Inner city cargo vessels

A decision support tool for the development of new zero emission inner city cargo vessels

Jorrit van Reeuwijk
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By

Jorrit van Reeuwijk

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Company supervisors
Daily supervisor: D. Moolenburgh
E-mail: Daniel@enviu.org
Supervisor: T. van Vrijaldenhoven
E-mail: Tim@enviu.org

Thesis exam committee
Chair/Responsible Professor: Dr.ir. J.F.J. Pruijn
Staff Member: Dr.ir. E.B.H.J. van Hassel
Company Member: D. Moolenburgh

Author Details
Study number: 4346718
Author contact e-mail: jorritvanreeuwijk@gmail.com

Preface

Growing up in Friesland I have always been surrounded by water. It started off by playing with little boats on the lakes and later by sailing at sea. A study Marine technology was no surprise for everybody around me. Finishing this study has always been a dream of me and this report is the final step in fulfilling this dream.

Fulfilling this dream would not have been possible without the help of friends, family and my supervisors. I would like to pay my gratitude to Enviu for giving me the opportunity to preform my master thesis with them. Specially to my supervisors T. van Vrijaldenhoven during the initial phase of the project and D. Moolenburg during the thesis itself. Your assistance and knowledge have helped me develop a better understanding of the concept.

I want to thank Dr.ir. J.F.J. Pruijn for being the chair of my thesis exam committee and for taking the time to read my report and giving useful suggestions. Also, I would like to thank my daily supervisor Dr.ir. E.B.H.J. van Hassel for all the support you have given me during this project.

A special thanks to my family and girlfriend for listening to everything I had to say about the project and for their support. I look forward to the developments in the Portago project and hope to see the vessels sailing on the canals of Amsterdam in the near future.

Jorrit van Reeuwijk
Arum, March 30th 2022

Summary

Trucks delivering goods in city centres have many negative impacts for society like emissions, crashes, noise and vibrations [52]. Especially in places where there is a vulnerable road network, big trucks can lead to big damages. The bridge and canal walls in the city of Amsterdam are in a bad state. Because of this, trucks with a weight of more than 7.5 tons are only allowed when they have a special exemption [35]. This makes it very hard for companies to operate with bigger trucks and creates the need for a so-called different last mile solution. Combining this with the fact that Amsterdam has the ambition to reduce the CO_2 emission generated in the city by 55% before 2030 compared to 1990 [37]. This represents possibilities for new ways of cargo transportation.

Because there are more and more limitations for road-based transportation in the form of size, weight and emission regulations the water is presented as an alternative. A new possible way of transporting goods to the city centre can be by boat. This new concept is researched further in the report. Because this new concept has a lot of unknowns, the report aims to generate insight by answering the following main research question:

What are the critical aspects for the design concept of a water based inner city transport vessel in the city of Amsterdam to be competitive as a last-mile solution?

With the rich history of trade over water in Amsterdam the canal system presents the possibility to supply a lot of potential customers with their goods. The last mile transportation of goods can be done easily by inner city transport vessels via the already in place canal system. The advantage of the concept is that the vessel makes use of city logistics where goods are sorted at hubs on the outskirts of the city from where different last mile solutions deliver the cargo to the end-customers. The goods will be transported in standard size rollable containers.

To generate more insight in the concept a decision support tool is made. This tool uses different logistical, cost and design related parameters to calculate the cost price per container carried from hub to city centre. By using the tool, a lot of different considerations are tested which resulted in several sensitivity analyses. The results of these analyses are used as general rules of thumb for the future development in these new zero emission inner city cargo vessel. These analyses also highlight the critical design aspects that have the biggest influence on the overall costs and thus the cost price per container.

Based on the original design concept and the knowledge generated from the decision support tool and sensitivity analyses a new improved design is presented. This design is bigger than the original concepts and reduced the cost price per container to only 37% of the original calculated cost price per container.

Contents

1 Introduction

It is expected that the number of residents in the cities will grow in the future. Especially in the medium and large cities this growth of residents in 2035 can be more than 10 percent compared to 2018 [10]. All these new residents will generate a bigger stream of goods that need to be transported to the city centres where there is already limited space available. To reduce congestions on the road new possibilities for goods transport are evaluated. In cities like Amsterdam where there is a lot of water available, it feels like a logical choice to research the possibility of using the water for the transportation of goods in inner cities. Moving the goods transport from the road to the water will reduce the risk for accidents and reduce congestions. Especially in cities like Amsterdam where there are a lot more rules and regulations for trucks in the city centres, it is necessary to look at alternatives. When moving to the water this gives the opportunity for more environmentally friendly solutions because they are less restricted in size.

This research will be carried out in collaboration with Enviu, Rotterdam. Enviu is a social venture building studio, building companies to solve social and sustainability issues in society. For this research the company wants to investigate the possibility of using vessels for the transportation of goods in city centres. The project is called Portago and is part of the THRUST program, which stands for: Towards Hydrogen-based Renewables Used for Ship Transportation. THRUST's goal is a zero-footprint maritime sector. This creates an opportunity overlap with the challenges city distribution faces, and the goal that cities like Amsterdam must reduce their harmful emissions. Therefore, Portago aims to use highly efficient zero emission vessels. To fit within the program, these vessels need to be emission free, which also fits with the ambition of Amsterdam to reduce its CO_2 emissions in 2030 with 55% compared to 1990 [36]. The development of new last mile solutions within the European city centres gives new possibilities to improve the quality of live within these cities.

This report starts with a problem statement in which the objective, research questions and scope are given. The next chapter investigates city logistics and the different last mile solutions that are currently used. The fourth chapter investigates whether there is a possibility for the use of vessels on the water as a last mile solution. Therefore, an exploration is done from a technological and economic standpoint. This is extended in chapter five where the link is made to the city investigated in this research, namely Amsterdam. After looking into Amsterdam, the different customers located in the city centre are investigated including the goods that are transported to and from them.

After the research on the logistical aspects and background a decision support tool is made. The tool includes all design aspects of a vessel capable of sailing on the canals and all the logistical aspects relevant for the calculation of the costs for the concept. By implementing the initial design as proposed by Enviu the cost is calculated. Afterwards the decision support tool is used to alter the design resulting is a cheaper solution. This is done by making a sensitivity analysis for several design and logistical aspect from which general rules of thumb followed. By combining these insights, a new design in proposed that can be used by Enviu for future studies.

2 Problem statement

In this chapter the main purpose is to introduce the research topic and the objective of the research. At first, the issue for the current transportation system in cities is explained and the possibility to use the water for transportation. The gap regarding the design of specific transportation vessels will be described in section 2.1. Thereafter, the objectives of this research will be described in section 2.2. In section 2.3 the main question and sub questions are discussed. At last, the scope of the research is defined in section 2.4.

2.1. Problem description

With Amsterdam expected to have more than 1 million residents in 2035 compared to the 870.000 residents today, the demand for logistical transport will grow [10]. Combining this with the increase of people movements will result in bigger congestions than we know today. Solving this issue will require a better use of the available space or less road users. By implementing the so-called city logistics, the aim is to reduce the hindrance created by transport. While this will result in a more efficient way of transporting goods the congestion associated with the loading and unload of various transporters will stay. Reducing the number of road users can be done by using the current road users more efficient or by moving them away from the road.

Trucks delivering goods in city centres have many negative impacts for society like emissions, crashes, noise and vibrations [52]. Especially in places where there is a vulnerable road network, big trucks can lead to big damages. The bridge and canal walls in the city of Amsterdam are in a bad state. Because of this, trucks with a weight of more than 7.5 tons are only allowed when they have a special exemption [35]. This makes it very hard for companies to operate with bigger trucks and creates the need for a so-called different last mile solution.

Amsterdam has the ambition to reduce the CO_2 emission generated in the city by 55% before 2030 compared to 1990. This is done partly by limiting the emissions produced by trucks and cars. In 2025 only commercial vehicles that don’t emit any harmful emissions will be allowed within the A10 ring road of Amsterdam [37].

The canals in Amsterdam have been used for transport in the past. Because the improved road network, the need for this water-based transport disappeared. But with the new proposed transport hubs, new last mile solutions are investigated. These transport hubs are located outside of the city centres and distribute the goods that come in. Here the goods come in with various ways of transport like by road, rail or water. The so-called last mile distribution can be done by smaller vehicles over both the road and the water and will reduce the number of individual suppliers entering the city centre.

