty takes many forms. Initially, it could be the design anticipates another power system to be refitted halfway through the vessel's lifetime, with new pipes, new fuel tanks, a change to the cargo holds or a lengthening of the vessel to offset this, all with the uncertainty of not knowing which fuel it will be, or what regulations will apply. Furthermore, the energy transitions will open new markets, for example, less oil exploration and more windfarm maintenance, or transportation of new fuels.

The current design is point based, which means it is focused on generating a single design option and this option is optimized as much as possible. Therefore, the requirements are commonly captured in the contract and the design is therefore focused on achieving the contract specifications. Dealing with such uncertainty would require making a single design for each optional situation, and using that to compare and combine these designs. As was described in the previous chapter, merely considering fuels would lead to over a hundred options, and designing all of them would be a Sisyphean task. Thus, the current approach is not very open to flexibility.

Image 2: Shoes in a box, an example to explain modularity

Addressing the ugly side of shipping has led to increased legislation on emissions and sustainable material use. However, technical solutions are lagging behind and as a result, there are increased levels of uncertainty. To deal with this a different design approach is required. Modularity is a flexible (multi-objective) design approach that can deal with changing requirements, as opposed to point-based design, which is a fixed design approach dealing with fixed requirements. The US Navy already recognized this in the early 2000s when faced with replacing a number of coastal combat vessels where each type was designed for a specific task. They decided to replace all ships with one flexible platform able to deal with a variety of demands. Although not focused on uncertainty or new fuels, such an approach could be useful to deal with future fuel uncertainty. For the US Navy, the result was the littoral combat ship (LCS). This ship was meant to be a fast platform with no specific naval function. It could therefore be outfitted with various mission modules. This way fewer ships are needed to perform an array of functions in coastal waters that were formerly performed by a variety of ship types. Originally, the ship had mission modules for mine countermeasures, anti-submarine warfare and surface warfare. Later on, a new module was added to the list, focussing on amphibious assault. Like Lego blocks, clear connection interfaces and spacings were key to this success and the translation to modular engine rooms would be interesting.

Despite these positive aspects, the LCS was not a success. To explain this, consider a shoebox (like the one in Image 2). The shoes are the modules, and someone owns various types of shoes. Now the customer needs one box that will fit each pair of shoes as a platform. As a shoe is a module, it needs to be protected by its own individual box and can be combined with any other shoe. The resulting box will be much bigger than any current box and much more material is needed to stuff the box. This is exactly what happened with the LCS. The mission modules were heavier than the regular mission equipment as support was not integrated with the ship. More space was needed to accommodate them, and the ships had to become bigger to support all this extra volume and weight. These ships were much larger and more expensive than the single-mission vessels. This was expected and in itself not an issue, as fewer vessels would be needed. However, if your focus is on littoral waters, so close to the coasts and often even up a river, size does become an issue. Furthermore, these ships had the same armament as coastal ships as they were seen as coastal ships. Yet their size was more in line with that of a frigate, meaning they had become easier targets to hit and needed to be given more effective means to defend themselves.

There were many more issues with the LCS, but these best illustrate the design challenge. All in all, the result is that the first ships are currently being considered for retirement, after only seven years of service, whereas fifteen to twenty years is the normal life for a navy vessel.

The issue of the naval ship is inherent to any modular design approach, which means that vessels using modularity for their power systems, would become too big and too expensive to compete. Modularity is not always bad: it worked very well for a cargo system. In this case, cargo is swapped every trip and loading and unloading times are reduced, hence the success of the container.

So, both approaches, point-based design and modularity, are not well suited to deal with the uncertainty of the energy transition and the shift to sustainability. However, these form only two of the four possible areas of the matrix (see Figure 9). You could still consider a flexible design for fixed requirements and a fixed design for changing requirements. The first option is irrelevant as a flexible (multi-objective) design for fixed (single-objective) requirements is a waste of effort. The second one, however, is an approach called robust design. Within the robust design approach, you create one integrated solution that is able to perform competitively in multiple situations. Perhaps it is not the absolute best in all situations, but it is a relevant competitor and able to switch between situations or markets. For robust design, the need to change comes externally and is executed once only. If the change is reversible, the design is more flexible and could be seen as an adaptable design. Thus, both design approaches deal with changes in requirements explicitly. An adaptable design is one design, which is suited for multiple situations. A robust design is one design, which can be adapted more easily if the situation changes. The change is made once and is not reversible.