A main benefit of using the water as a last mile solution is that it opens the space on the road. Especially with an increased number of last mile solutions, the number of road users will rise. By making use of the already in place canal system, the activities on the road will reduce resulting in a saver environment. The downside is that these canals are sometimes located further away from the customers than the road network.

In order to develop vessels that fit within the new logistical concept, a new design needs to be made. Because these vessels are very specific, it is helpful to develop a decision support tool that aids in the designing process. This model can give different designs based on the design criteria and will be able to calculate the costs for the different solutions. The design considerations and cost can then be used by Enviu to support business plans in the future.

2.2. Research objective

The main goal of this research is to generate insight in the possibility of using vessels for the transportation of goods in city centres. This is done by developing a decision support tool that aids in the development of new inner city cargo vessels that are competitive as a last-mile solution. The tool will be used to give insight in the connection between different logistics, design and cost decisions. By expressing both logistical decisions and design decisions in terms of costs it is possible to compare several different designs and business structures. This knowledge will help with the development of the first transportation vessels and is used to proof whether there is a possibility of using the canals in Amsterdam for the transportation of goods in the future.

2.3. Research questions

Based on the research objective from section 2.2. the main research question is formulated:

What are the critical aspects for the design concept of a water based inner city transport vessel in the city of Amsterdam to be competitive as a last-mile solution?

In order to be able to answer the main research question, the following sub questions need to be answered:

1. How is city logistics evolving and what are current last mile solutions?

2. How can the water system be used to create a new last mile solution for transportation goods in cities?

3. What types of limitations can vessels within Amsterdam encounter?

4. Which types of cargo are carried in Amsterdam and can be transported over water?

5. How can a decision support tool be supportive to generate a concept design for a vessel as a last mile solution in the inner city of Amsterdam?

These sub questions will help to guide the research. The different chapters of the research will answer the sub questions one by one.

2.4. Scope of the research

The focus during the thesis will be on one city namely the city of Amsterdam. The developed tool can later be adapted to suit other cities but that is not part of this research. The model will give different emission free solutions. Not only hydrogen but also solutions such as purely electric will be included. The model needs to be able to help in the decision process between the different solutions by displaying their impact on the costs. With this data it becomes possible to give conclusions for different feasible and cost-effective propulsion methods.

The design will include the main dimensions based on the limitations for a given logistical concept. These main dimensions will at least include length, width, depth and weight. Other dimensions included are cargo hold dimensions and payload, freeboard and propulsion and power size.

A case study will be used based on the first insights generated by Enviu. After implementing the case study in the model, a sensitivity analysis will be done on the size of the vessel by changing the number of containers transported. Based on these analyses an additional design is formulated from where a more detailed sensitivity analyses follows to acquire general rules of thumb for the design of inner-city cargo vessels. Each of them investigates a different relationship between different design considerations like speed, distances, costs etc. The focus is on goods transported towards the city centre but return flows will be added as an indication of added income in the future. Based on the sensitivity analysis a new design will be proposed that is compared with the current road-based system.

2.5. Methodology

This study will be researched from the perspective of the maritime engineering field. The thesis is divided in three parts: the explorative research, the development of a model, and the rules of thumbs. These parts are the basis for the structure of the report. The parts are arranged in order so that each part provides information for the next part. The multiple parts together will answer the main research question.

The explorative research

The research thesis starts with a problem analysis of transporting cargo in the cities. The process of city logistics is analysed in order to check how the water could play a role in this process. Following the outline of water-based city logistics the possibility of implementing this in the city of Amsterdam is checked. This is done by determining the possibility of using the water for the transportation of cargo in Amsterdam the types of cargo that would be suitable for this mode of transport is analysed.

The development of a model

To test different design options a decision support tool is made which includes a model of the vessel and a cost calculation. This model includes all the main design parameters required to establish the performance of the vessel. The logistical system will be simplified before implementing the main contributing factors. This information will then be combined with a cost analysis resulting in a method to compare different designs and logistical systems.

The rules of thumb

By comparing the results from a case study on a cost basis, general rules of thumb for the development of inner-city cargo vessels are acquired. These will include logistical and design related recommendations. The thesis concludes with an improved starting point following the case study which will function as a starting point for future development of the concept.

3 City logistics

This chapter will start with a definition of city logistics. The implementation of city logistics results in different last mile solutions – the logistical transport of goods from a hub on the outskirts of the city to the city centre. These different last mile solutions will be described in paragraph 3.2 and are ways to transport the goods from hubs where the goods are collected and sorted to the end-users within the city centre. The chapter will end with a small conclusion.

3.1. Definition of city logistics

City logistics is a development in the transportation of goods in cities. A more traditional way is to transport the goods from supplier to the end customer directly. Here lots of transporters enter the city centre for their deliveries. The deliveries are grouped by the nature of the supplier. So, all deliveries from one supplier are grouped before delivery. With city logistics the deliveries can be grouped different. For example, based on the end-customer location, by grouping all deliveries for one street before delivery by one vehicle.

City logistics is described by Taniguchi as: “the process for totally optimizing the logistics and transport activities by private companies with the support of advanced information systems in urban areas considering the traffic environment, its congestion, safety and energy savings within the framework of a market economy” [53]. Without compromising the other activities in the city centre, city logistics aims to reduce the impact of freight transportations in ways like less congestion, less pollution and increased mobility [13].

The city logistics system works with various hubs; in literature the hubs are also called city distribution centres (hereafter called: CDC’s). At these hubs various long haul transportation vehicles dock to unload their cargo. The goods are sorted and distributed over different smaller vehicles that deliver them to the final customers [13]. This system is especially useful in cities where the hubs are located close to the end-customers. Cities with a large distance from the hub to the various delivery locations, the transport time from and to the hub forms a limiting factor. In these places a Two-tier system has been proposed [14]. The Two-tier system makes use of so-called satellite platforms. These small locations are located inside of the city centre and are used to transfer and consolidate the goods from bigger to smaller vehicles. This differs from the hubs that also facilitate storage of goods. The smaller vehicles are than used for the denser areas. By using satellite platforms, the overall total road use is even further reduced. Figure 1 shows a Two-tier system. Here the goods from the different suppliers are collected at the CDC from where they are distributed towards three different satellite locations. These satellite locations form the starting point from where different city freighters or last mile solutions are used to distribute the goods over the end-customers.

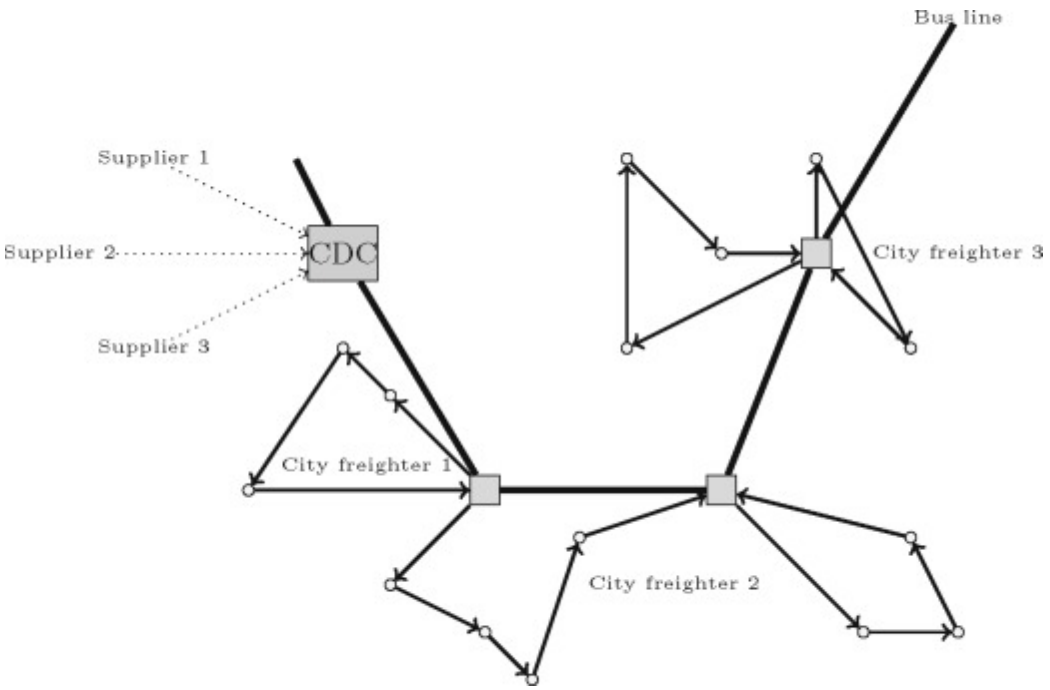


Figure 1. Two-tiered distribution system. [41]

3.2. Different last-mile solution transporters

Several different transporters can perform the transportation of goods. Examples are trucks and small vans but nowadays there are also more examples of different last mile solutions. These solutions all developed because of a need for smaller or more environmental vehicles. Examples are electric trucks, bikes and light electric vehicles (hereafter called: LEV's). Where these solutions reduce emissions, they still make use of the limited road space.

For heavier or more voluminous deliveries often trucks are used. These trucks have many negative impacts when operating in urban areas like congestion, emissions, crashes, noise and vibrations [52]. Figure 2 shows the emission impact of these trucks in the city centre of Amsterdam. It shows that this category cause 29% of the total nitrogen oxide (NO_x) and 13% of the total particulate matter emission in Amsterdam [38].

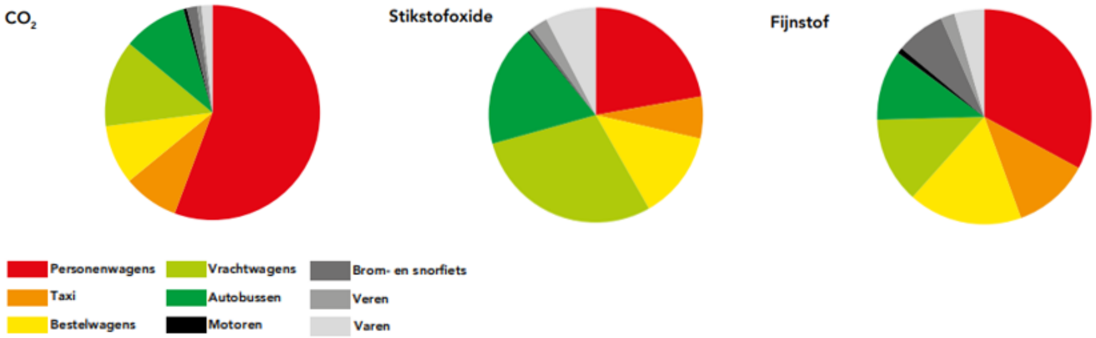


Figure 2. Emissions by sector in Amsterdam – the Netherlands. [38]

While making the trucks more environmentally friendly for example by using electric trucks, which reduces the emissions and the noise, this will not reduce the crashes, nuisance and vibrations. Especially in places such as the centre of Amsterdam these vibrations can cause a lot of damage on the roads, bridges and canal walls.

Smaller deliveries ask for smaller solutions. A method that is often used is making use of two wheeled vehicles like (electric) bikes or (electric) scooters. They are already very common for the delivery of meals within cities. Recently there are also other vehicles developed like the previously mentioned LEV's. These LEV's range from electrically power bikes to small golf cart sized electrically powered vans. An example is the LEV's used by Picnic for the delivery of groceries in densely populated places. LEVs are in general mostly used for smaller, time critical deliveries in busy neighbourhoods [57].

There are also other innovations that don't use the road. An example is the use of drones to deliver packages via air or underground networks to deliver goods. Even Amazon is interested in using drones for the delivery of small packages [56]. The underground network option is a very expensive alternative to transport goods in densely populated places.

Another way that is proposed is making use of waterways when they are available. Because in the past the water has been an important way of transport a lot of older cities are located close to the water. With the water of the canal system already in place this would require a limited investment before they can be used for the transportation of goods as they did in the past. The main investment will be in the infrastructure needed for the loading and unloading of goods at several different places. With cities like Amsterdam wanting to stimulate making use of the canals and investigating the placement of docks for the transportation of goods, this last mile alternative will be an interesting solution in the future [4].

3.3. Conclusion

This chapter serves to answer the first sub question of the research:

> How is city logistics evolving and what are current last mile solutions?

City logistics aims to reduce the nuisance created by the transportation of goods in cities. It tries to reduce the space of the road used for transportation while lowering emissions of all the different transported. While a lot of road-based solutions are researched and implemented, the water that is available in a lot of cities is not often used. Making use of the already in place canal system in cities like Amsterdam creates new possibilities to reduce the space used on the road even further while also tackling the other aspects like harmful emissions, vibrations and accidents.

4 Water as a last mile solution

In the past the water was often used for the transportation of goods to people. With the arrival of a better road network the use of vessels for transportation lost popularity. On a national level transport over land became quicker and more convenient because most places got road access. Because of the limited space available and congestions on the roads in city centres and the limitations in weight, vibrations and emissions for road transport, the water is investigated as a promising solution for the growing demand of transportation and for the voluminous or heavy transport in city centres.

This chapter will start with a description of waterborne transport in general. After that in paragraph 4.2 the proposed concept for the use of vessels as al last mile solution will be explained. Paragraph 4.3 gives an overview of the different stakeholders related to the concept. The next paragraph will investigate transportation hubs that are required to use water as a last mile solution. The paragraph will finish with a brief conclusion on water as a last mile solution.

4.1. Waterborne transport in general

Waterborne transport is the transport of goods and people making use of different waterways. The waterborne transport can be divided in two main shipping trades:

- Seaborne trade: the seaborne trade accounts for around 11 billion tons of goods transported each year. This equals 1.5 tons of goods per person based on the current global population. When comparing by volume, shipping accounts for 80% of the total imports and exports within the European union [21].

- Inland shipping trade: the inland shipping trade is a very important part of the shipping trade in the Netherlands. There are around 8.000 inland ships sailing under the Dutch flag [20]. The Dutch are the biggest player in the inland shipping trade in Europe with a turnover share of no less than 46,4% in 2017 [6].

With this heritage in mind and the large shipping infrastructure in place, it would be a logical choice to also expand the waterborne transport in the Netherlands even further. Taking more transport from the roads towards the water. Especially in crowded places like inner cities this will result in large benefits for the citizens.

4.2. The concept of waterborne transport as a last mile solution

In order to make use of the canals in the cities for the transportation of goods, Enviu has set up the first concept for the development of a vessel used as a last mile solution. The vessel will need a propulsion system that is free of harmful emissions in order to be able to operate in city centres in the future. Also, the idea is to equip the vessel with a rigid chain lift for fast loading and unloading. The deckhouse will be placed on the front for better visibility. The vessel will operate between one or more hubs and one or more delivery locations. The locations and distances are not yet determined and can be determined later in this research.

There are two different ways investigated for this concept to operate a vessel. Firstly, the operator can choose to deliver several individual orders to different places. Secondly the operator can bundle its deliveries based on location. How this would work is described further below.

- **Individual orders**
  The vessel operator will work more like in the current situation. It will receive for example goods from a single supplier and will deliver the order to the different locations around the city. The supplier can be a manufacturer, wholesaler or city hub – that bundles the goods which the vessel can distribute. By doing so, the vessel will need to cover a great distance and will have to moor several times at different places. An advantage is that fewer parties are involved, this makes it a more suitable short-term option.

- **Based on location**
  The vessel operator will group its deliveries based on the geological orientation of the customers. For example, all the orders that need to be transported to a certain canal. When doing so it is necessary to collect the products from the different suppliers at an external location like a hub. When the goods are collected, they will be bundled for each customer before shipping. In this way the vessel will only travel from and to the canal where it will drop off its cargo before returning to the hub. Another benefit is that the vessel needs to berth at fewer places.

For both ways of operating a vessel, the hub is a central point for the delivering of goods. The hubs are essential to make it possible to transport goods from the supplier to the customer. From a certain hub, it is possible to leave the hub at different moments and with a different mount of cargo. There are two different moments for a vessel to leave the hub:

1. The vessel could leave on regular time intervals. This way is the so-called “beurtvaart”. This is a scheduled sail, independent of the cargo demand, between two or more destinations [58]. An example could be that each day there is a vessel leaving at 9 o’clock towards one canal or street. The suppliers deliver their goods to a hub, see paragraph 4.3, before 9 o’clock so they can be delivered at an arrival time of 10 o’clock. When the vessels docks around 10 o’clock, all customers can collect their goods or they can be brought to their doorstep. The advantage for the customer is that they will receive their orders collected as one delivery at a fixed moment each day or week depending on their needs.
   This is most in line with the idea of operating individual orders.