I am not yet aware of a well-known robust design. But, as explained, robust and adaptable share a similar focus, and adaptable is only different in that it changes its function more frequently, so I will use two examples of adaptable design to illustrate this flexibility. The ore-bulk-oil carrier (or OBO carrier) is my first example that shows the potential and the risk of such designs. As the name already indicates, this ship is able to carry both oil products, or liquid bulk cargo, and (iron) ore or other heavier dry bulk cargo. This concept was developed in the 1960s and was intended to reduce the number of empty sailings. Both ore carriers and oil tankers tend to sail back empty to the starting point, as there is no similar cargo for the journey back. Besides this commonality, the oil and dry bulk market are quite similar in nature, offering similar freight rates, fixed patterns, et cetera. Therefore, the fact that the vessel did not have to earn a full trip back with the cargo compensated easily for the higher initial investment. This made the OBO carrier a successful niche investment at that time. Even today they are still around, but not as many as in the earlier period. Higher maintenance at an older age was an issue in the end. Also, another side benefit, the different timing of cycle peaks and throughs in the dry and wet bulk market, has disappeared. The latter is most likely caused by the further globalisation of our societies. Nevertheless, the OBO carrier should be seen as a successful adaptable design example, although with a limited lifespan of twenty to thirty years.

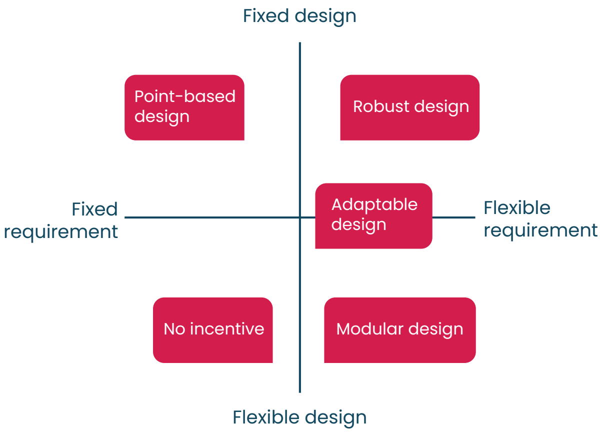

Figure 9: Design approaches based on results and accepted input

The second example is the all-purpose chemical tanker. This ship was designed to be able to carry all kinds of chemicals and oil products. Ships in this sector are usually smaller with a high number of holds to allow the transport of several smaller parcels of closely related chemicals. Chemicals are classified according to their hazardous nature and environmental impact in three IMO types. IMO type 1 is the most dangerous group, and IMO type 3 is the least dangerous group. Different types of measures and training of the crew are required for each type, with IMO type 1 having the strictest measures in place. This design was able to transport all types and included extra systems for cleaning to prevent contamination beyond the standards of its time. However, in this case, the three markets are significantly different markets, with different routes and especially different rates. This made the all-purpose carrier too expensive for the IMO type 2 and 3 cargo, leaving only the very limited market of the IMO type 1 cargo. However, this is a small and easily saturated market, leaving only occasional leftovers for the vessel. In short, the tanker was not a success and after the company went bankrupt, it was taken over for a low price and now operates in the IMO type 1 market with many systems needed for the other cargos switched off permanently.

The two examples demonstrate that adaptable design is a powerful concept to bring a steadier income to a ship owner, but only in the right circumstances. Thus, increasing design flexibility is not always a good solution. This will also hold for robust design. This solution could alleviate the pressure of uncertainty in the specific situation of the energy transition. A key element is that the situations or markets the ship is designed for, are to some extent similar and allow for the costs of extra flexibility. In light of the energy transition, a robust design would install a diesel engine and preparations for dual fuel, but also for a fuel cell and perhaps even other options, without already fixing the future energy carrier.

Since moments of changing are limited, I believe that the energy transition creates the right circumstances for robust design. Within 25 years from now, ships will need to reduce their emissions by 70-85%. The legislation seems to move beyond this and for other sectors, the aim has already been adjusted to 0% (GHG) emissions. Not only is the regulation changing, but at the moment there is not a single suitable alternative for the entire sector. This means a ship owner building a ship today, knows he or she will need to convert the vessel to a new fuel. Only the moment of conversion and the type of fuel is not known yet. So at some points in the ship's life, the requirements for the energy system will be changing. This may be at one single point, but could also be in multiple phases.

In need of a new vessel, the owners currently have two options. They can build a vessel like before and accept the high refit costs once the change is required. This is what almost all owners do. Or they can build a vessel that is already capable of running on a future fuel. This is what Maersk did when ordering a series of large methanol-driven container vessels (Maersk, 2021). However, the new fuels are much more expensive and therefore there is a chance the vessels will not get any work when customers are not willing to pay the premium. The benefit is that once a switch to another fuel is needed, this vessel has no conversion costs if the future fuel is indeed green methanol.

Now with robust design, there is a third option: a vessel that is designed to meet the standards of today but has already taken up key measures to support other fuels in the future. As the building costs are five to ten times lower than the refit costs for the same parts, crucial support is already installed, but the final equipment will be installed once the conversion is required. This way the costs of the vessel are almost the same, but the costs of conversion are much lower compared to the case where no preparation has been made. Some initial research has shown that the first option is profitable only when the conversion is done late in the lifetime of the vessel, while the second option is profitable only when the conversion is required early in its lifetime. The robust option showed slightly smaller profitability, but with indifference to the timing of the conversion. So robust design will be the ideal solution to allow ship owners to take up clean power and energy systems once the technology has advanced far enough to be implemented. At the same time, to do this, the dismantling potential is improved as well, as it is required to consider partial dismantling for the refits with new energy systems. Combined with the increased reuse of materials in Europe, this can help make proper dismantling (in Europe) even more attractive and thus also address the substandard dismantling facilities.

To be able to create such robust designs, the conventional method of design, where partial solutions are combined to come to a complete ship design, is not suitable. Due to the complexity of the required systems and the interaction between them, you need a method that can a) identify the links between systems to minimise the impact of changes, b) deal with multiple alternatives to find suitable ships for every potential future and c) is able to trace the fulfilment of requirements to allow the impact of possible changes in legislation. Systems engineering is such a method.

Systems engineering

During the Second World War, there was rapid growth in technology with a significant rise in the complexity of systems. Because systems engineering focuses on the effectiveness and economic result of systems, it was first recognized as a separate activity in this period. Before that, the principles of systems engineering were already applied in the design of complex systems, so in fact, it is much older (Kossiakoff et al, 2011).
Nowadays there are many tools available to assist an engineer in developing and designing systems, but the core principle remains the same: a design approach that takes the systems as the basis. This approach has the following characteristics:

- It studies the system from the outside. What happens inside the system is considered a black box. The focus is first on the interaction with other systems and the environment. Only when all these are identified, the box itself will be opened and studied in the same way. So, inside a system, you expect to find a more detailed set of systems to be studied in turn. These interactions are not limited to (technical) interfaces, but also include customer demands and capabilities of operating personnel, for instance.

- The focus is on the concept phase of the project, which is at the very start of the project. In this phase very little is known, especially when designing a new, innovative system. Therefore, the method accepts uncertainty and qualitative judgement as part of the process and helps with balancing this in the judgement and making of choices, by explicitly tracking this.
- It is interdisciplinary and bridges the more traditional engineering disciplines like electrical engineering and mechanical engineering. It studies the physical and functional interactions between the different system elements to ensure the systems chosen are mutually supportive and do not lead to conflicts.
- It is much more focussed on requirements, relations, traceability and achievement than other design approaches. Furthermore, it is far more structured in decision-making, so that in a later design stage, previous decisions and alternatives can be easily retrieved.

All in all, systems engineering provides designers of complex products with several advantages. It starts by setting the system as a whole and the success of its mission as a central objective, and this is key. All other steps or decisions are derived from this. This means that any other individual goal or attribute is subordinated to this primary goal. All further requirements are derived from this primary goal. Detail is increased along the way, and requirements of the complete system supersede those of subsystems. In that way, a complete, hierarchical set of requirements forms the basis of systems engineering. Any decision taken in the design process must be linked to any of the requirements.

Furthermore, as already mentioned, systems engineering is far more precise in keeping up with any changes, choices and decisions. So apart from the approach of hierarchical requirements, systems engineering is beneficial because of the traceability of decisions. This means that when a ship is designed with a certain power system, and further engineering of the chosen solution shows that the power module might for instance not meet the range requirement, the solution can quite easily be replaced by going to the point where the propulsion type was chosen without hampering choices before that. In light of the energy transition, a fork in the design could be created at this point, to accommodate multiple energy systems, and determine how to address their different detailed requirements within the overall design.

This process is often described in a V-diagram, such as the one in Figure 10. The process flow is from left to right and down the V the detail increases, while up the V the higher-level systems are validated. Although in the image this seems like a forward flow, the strength of systems engineering, which is the iteration between all steps, does not