2. The second moment for the vessel to leave the hub is to wait with delivery until the vessel is full. This will give a more irregular delivery interval but would make it cheaper because the vessel does not have to sail almost empty. A downside is that most customers are used to their own preferred delivery time. For them to embrace these bundled deliveries, they will need to be stimulated either by regulations or by a reduction in costs or environmental impact. This is also known as full truck load (FTL) [61]. This is most in line with the idea of operating based on location.

There is also the possibility of a combination of both systems. For example, that a vessel waits for a maximum duration of 1 hour for a full truck load before leaving. Also, it is possible that the vessel will sail at reduced capacity for critical deliveries. This would need to be compensated by a higher price paid by the customer.

4.3. Logistics hubs

Because of the increase in transportation of goods due to the global economic mega-trends, the transport networks become very complex. More and more goods are transported because of the increased demand for goods. This makes it hard to manage the transport of goods and therefore logistics hubs are introduced. According to Huber, Klauenberg and Thaller (2015) [60], logistics hubs are:

> *Linking points – infrastructure facilities and nodal points – in logistics networks. They serve primarily as transhipment points for flows of goods.*

An example of a logistic hub is seen in Paris where Goodman - a large international industrial real estate group that owns – develops and manages modern and strategic real estate [19] is working on a unique multimodal platform for urban distribution: GREEN DOCK [18]. Seeing that companies like Goodman are working on water based urban distribution solutions states the importance of this concept in the future.

These hubs are a transhipment point where goods are collected and transferred over the different last mile solutions. These hubs can be specialized in the collection of goods for their own deliveries like a Post NL or DHL sorting station, but they can also be a place where different deliveries from different transport operators come together. Also, some wholesalers can function as a hub by collecting goods from different suppliers. An example is Bidfood that opened their network for local specialist. They combine their own orders with the external orders and will than distribute the goods over the different last mile solutions for example by using bike deliveries [59]. How these hubs can operate is illustrated in figure 3. Both the collection of orders in the first step and the bundling and delivery of goods in steps 2 and 3 are managed by the hub. This hub gives the possibility to different catering sector companies to order their goods on one platform from different suppliers. After placing the order these suppliers will deliver their goods to the hub where they are bundled before delivery to the end-customer via a last mile solution that suits the order.

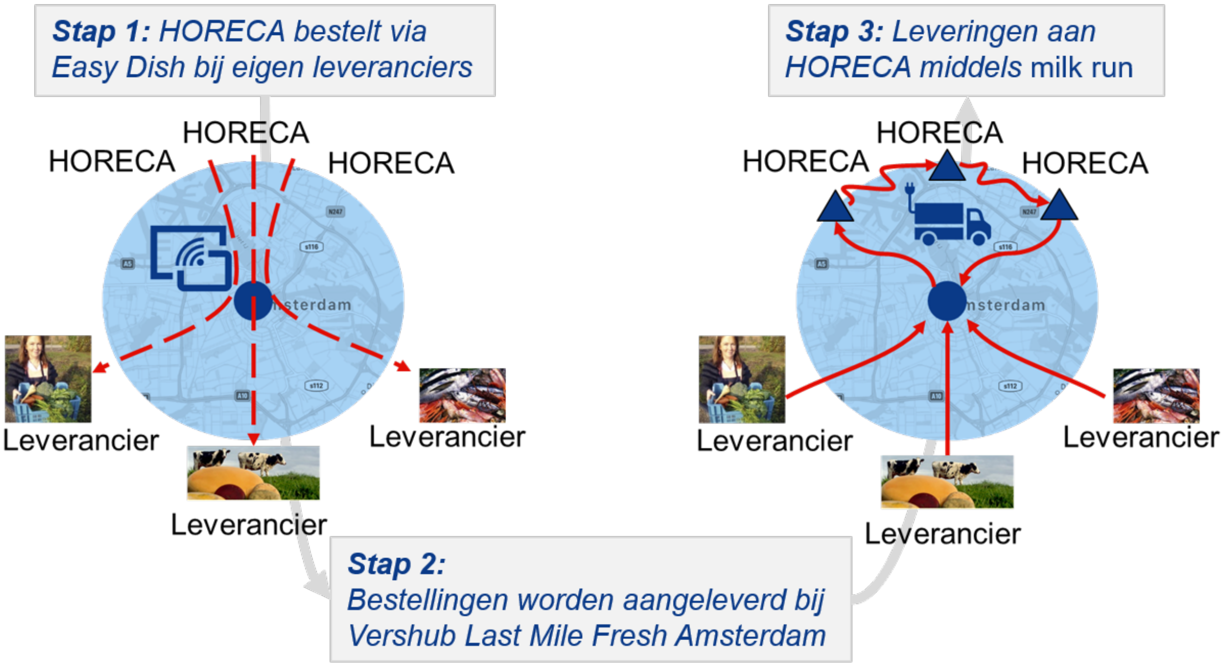


Figure 3. Illustration of using a hub with a software program for the ordering and distribution of goods as used by Easy Dish.[5]

Logistics hubs play an important role in new urban distribution concepts because they will not depend on only one carrier to transport the goods from supplier to end-user. In order to increase efficiency, the goods are stored and bundled before distribution via different last mile solutions. Also, these hubs create the possibility to use water as a last mile solution when they are located near the water. And suppliers that have no water connection can make use of water-based transport when using these hubs for transhipment.

The main right to exist for these hubs is their bundling of goods, which increases the efficiency and limits the number of large trucks entering the city centre. Because of the bundling there is only the need for one carrier to enter the centre instead of for example 6 different carriers. This reduces the overall number of road users but also limits the number of times the end-customer receives packages. Overall, this saves the end-customer time and reduces the nuisance for other residents. An overview of different hubs is given in paragraph 5.4 Hubs in Amsterdam.

4.4. Stakeholders

There are different stakeholders involved with the water based last mile transportation. The main stakeholders are:

- Vessel operator

  This is the party responsible for the exploitation of the vessel. The way the operator uses the ship changes the way it is used to generate income. This has a big influence on the model. For example, does the operator drop single deliveries or will it supply a single canal at once. Also does the operator use a fleet of vessels or just a single vessel?

- City council

  The council is responsible for the rules and regulations concerning a vessel making uses of the canals. They will have certain rules concerning the dimension, but they will also very likely regulate the moments when vessels can make uses of the canal system. Probably they will outsource regulations concerning the safety of the vessels. For instance, rules and regulations about using hydrogen on board as a fuel. Also, the council will be responsible for the infrastructure. The canals are already in place but loading and unloading place may still be limited. In order to increase the number of docks they will make considerations of where to put these. This can have a big influence on the time needed to transport the goods from the vessel to the end-customers.

- Supplier

  This is the party sending the goods/products to the end-customers. They are normally responsible for the arrangement of the transportation. It could be that they do the transportation in-company, but they can also outsource the transportation. Because of the new rules and regulations is becomes more complicated to do in-company transportation so there will come more opportunities for concepts like transport over water. An example of a supplier is a wholesaler.

- End-customers

  This is the party receiving the goods/products. They want to receive their goods at the right time. In this research the focus lies on businesses in the city centre as end-customers. Nowadays more and more businesses want to work on a more sustainable company. They want to attract more customers by lowering their harmful emissions. Because of this they will have higher requirements regarding the transportation of the goods they use and sell.

- Residents

  These are the people living on or near the water. By transporting goods over water, the nuisance on the road will reduce. This is beneficial for those who live in the city centre. But the transport over water will also generate disturbance for the residents. For example, more water users, waves and more place needed for the mooring of the vessels.

- Hub operators

  These are the other parties involved in the logistic network. For example, the hubs that are used to collect and distribute the goods. These hubs form a vital role in the transport over water concept. Because most suppliers are not located near the water it is important to have hubs where road and water transport come together.

- Logistics providers

  Alternative logistics providers are also important stakeholders. Maybe there are new possibilities to cooperate with competitors to improve the customer experience. For a lot of companies transport merely over water isn’t possible because of their proximity to the water. In this case it is important to cooperate with other logistics providers to transport goods from supplier to customer.