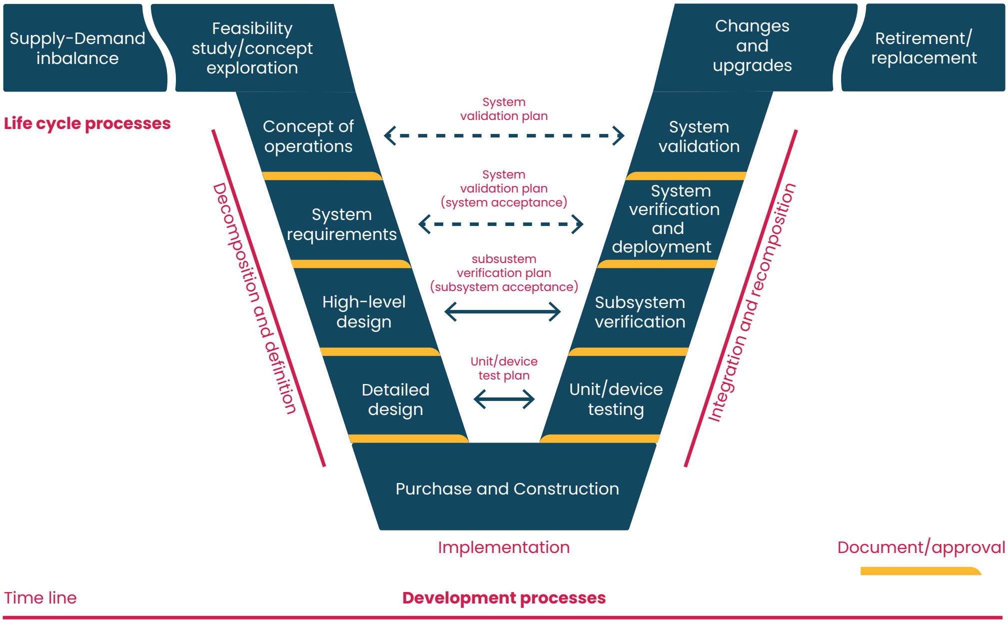

Figure 10: V-diagram for systems engineering (Inspired by the work of Kossiakof et al (2011))

become apparent in this image. So, if for example the system verification and deployment fail, several subsystems will be redone following the updated requirements and insights. Also, it is common to develop briefly multiple options in the concept selection phase to get a feeling for the impact of choices on the performance.

The method of system approach and the development of multiple alternatives in the first stage is why systems engineering aligns very well with a robust design. Systems engineering will minimise the interfaces with other subsystems and improve the potential to change between different systems later in the vessel's life. This approach is essential when it comes to preparing a design for multiple future fuels or reducing the impact it has when recycled. It enables designers to study more options without losing grip on the ship as a whole. Therefore, the development of systems engineering for maritime systems is necessary and the second part of my work as a professor at Rotterdam University of Applied Sciences (RUAS). It will be a key building stone to support the vision of robust design.

Based on the specifications of both systems engineering and robust ship design, the combination of both will lead to better ships that have the potential to meet all future sustainability requirements and still keep the design, construction and operations of the ship affordable. Exploring the actual benefits of the new approach and design goals is advisable. Especially as maintaining the path that is now common in shipping will in the end destroy both the environment and the maritime economy.

The road ahead

So, in theory, systems engineering is extremely useful to create robust designs. This is what the maritime sector needs, as the robust design approach helps to address sustainability in general and the energy transition specifically. Unfortunately, it is not that straightforward. Systems engineering is available for spaceships, aeroplanes, cars and software, but not yet for ships. In the other sectors, a large producer or client (like NASA) forced the use of systems engineering on all participants. This is lacking in shipbuilding, and the benefits are larger when all partners in the supply chain make use of it. At the moment, interest in the method is growing, which leads to a further need for this development (NAVAIS, n.d.).

Tools and methods in line with the systems engineering process will need to be developed for this. Also, robust design works in principle, but it is not known yet how to determine which elements to install during construction and which to do later. These are most likely influenced by vessel properties, but also by our knowledge of the new fuels and power systems. Furthermore, a change in legislation may impact these decisions as well. This means that research, both theoretical and practical, is required to develop and prepare the application of systems engineering for robust designs. To achieve this is to change the (Dutch) maritime sector.

The introduction of robust design and systems engineering is about innovation. Many bright minds have for a long time studied how innovation happens and more specifically how a sector will or will not be changed by innovation (Geels & Schot, 2007, Wieczorek & Hekkert, 2012). The maritime sector consists of shipyards and ship owners but also includes design and engineering offices, suppliers to yards and owners, classification societies, branch organisations like the Netherlands Maritime Technology (NMT) and the association of Dutch shipowners (*Koninklijke Vereniging van Nederlandse Reders*, KVNR), banks for financing, ports, and bunker suppliers, regulatory bodies and knowledge and education institutes like RUAS. Together they form a sector with many intertwined subsectors, like the offshore wind industry or the short-sea shipping sector. All the actors in the sector interact with each other, own or use infrastructures, and share habits and culture. For an innovation to succeed the involved actors and all their relations must align with the innovation. If this is not the case, there are barriers to innovation that need to be overcome. By studying this, researchers have identified seven types of barriers to innovation that can be present in a sector:

1. Economics. This is generally the lack of a profitable business case. This could occur for a wide variety of reasons. Banks are unwilling to finance, markets are too small, competition with established alternatives, et cetera.
2. Knowledge. For innovations to become successful, the creation and dissemination of knowledge are crucial. Especially the latter is often lacking as this is very difficult. For example, many companies sit on a patent but are not applying it, halting possible innovations.
3. Standards and regulations. These can support innovation through subsidies or taxes, for example. However, often they may be completely missing, as is the case for safety legislation for new fuels. This basically forbids ship owners from installing such systems on board, or at least they risk not being able to acquire insurance.
4. Interaction. You cannot do innovation by yourself. You need to convince stakeholders of the value of your innovation.
5. Directionality. Any form of uncertainty can kill innovation. A clear vision is required and needs to be supported to allow for innovation to happen. As described earlier, biofuels might be a part of the energy solution, but it is very uncertain if their source materials will continue to be allowed, and this is holding back investments for scaling up and improving production.
6. Technology. Innovation is almost always thought of as technology. Without a working technology, there is no innovation.
7. Infrastructure. Trains require rails and cars require roads. The first train required setting up a new infrastructure. The belief in this innovation was so big that this was created. Still, if I were to design a new train requiring, for example, a monorail, the question is if the benefits would outweigh the costs of the required infrastructure. For a significant speed increase (for instance bullet trains or TGVs), new tracks were laid, but only for a limited number of destinations.

As described, the current status of the maritime sector is one where solutions are frantically being sought, but the commitment to solutions is lacking for fear of making the wrong commitment. Quite frankly the sector is in a light state of panic, which is however good news for innovation. In this state, all actors in the sector have more interactions, are better aligned and share more knowledge with each other. As the governing instances are also aware of this, standards and regulations, like subsidies and exemptions for technologies, are more easily achieved. As a result, a lot of research is being done and many companies have started offering technical solutions. Hence five out of the seven barriers are lower than before. The other two, infrastructure and directionality are at this moment the key barriers to address. Robust design and systems engineering make the design indifferent to the impact of these barriers, by allowing the directionality and infrastructure to be realised at a later date. It is one of the few innovations able to address these crucial barriers, and thus support a transition to a more sustainable maritime sector as a whole.

As the first goals in reducing GHG emissions of ships are set for 2030, it is crucial to make haste. That is why I will focus during my professorship at RUAS on developing systems engineering for maritime, and bringing that to education, not only at RUAS but to all higher maritime educational institutes in the Netherlands. I will also work on and validate the concept of robust design linking academia and practical research together in a reinforcing feedback circle, where developed concepts are applied and the feedback and insights from practice support the improvement of the concepts. Finally, to understand the potential, it is important to keep track of promising innovations for the maritime sector and identify gaps that require more research to establish their potential. I will make these ambitions more concrete in the next chapter.

4

The magnificent 7

Despite the good news on the barriers, I would never claim to be able to change the sector on my own. Ideas need to resonate within a sector with many actors and especially individuals before innovation can take place. I believe that RUAS as a part of this intricate sector can play an important role in achieving these (grand) ambitions.

The seven of RUAS

Although RUAS is not directly part of the value chain for the maritime sector, for the energy transition it is actually one of the key actors. The title of this chapter not only refers to a small group of above-average cowboys that come together to fight the bad, but it also refers to seven factors that are present at RUAS and will allow RUAS to support the proposed change in the design approach and method for the maritime sector. These seven factors are: the students, lecturers, researchers, regional networks, research networks, facilities, and culture. Together these seven can be a source of inspiration, provide directionality, and over time achieve the innovation of the design approach set out in the previous chapter to achieve a sustainable maritime sector.

1. The **students**. They literally are the future. Knowledge gained in education is their weapon. Once they leave the university, they will start their careers in the sector, providing a sought-after workforce that is ahead of the curve, if they are taught the right content. I have worked primarily with students of Rotterdam Mainport Institute (RMI) but will extend this to related fields at the School of Engineering and Applied Science (EAS) and School of Built Environment (SBI), especially those of international logistics.
2. The **lecturers**. They are just as important. They are the linking pin between research and education. By contributing to and partaking in research, they will be able to create the lecture material to address the future needs of the sector. Without that, you are teaching 19th-century physics with a 20th-century mindset, not enabling them to tackle 21st-century issues. In this case, I have started some projects and look forward to working with lecturers from the same faculties as the students (RMI, EAS and SBI).
3. The **researchers**. Although doing research with lecturers is important and a cornerstone of RUAS, sometimes you need dedicated researchers working on complex problems, to allow us to grasp the concept, advance our knowledge, and then bring it to education. Since her arrival, researcher Hongyu Yang has provided support to Martine van den Boomen and me for condition-based monitoring and other data analysis aspects that are relevant to the sustainability of our sectors.