- Other water users

Other water users have impact on the space available on the canals. When a lot of other vessels are on the water this could lead to congestion.

4.5. Conclusion

This chapter aimed to answer the following research question:

> How can the water system be used to create a new last mile solution for transportation goods in cities?

There are different solutions when implementing water as a last mile solution. The operator can sail with different individual order or can bundle the orders to maximize the use of the vessel. Also, the operator can choose to sail on different schedules. The implementation of using water as a last mile solution will require several different parties. One on these parties are the owners of transportation hubs that are used for the collection, storage and distribution of goods. These hubs need to be located close to the water so a transition from the road to the water becomes possible. The other stakeholders need to be considered when looking at the use of water as a last mile solution.

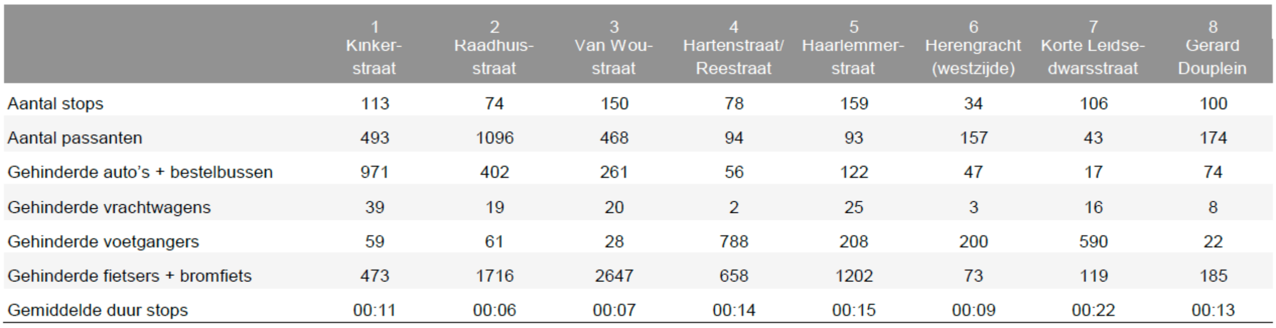
5 Amsterdam and the use of water

Water has played an important role in the development of the Netherlands and their trade heritage. Currently the waterways are mostly used for leisure, person transport and transport of large quantities of goods. The Netherlands has a lot of canals, lakes and waterways that are used for transportation. This is important from an economic point of view, but also as an energy efficient alternative for the transport over land. That is why the Netherlands is continuously improving their waterways [49].

This chapter will start with the current situation of transportation in Amsterdam. After that an overview is given of the history of waterborne transport in the Netherlands and the connection this has to cities like Amsterdam. In order to know whether there are possibilities for transport over water an overview is given of the waterways in Amsterdam. At last, the users that currently make use of the canals in Amsterdam will be given before concluding whether there are possibilities for water-based transportation in Amsterdam.

5.1. Land based transport and the regulations in Amsterdam

The current way to transport goods in city centres mostly makes use of the road. This also means that trucks and vans need to stop on the road to load and unload their goods. At some places there are designated places for loading and unloading. Table 1 shows the hindrance created by trucks and vans stopping on different roads. As shown in the graph each stop results in a multitude of hindered persons, cars, trucks, vans or bikes. The research also shows that for example on the Kinkerstraat, almost half of the stops are on the road surface hindering a lot of other road users [1]. In the report it is stated that the stops where people park on the road surface on average take 6 minutes.



	1 Kinkerstraat	2 Raadhuisstraat	3 Van Woustraat	4 Hartenstraat/ Reestraat	5 Haarlemmerstraat	6 Herengracht (westzijde)	7 Korte Leidsedwarsstraat	8 Gerard Douplein
Aantal stops	113	74	150	78	159	34	106	100
Aantal passanten	493	1096	468	94	93	157	43	174
Gehinderde auto's + bestelbussen	971	402	261	56	122	47	17	74
Gehinderde vrachtwagens	39	19	20	2	25	3	16	8
Gehinderde voetgangers	59	61	28	788	208	200	590	22
Gehinderde fietsers + bromfiets	473	1716	2647	658	1202	73	119	185
Gemiddelde duur stops	00:11	00:06	00:07	00:14	00:15	00:09	00:22	00:13

Table 1. Number of hinders in Amsterdam [1].

The hinder of the traffic in Amsterdam contributed to the fact that the municipality has taken more restrictions to reduce the pressure on the road network in Amsterdam. The important restrictions for transportation goods on the road are:

- Dimensions restrictions

  Trucks mainly do the transport of large quantities of goods. In the Netherlands there are limitations in size for such trucks. The main dimensions for trucks are that they can have a maximum length of 12 meters, a height of 4 meters and a width of 2.55 meters. For conditioned transport this with may be 2.6 meters [51].

- Weight restrictions

  In Amsterdam there are weight restrictions because of the weak quay walls of the canals. Where heavy trucks with a weight of more than 7.5 tons used to be able to just enter the city centre, they now need a waiver. Also, from October 2021 trucks with a weight of more than 30 ton are not allowed to enter anymore [35]. This weight limit used to be 45-ton truck weight. When carriers with a truck that weights more than 7.5 ton want to enter there are next to the waiver strict rules on where that can drive and where they can unload. Where it used to be possible to park at a bridge while unloading this now is not allowed. These rules make it harder to supply the different customers in the city centre.

- Other restrictions

In Amsterdam there are also other limitations. Just like in a lot of other cities, the city centre is a controlled emission zone. For trucks this means that only trucks with an emission class of 4 of higher may enter since the first of November 2020 [42]. In Amsterdam there is also an emission zone for private and commercial vehicles that are lighter that 7.5 tons. Again, vehicles with an emission class of 4 or higher can enter [37]. There are exemptions but the main group of transporters need to comply with these regulations.

In the future these regulations will become more and more strict. From 2022 only trucks with an emission class of 5 or higher will be allowed to travel within the A10 ring road, see figure 4. This will become even stricter in 2025 when only commercial vehicles that don't emit any harmful emissions are allowed within the A10 ring road. This will also include vehicles making use of the water [37].

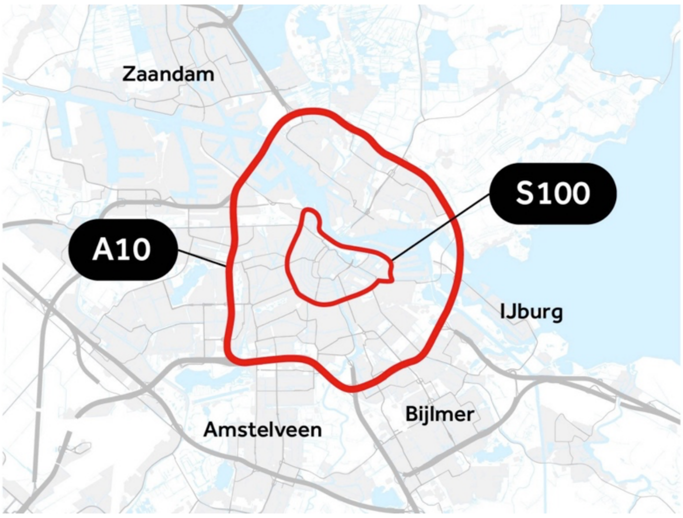


Figure 4. Ring road A10 and the road around the city centre of Amsterdam - S100 [34]

With the restriction of dimension and weight and the emission regulations becoming stricter, it is necessary to come up with new ways to transport the goods within the city centre. Whit the prospect of these vehicles having to be completely free of harmful emissions alternative could be an electrically driven vehicle or vehicles making use of hydrogen or no longer using the road but using the water.

5.2. History of water-based transport in Amsterdam

For decades, goods have been transported over water. Early on, it was discovered that water enables more efficient travel compared to going over land. Therefore, the waterways are critically important for transportation throughout the world. Long-distance transport was the way to exchange goods between different countries over the world. Also, for the Netherlands, the waterways became important, mainly for trade. The Dutch waterways are formed by both the international and the national history. For the Netherlands, the transition of the canals and the constitution of the big body of water – originally called the Zuiderzee – were very important for the inland trade.