4. The **regional network**. There is a complex and intricate network linking maritime sector companies in the region to RUAS and its students, lecturers, and researchers in a two-way relationship. The companies provide students with practical issues, and the knowledge of students, lecturers and researchers finds its way into the companies. In my case work has already started with InnovationQuarter and with *Kwartiermakers Maassluis* on projects in the area, but the Port of Rotterdam, the NMT and KVNR are also linked to work and projects for my research. Of course, many shipping companies and shipyards are part of this network as well.
5. The **research network** of higher vocational institutes and universities related to the maritime sector. Through close cooperation within this network, the complex challenges of our society can be addressed by alternating the theoretical to the practical axis, as well as the aspects of the sector (e.g., chain level versus single ship, or inland versus short sea). The themes of my work are in line with the research of van Duijn (funded by the program *Stimuleren van Praktijkgerichte Onderzoeks-groepen,* the SPRONG), but also with the work of Thierry Verduijn, Marcel den Hollander and Gijsbert Korevaar. Furthermore, on a more conceptual level, the work of Martine van den Boomen has many overlaps with my own research focus, as was already indicated above. My work at TU Delft is also related to this research and is strongly linked to my network within my department of Maritime and Transport Technology, but also on an interfaculty level with Ports and Management, Ecology and Logistics.
6. The **facilities**. None of this research would be possible without the proper facilities. In order to develop research and especially practice-focussed research, it is crucial to have or be able to attract future-focused facilities. Trying out and learning from experience is key in this approach, and without the options to do this, no progress can be made. Although creating a new design approach will primarily require desktop research, for several innovations I am looking forward to working with the facilities of RUAS. I will elaborate on this further below.
7. The **culture**. Where universities seem to excel at a competitive approach to research and results with some distant future application, the practical research approach is one of cooperation and ambition to contribute to the current needs of society. What both cultures share is being driven by curiosity. How does it work, why does it work, and can it be improved? I can only be grateful for the interest and openness of those I have worked with so far.

Although all seven factors are present, I would like to highlight one recent development that will strengthen many of these factors. This is the start of the Prof essional Doctorate (PD) pilot in January of this year, in which maritime studies are represented as one of only four fields. The PD is a professional who tackles a complex practical problem from his or her work environment, while simultaneously being supported to develop his research skills. Unlike a PhD, where the development of theory comes first, a PD will select, combine and apply theory to a practical situation to learn about the limits of that theory and to structure his or her innovations. This is of course a great opportunity to test the ideas and concepts of robust design, strengthen research capacity, and bring research ideas into the company at a point much closer to their application. With that also our practice and research networks are improved. At the moment of writing, the first PD has not yet been selected, but it will definitely align with my research, applying concepts of systems engineering or robust design in practice and thus delivering new insights and input for research.

I believe our magnificent 7 will assist greatly in the struggle for a sustainable maritime sector. Their combined strength is that they can influence the sector in a continuously expanding circle. Where over time former students will become the initiators of new projects at RUAS, and innovation will be supported both bottom-up and top-down. It is along these lines that my research projects will create an impact in my professorship. Therefore, I will focus on three related research themes to achieve the vision of the previous chapter: systems engineering for robust ship design, robust design to achieve a sustainable future readiness for ships and innovative technologies for a sustainable maritime sector. I will elaborate on each of these in a subsection below.

Systems engineering for ship design

As identified above systems engineering for ship design is still not available. Besides being a fundament of robust design, the increased focus on defining the right requirements and linking design decisions to them is beneficial to all design efforts. Especially when considering the new types of powertrains, a ship cannot be designed using existing alternatives but needs to be developed from the inside out, striking a new balance between systems. Of course, you can continue to reuse many of our existing tools, but others will need to be reinvented to work in the new situation. Systems engineering supports this better than any other method.

Through a combination of short- and long-term research, a sound foundation for systems engineering has been created. At this moment, the focus of this research should shift to the application, as the devil is always in the detail. In the next five years, experience is gained with these systems and approaches. This includes the development of new tools and processes to support them, tailoring them to the maritime sector and its unique aspects. For the structured application of systems engineering in ship design, I will align and bring together education, and practical research with industry and scientific research, thus bringing the holistic view and ideas to a broadly applicable and accepted set of tools and procedures.

As part of a consortium of European partners made up of software providers, design offices, shipyards and research institutes, are working on this. The focus is on an open-source system available to the entire industry. This includes the development of open-source education modules. Ahead of these activities, I have started up the discussion between practice and almost all of the maritime-related educational institutes (RUAS, NHL Stenden University of Applied Sciences, HZ University of Applied Sciences and TU Delft) on the options and approaches to bring students in contact with systems engineering.

Through this research, the lecturers and researchers I work with will first develop a holistic view of systems engineering. Once this is sufficiently developed, they can implement aspects of that knowledge into their teaching. Even more students will be reached and also these students will join companies, so the knowledge will enter the sector from the top through research, and from the bottom through the new employees.

Robust design to achieve a sustainable future readiness

As explained in the previous chapters, systems engineering lays an important basis for the use of robust design. As stated before, a robust design method will allow the maritime sector to better include future uncertainty in the design of the vessel today. Robust design is an approach in development, and a plethora of techniques have been identified to deal with uncertainty, but actual insight into system variation and impact on the design is currently lacking. To fill this gap, I will conduct practical research alongside the more scientific development of theories and methods. Creating insight into when robust choices are beneficial for the design of future-ready ships.

In the PATH2Zero project, the possible routes for the inland shipping sector to become emission neutral by 2050 are investigated. This is a large project with over thirty partners from industry, policymakers and academia. All kinds of stakeholders in inland shipping, like local governments and ports, ship owners, charterers and research institutes are part of the consortium. The project is funded by the Dutch Science Counsel *(Nederlandse Organisatie voor Wetenschappelijk Onderzoek, NWO)*. It covers all aspects from policy, via transportation networks and routes all the way down to the vessel and power plants. Although I believe our research will be important for the discussions on a feasible approach to a zero-emission inland shipping sector, the actual power of the project is bringing all these parties together and encouraging them to discuss their goals, fears and reservations. The project will be able to support these discussions with data-driven insights from our models and studies. The work will be open source as much as possible, which I think is a great achievement, as it opens up our research to others outside the project, and invites them to contribute as well, further strengthening the initial community.

My focus within this project will be on the robust design of inland ships, but the project offers all other aspects and insights identified to enable the development of a robust design. Besides defining my research for the coming five years it will also function as a framework to link other smaller projects and studies through open collaboration, which is a key aspect of this project. That is why I am very happy with this project.

The robust design knowledge can also be used to identify potential paths for existing vessels to achieve lower emissions. A special group, in this case, are the heritage vessels, like the historic tugboats located in Maassluis, or the flatbottom sailing ships, known in Dutch as the *Bruine vloot*. Where classic cars are seldom used, these vessels have often gained a new function as passenger tour boats instead of cargo ships. As a result, they sail more often and also in densely populated areas. This increases the impact they have on the environment. In this situation, the goal is not only to reduce emissions but also to maintain the historic value of the vessels. This means that, for instance, an extension of the hull is not possible if more space is required. Also, both the original function and the current function will need to be maintained. On top of that, there is a heritage of systems and partial conversions and updates on board, making every case unique. A start was made with the support of their conversion to lower emissions and achievement of the sustainability goals, by having students look at the technical, economic and policy sides of the work. However, involving students of vocational colleges at a later stage is also considered. This would allow them to become familiar with the alternative technologies for ships, and work on these vessels under the supervision of experienced yards and contractors.

Innovative technologies for a sustainable maritime sector

As stated earlier, with the current technologies used in shipping, we can only achieve a further reduction of the impact of a maximum of 30-40% per ship. Innovations are required to go beyond this. For the powertrain over a hundred innovations are investigated, tested and even already implemented, as discussed in the 'The missing' chapter. The efforts of the maritime sector should therefore be focused on the assessment and validation of the value of these innovations for particular ship types. Within my research, I will follow the developments and, where practical, contribute to the knowledge, like for instance with the Ab Initio training ship and its new propulsion systems. I see this work as being closely linked with robust ship design research, as it provides crucial knowledge on new systems reducing uncertainty.

At this moment less innovation and research occur for the resources and materials pillar of sustainability. However, I believe there is potential for sustainability here as well. One such technology is the 3D printing of metals. 3D printing, or additive manufacturing as it is officially called, has been around since the 1980s but has taken a big leap in the early 2000s. Printers for plastic have become better and cheaper, making mass customisation of products possible. As a result of this, research is also being done on the development of fibre-reinforced plastics printing, concrete printing, steel printing, et cetera. For the maritime sector, steel printing is the most relevant. It could be used to print spare parts or complex parts that are currently cast. In the past a propellor for a vessel has already been printed, but, although successful, it was not yet commercially viable to continue along this line. One issue is that the 3D printing of metals is basically creating a shape by continuously welding material together. Welds tend to have a round form and the resulting shape looks like a very long series of speedbumps (see Image 3). To get a smooth result the excess material needs to be removed. This is an issue as this means more material and more time are needed to produce the original shape, followed by a removal phase.

Over time, new methods for metal printing have been developed. Recently the potential of such techniques for the maritime sector has been investigated. To see whether a potential for further research as well. This investigation was performed with lecturers from RMI, the NMT (representing shipbuilders and equipment manufacturers), TU Delft, Layertec (offering the new technology), and Heerema (among others, offering experience with 3D printing). Many more companies in the sector have shown an interest in the technology. Together with TU Delft, RUAS is also working on setting up a national additive manufacturing cooperation to align this research with different fields. I expect that despite some initial technical and legal hurdles, there is potential for additive manufacturing to decrease the footprint of the vessel further while reducing transportation costs and material use, and supporting recycling and deconstruction.