5.2.1 National history

For centuries transport over water took place on natural waterways. It was in the 16th century that the first purposes build canals were dug for mostly the transport of sand. Sand barriers were excavated and transported on special dug canals towards cities. The sand used in the construction of the ring canals in Amsterdam came from Haarlem and was transported over water. In this time the canals where also used by farmers for the transportation of animals, hay and other products [48].

In the 17th century more canals were dug for the transport of peat. The excavation of peat already started in the 15th century. The peat came from the eastern parts of the Netherlands. From here it was transported over water towards the cities, like Amsterdam where it was used as fuel for the heating of houses. The vessels used for the transportation where specially developed with a limited draft for the shallow waterways. The use of peat continued all the way until the 1920s when the market collapsed due to the rise of coal [29].

The Zuiderzee is a large body of water located in the centre of the Netherlands nearby Amsterdam. The Zuiderzee now is split up in the IJsselmeer after the building of the Afsluitdijk in 1930 and the Markermeer after the building of the Houtribdijk in 1976. The Zuiderzee played a big role in the fishing industry in the Netherlands. Especially in the 1850s when the sales territory increased [26]. Here both sea going and inlands vessels had to find their way between the shallow waters. Due to the lack of driveable roads, the Zuiderzee also played a key role in the transportation of goods and persons within the Netherlands.

5.2.2 Golden age

Amsterdam has become an important city during the 17th century because of the international trade. Goods were transported to and from Amsterdam where the big warehouses were used to store and distribute the goods. An important start of the international sea shipping trade was the founding of the VOC, Dutch East India Company, in 1602. It started as a chartered company to trade cotton and silk with Mughal India but soon got the monopoly for the spice trade with Asia. This trade was very important for the Dutch republic because it had just declared its independence. Because of the trade they brought in new wealth from outside of its small country. This period is also known as the golden age because of the wealth it brought to the country [30].

But during this golden age there was another important water-based trade. This was the trade with the Baltic. This Baltic trade forms the foundation of the growing economic wealth during this period. The trade included produce like salt and herring to be transported to the Baltic. The luxuries coming from all corners of the world were also important goods. On their way back the Dutch brought wood with them and produce like grain. This grain was transported, via Amsterdam, towards England, France, Spain and Portugal. The boom of this trade was during the 16th and 17th century. After that, it declined because of the growing competition and the decreasing demand for grain [25].

5.3. Waterways in Amsterdam

Because of the historical shipping trade in Amsterdam there are a lot of waterways. Where these waterways and canals where important for trade in the past they are now mostly used for leisure activities and on some canals, people even live on the water in houseboats.

The most two important waterways in Amsterdam are the IJ and the Amstel. The waterway IJ separates the city centre of Amsterdam from Amsterdam-North. The smaller waterways in the city centre of Amsterdam lead to this large waterway. The Amstel flows from the city centre to the south of the Netherlands. Figure 5 shows the different waterways in Amsterdam.

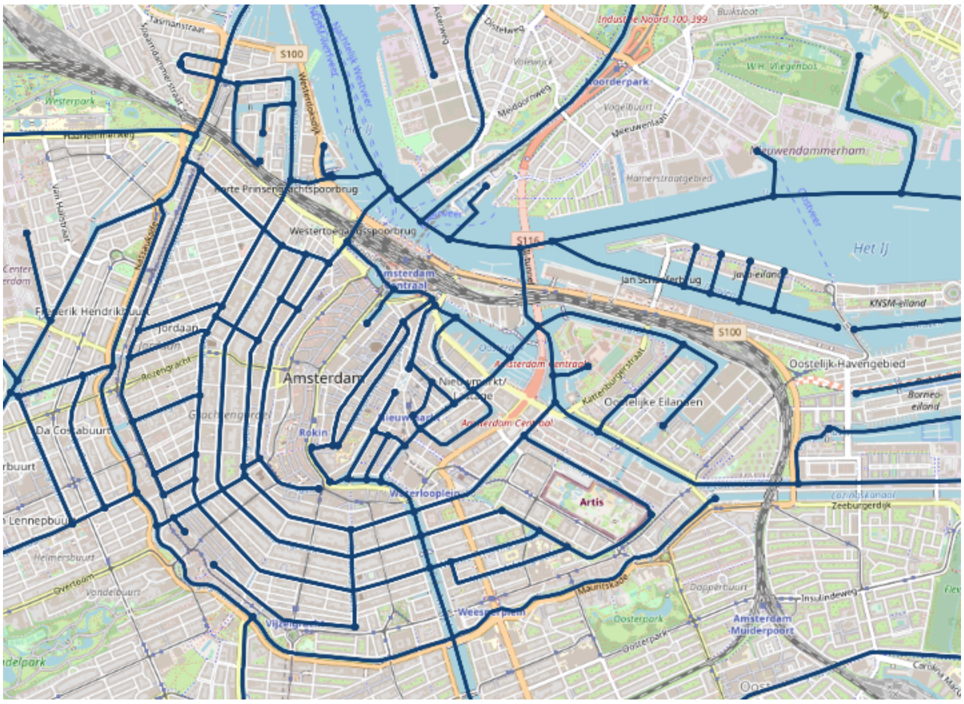


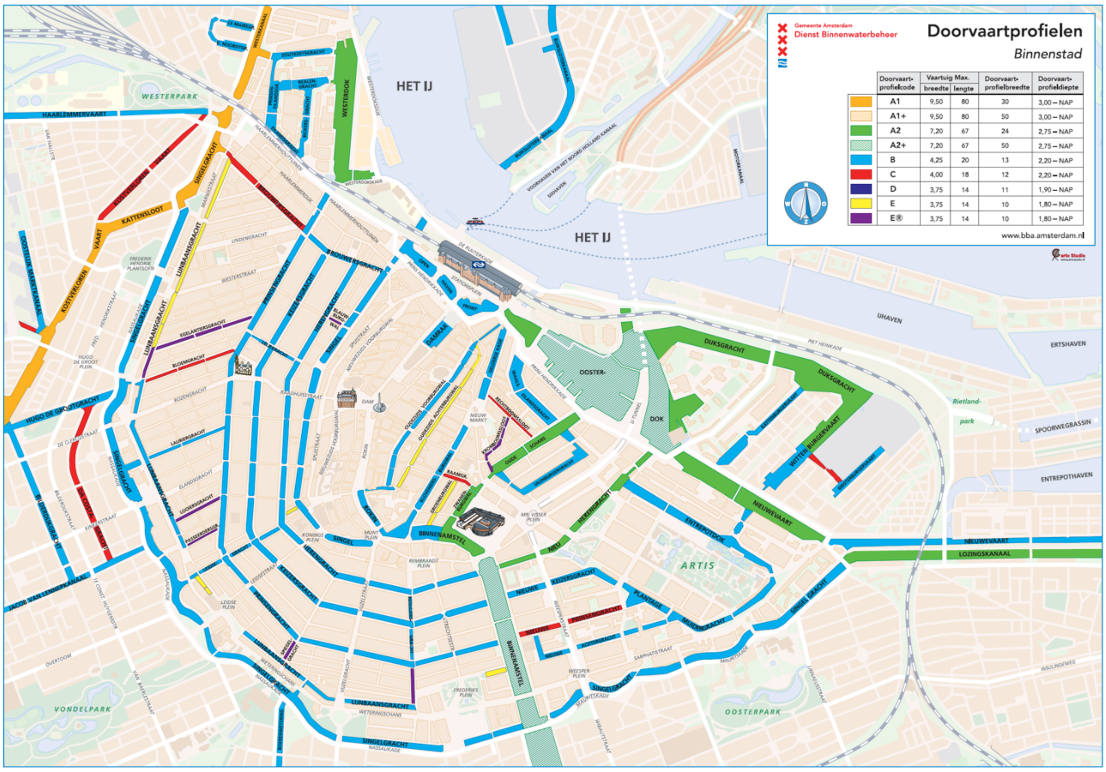
Figure 5. Overview of the waterways in Amsterdam. [50]

Around the heart of the city centre, there are four main canals. These are the Singel, the Herengracht, the Keizersgracht and the Prinsengracht. These canals flow parallel to each other to the southeast, making four gentle bends and ending in the Amstel.

5.3.1 Limitation of using the waterway

The many waterways in Amsterdam can be used for transportation of goods. Just as the transportation of goods on the road, there are also limitations for the transport of goods by water. For the transportation of goods over the waterways in Amsterdam, the passage profile (called in Dutch: doorvaartprofiel) is one of the most important limitations.