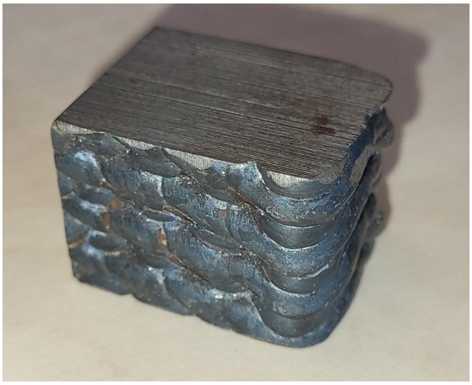

Image 3: Example of a section of a 3D printed metal part (Photo by the author)

These are all aspects where the development is advanced enough for practical research applications, such as creating insights into the estimation of material quality and the integration into the production process.

Of course, 3D printing is not the only innovation to investigate. At RUAS, many more options are being investigated, such as hydrogen, batteries and catalysers for ships instead of cars. Sometimes I only follow them, and sometimes I consult or discuss opportunities with the people doing the research. Although I have spent time at RDM-campus and RMI, there is much of RUAS I still have to discover. New insights, connections and opportunities will arise, as no one can predict the future. I can only say that I look forward very much to continuing the work I have started with those involved and look forward to getting acquainted and working with those whom I do not yet know, but who have been inspired by this story.

THE END

5

Credits

PUBLICATION

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SUPPORTING CAST

The support group	Department MTT
Inspirators	My PhDs @ TU Delft

SPECIAL THANKS

My Lead Support	Anja Pruijn
Set Builder	Thomas Pruijn
Misc. Stunt Performer	Sebastian pruijn

6

About the Lector

Dr.ir. Jeroen F.J. Pruijn is a professor of Maritime Innovation at *Kenniscentrum Duurzame Havenstad* at RUAS. He is also an associate professor in Maritime Operations and Management at the TU Delft. Besides combining his research at both institutes, he's also very active in education. As director of the Maritim Bachelor study at the TU Delft, he is currently revising the curriculum of the bachelor, to improve coherence, knowledge retention and study success. He is perhaps best known, at least by his former students, for his Maritime Business Game. This is a course he laid the foundations for in his first year at university, and he has continued to develop to the current version released at the end of 2022. In this game, students play a ship owner and learn about the link between technology and economics and how variations in technology can open or close aspects of a market.

He has worked exclusively for TU Delft since he graduated there (Master Marine Technology) in December 2003. In the past nineteen years, he has only been away for a round-the-world trip of a year in 2005-2006. Upon his return, he started his PhD on a part-time basis, while continuing to be involved in education and other research projects. He completed his PhD seven years later in 2013, at which time he had already started as an assistant professor on Maritime Operations and Management. He continued to work in that role till September 2021, when he started as a professor for RUAS and became an associate professor.

At the start of his career, his research was primarily focused on ship production, but with his PhD, this shifted to involve shipping management more and more. With his first PhD (2006-2010), focusing on ship recycling, he started to become more and more interested in sustainability. As a result, he is now applying his knowledge of ship production operations and recycling to improve the design approach of vessels, looking to incorporate future uncertainty in the design and create benefits for all phases of the vessel's life.

Through his work in academia, he has published extensively in conferences and journals, but also less scientific outlets, such as interviews in magazines and even a page on the site of NEMO Science Museum in Amsterdam, or a podcast for Marsh both about the Northern Sea Route.

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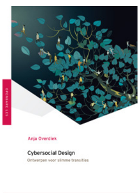

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Jeroen Pruijn

No ocean for old ships

Robust design for a sustainable future of shipping

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Ships are a crucial link in any production supply chain and provide up to 90% of all transport. However, ships are also a major contributor to GHG emissions, local emissions and contain many hazardous materials. To change this, we need to consider the full lifespan of the vessel, including its dismantling and the proper reuse of the materials used during construction.

Legislation and policy are forcing us to reduce the negative impact of ships at a rapid pace. Technologies to support this are promising, but not yet fully developed. Furthermore, insight and data are lacking for determining the exact positive impact of a solution. As a result, there is much uncertainty about the future of vessels, and ship owners are looking for ways to deal with the future during the design phase of vessels, without losing their competitive edge today.

To address this, Jeroen Pruijn, professor in Maritime Innovation of *Kenniscentrum Duurzame Havenstad* at the Rotterdam University of Applied Science, focuses on the development of a robust design approach for ships that are based on systems engineering. This will allow us to create future-ready ships with good performance both in the future and today, as well as investigate potential solutions.

praktijkgericht **onderzoek**

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