For each canal in Amsterdam the passage profile can be defined. The profile describes the main maximum dimensions for each specific canal. This mainly concerns the width and length of the vessels through this specific canal. See figure 6 for the passage profile of the waterways in Amsterdam.



	Doorvaart-profielcode	Vaartuig Max.		Doorvaart-profielbreedte	Doorvaart-profieldiepte
		breedte	lengte		
🟧	A1	9,50	80	30	3,00 – NAP
▨	A1+	9,50	80	50	3,00 – NAP
🟩	A2	7,20	67	24	2,75 – NAP
▨	A2+	7,20	67	50	2,75 – NAP
🟦	B	4,25	20	13	2,20 – NAP
🟥	C	4,00	18	12	2,20 – NAP
🟦	D	3,75	14	11	1,90 – NAP
🟨	E	3,75	14	10	1,80 – NAP
🟪	E®	3,75	14	10	1,80 – NAP

Figure 6. Passage profiles of the waterways in the city centre of Amsterdam [39]

As shown in figure 6, most waterways in Amsterdam have a passage profile of B. This means that the profile width of the passage is 13 meters, and the profile depth is 2.20 meters NAP. Therefore, the vessel can pass through one of these canals when the vessel is no wider than 4.25 meters and no longer than 20 meters. There are some smaller waterways. However, these are only a few in the city centre of Amsterdam.

5.3.2 Activities on the waterways in Amsterdam

In order to check whether there is enough space on the canals in Amsterdam the municipality of Amsterdam preformed the following research called “Drukte op het water?” which means, “Bustle on the water?” In this research from 2003 they counted the number of water users on various days throughout the year on various places. They noticed that in general the weekends where busier than the weekdays although this difference is less big during the winter months. The respondents to the questionnaire called the canals busy but they don’t experience this as disrupting [27].

Figure 7 is part of the findings from the research to the bustle on the water. This graph shows the number of boats making use of a busy canal per hour. During wintertime this graph shows around half of the number of boat users per hour compared to the other seasons. From the peak in this graph, we can conclude that the number of boat users per hour before 14:00 is roughly half of the number of boat users per hour after 14:00. From research follows that 72% of the deliveries in the catering sector take place between 07:00 and 13:00 [22]. This corresponds nicely with the less busy moments on the canals. From the research it can be concluded that there is space available for vessels to deliver goods making use of the water. The loading and unloading space do need to be taken into consideration when implementing such vessels [27].

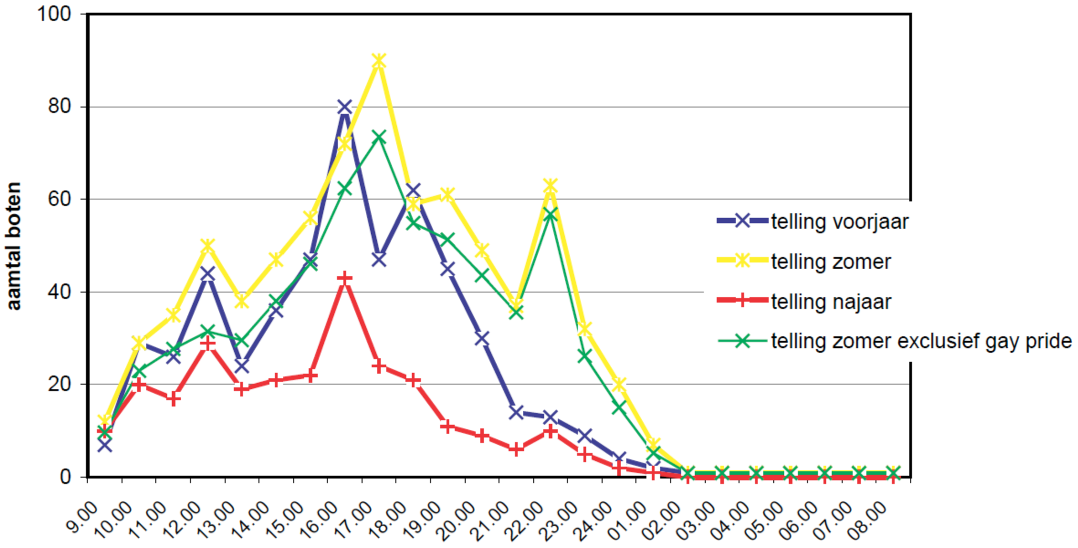


Figure 7. Average number of boats per hour at a busy canal. [27]

A similar conclusion was made by van Duin who simulated a case where four vessels were used for the transportation of goods in the inner-city of Amsterdam. He concluded that the waterborne inner-city transportation concept with four vessels would have no significant interference with other waterborne traffic [2]. Both the municipality of Amsterdam and the research of van Duin conclude there is space available on the canals for the implementation of inner-city cargo vessels.

5.3.3 Categorization of the waterways in Amsterdam

The crowd on the waterways and the limitations of the waterways ensures that careful consideration must be given to what the most efficient and effective way is for transport by water. Van Duin discovered that the waterways and canals should be split up in several different areas [2]. An example is the categorisation as seen in figure 8 as used by van Duin. Van Duin did a simulation study on freight waterborne transport in the inner city of Amsterdam. His model was developed to analyse the logistics performances and traffic influence for different fleet size configuration. From this research was concluded that a waterborne city logistics concept can reduce congestions in the inner city while satisfying the delivery requirements for shopkeepers.

Figure 8. A simulation study on freight waterborne transport in the inner-city of Amsterdam by J.H.R. van Duin.[2]

Because van Duin investigated the inner-city performances, the categorisation only includes the main canals in the city centre of Amsterdam. When looking at all the waterways in Amsterdam including the routes to and from the different hubs a new categorisation will have to be made for this research.

5.4. Different logistics hubs in Amsterdam

As mentioned before in chapter 4.3, logistics hubs make it possible to goods with different last-mile solutions. Currently there are several different hubs in Amsterdam. The next overview will give some of the different hubs in Amsterdam that are planned or already build. All hubs are located near the water and near main roads.

- **Amsterdam Logistic Cityhub**

  The Amsterdam Logistic Cityhub is developed to shorten the last mile to and from Amsterdam. It is located outside of the city centre near the main roads and the water. It will have facilities for lorry, bus, boat and (electrical) bicycles. The construction of this hub started at the thirtieth of April 2021 [11]. The focus of the Amsterdam logistic cityhub is to rent out spaces from where their customers can facilitate in the distribution of goods. They facilitate in the logistics of both building, catering sector and e-commerce.

- **Bouwhub**

  This hub has the aim to reduce the public nuisance around a building project while building more efficient [7]. The company collects the building materials at a location outside of the city centre and will distribute, on time, the materials both over road and over water to the building sites. This reduces the overall number of trucks on the road, which reduces both their emissions and the risk of accidents.

- **Last mile fresh**

Last mile fresh is a proposed Fresh hub by the transportation company Leen Menken. It aims to bundle catering deliveries so zero-emission vehicles can distribute them [5]. Besides lowering the number of vehicle movements this also enables smaller suppliers to keep delivering their fresh produce to their customers. The customer uses the Easy dish platform to order their produce via the different suppliers. These suppliers will than deliver the goods to the Last mile fresh hub from where they are distributed over the customers [32].

- **Food center Amsterdam**

The food center Amsterdam is a wholesaler’s market in Amsterdam. They are specialized in a complete package of fresh and diverse produce. They have over 70 wholesales making this a big hub for fresh produce in Amsterdam. The food center is located close to the water making it possible to start distributing fresh foods over water to the different customers within the city center [17].

- **Cityhub**

Cityhub provides warehouses in different cities in the Netherlands such as in Amsterdam, The Hague, Utrecht and Roermond. The hub in Amsterdam is located outside of the city center near the water and focuses on business to business (B2B) transportation of goods. They deliver different green transport solutions ranging from small electric vehicles to the ambition of using electric vessels in the future [11].

5.5. Loading and unloading

The loading and unloading will take place at several hubs and locations in the city. The main selling aspect of the Portago concept is a liftable deck used for the loading and unloading of goods. By lifting a large section of the deck, the roll containers can directly be rolled on to the shore for quick and easy loading and unloading. The loading and unloading locations will need a facility so the vessel can moor. The detailed look into these load and unload locations is not part of this research and will depend on the mooring system chosen.

5.6. Conclusion

This chapter aimed to answer the following research question:

> What types of limitations can vessels within Amsterdam encounter?

The current situation where transporters make use of the roads in the city of Amsterdam creates a lot of nuisances. Also because of new rules and regulations it becomes harder to make use of trucks and vans for transportation. Based on the historical trade over water and the canal system in Amsterdam that has room for additional delivery vessels, it is possible to make use of these canals for transport of goods in the future. The main limitations encountered are size limitations on the canals. A vessel is only allowed to have a certain length and width for different sections of the city. Also, there are hight restriction because of the bridges. Because of regulations the vessel will need to be designed that is free of harmful emissions. From the research followed there is enough space available for inner city cargo vessels to make use of the canals for their deliveries.

6 Goods transported

In cities there are a lot of goods transported each day. Dablanc found out that in general in cities there are 0,1 load and unload operations per resident per day [16]. For the municipality of Amsterdam with more than 850,000 residents [8], this could mean on average 85,000 load and unload operations each day.

This chapter will cover the different customers for the waterborne transport concept in the first paragraph. In the second paragraph the different types of cargo are displayed. The next paragraph will look into the different ways these goods are transported. This chapter will end with a conclusion in which the possible customers and types of goods are summarized.

6.1. Who are the customers?

There are two different business concepts, namely Business to Business (hereafter named: B2B) and Business to Customer (hereafter named: B2C). B2B refers to the business between different companies [12]. An example is a transaction between a wholesaler and a retailer. B2C refers to the process where products and services are directly sold between businesses and customers [28]. This term is typically used when referring to online shopping. Most of these deliveries will contain large numbers of small packages delivered on a variable time schedule. Because of this a more relevant delivery method is the use of small delivery vehicles or bike. During this research the focus will lay on the delivery of B2B goods.

There are several customers for the delivery of B2B goods. The most important customers for this concept are listed below.

- **Hotels**
  According to the Statistics Netherlands (CBS), Amsterdam has over 500 Hotels with more than 40.000 rooms [9]. These hotels require a constant steam of goods. By using the right logistics and supply chain strategies the quality and services of the hotel company will increase while reducing costs [44]. Hotels are often faced with the challenge of dealing with different suppliers and distributors. The goods transported to and from hotels can range from linen and foods to trash.

- **Catering sector**
  The 5000 catering businesses in Amsterdam account for around 25-40% of the city logistics. Every day there are around 5.000 trips to transport 10.000 deliveries. Of these deliveries, 72% takes place between 07:00 and 13:00 [22]. With this the catering sector accounts for a big part of the nuisance generated by city logistics. There is a big difference in number of deliveries per trip. Where bigger distributors deliver 6 - 8 deliveries per trip, smaller supplier often only deliver 1 - 2 deliveries per trip. Because of this there is a big gain to be had when combining the orders from smaller customers in hubs. Every end customer in the catering sector on average receives around 12.7 deliveries per week from six different suppliers [22].

- **Shops**
  Besides hotels and catering facilities there are also a lot of shops in Amsterdam. These shops can range from department stores to smaller shops. Supermarkets are not included in the shop category and have their own category. The frequency of deliveries will vary widely depending on the shop. Shops will also create the possibility for a return stream of goods when they have a online shop where the packages are packet in the city centre. The vessel would be capable to collect these packages and bring them to the hubs from where they can be distributed via the already in place postal service network.

- **Supermarkets**

Supermarkets require large volumes of goods delivered each day. The frequency of the deliveries can range from one to two box trucks per day for small supermarkets to six to seven box trucks per day for large supermarkets [43]. This can lead to big congestions because it takes time to unload these trucks. Also, the size of the trucks and the prime location of the supermarkets can lead to nuisance.

6.2. What are the different types of cargo?

In order to get an idea of the requirements for a transportation vessel the different goods that are transported in the city of Amsterdam are categorized. The categorization is based on the categorization as used by Buck Consultant International and extra categories are added where necessary [54].

- **General cargo & Retail**

This category contains the supply for shops. Depending on the shop the cargo can have various sizes. It can range from pallets of goods to smaller packages.

- **Packages**

These are boxes of various sizes transported. This category mainly contains of packages delivered to consumers. Nowadays these packages are mostly order online. When the consumer places the order, a company collect the order and sends it to the customer.

- **Trash**

This category contains the trash produced by households and businesses. This is a large steam that is handled different depending on the city. In Amsterdam the trash is taken away by placing trash bags on the street that are later picked up by large or small garbage trucks. A new pilot started at March 2021 in a part of Amsterdam where small garbage trucks collect the garbage and bring it to a small vessel in a canal [40]. From here the trash is transported over water to the processing plant that is also located near the water. The vessel is just an open barge.

- **Dry foods**

Dry foods are the food deliveries to supermarkets and catering businesses. For example, boxed or tinned foods. These foods are often collected in roll containers for ease of handling.

- **Cooled foods**

Cooled foods are goods that need to be conditioned during transport. An example is the supply of meat or fish to supermarkets or catering business. Because of the shelf life of these products, it is necessary that they are cooled during transport. This brings additional requirements for the transporter.

- **Bulk**

Some goods transported are bulk goods. An example is the stocking of beer in pubs. The beer is brought by a big tank truck, which fills the tanks in the pub. These bulk products are often transported in special vehicles making it hard to transport them with the proposed vessel.

- **Building materials**

This category includes all material streams going from and to a building side. Examples are building materials like wood, concrete and building sections. These streams will also include the waste generated at the building side. In general, barges will transport these goods to and from a building side. Therefore, this category will be not further investigated in this research because they have their own transporters.

6.3. How are the goods transported?

The different cargos elaborated in the paragraph before can be transported in different ways. For the transport of goods in the inner city of Amsterdam, it is useful to investigate the different transportation systems and to decide which of these systems can be used for the deliveries in the city centre. Therefore, the three main general transportations systems for the transport of goods are elaborated below.

- **Shipping containers**
  The container is at the core a highly automated system for moving goods from anywhere to anywhere with a minimum of cost and complication on the way [31]. Modern shipping containers are made from steel and have several different lengths: 20 ft, 40 ft, 45 ft. They are very suitable for national and international trade but because of their dimensions they are less suitable for small deliveries in city centres. Also because of their size it is very hard to unload them using the limited space available in the cities. Because of this the standard shipping container will not be considered as a goods carrier for the proposed last mile solution.

- **Roll container**
  Roll able containers are widely used to collectively transport goods. Instead of transporting different boxes they can collect the goods in one movable package that can easily be loaded and unload. These containers have wheels making it possible to move them by hand from the truck with the help of a lifting platform to, for instance, supermarkets. There are several different sizes for the roll container depending on the products they need to carry [33]. The weight of the roll container is depending on the goods that are transported.

- **Pallet**
  Another way of packaging products is by placing them on a pallet. A pallet is usually made of wood or plastic and had different fixed dimensions. These dimensions fit in certain ways inside of shipping containers or truck to make the transhipment of goods easier. The most conventional pallets are the standard euro pallets, which have a size of 800 x 1200 x 144 mm. These dimensions are established by the European Pallet Association (EPAL). Each pallet should have a workload of at least 1.500 kg [46]. The second most used pallets are so called block pallets with dimensions of 1000 x 1200 mm. There are also more specific pallets like display pallets mostly used to be directly used in shops for the display of goods. These display pallets are usually 600 x 800mm of 400 x 800 mm corresponding with half or a quarter of a Europallet.

6.4. Conclusion

This chapter aimed to answer the following research question:

> Which types of cargo are carried in Amsterdam and can be transported over water?

There are several customers mentioned to function as end users. For this research, the focus will be on the delivery of goods to hotels, shops and the catering sector. There are two main types of goods carried to these businesses and supermarkets, namely goods that need to be cooled and goods that do not need to be cooled during transport. The preferred way of transportation is by using roll containers that can easily be rolled on board of the vessel. Another way the larger goods are transported is by using pallets. By using a pallet trucks these pallets can easily be transported on board via a liftable deck. The main use of water-based transport is for the delivery of lager goods to businesses. The smaller packages with a lot of drop off locations are more suitable for other road based logistical solutions. Also, the main use for water-based transport is when the hub and the end customer are located at close proximity to a load and unload dock.

7 Decision support tool

The main use for the decision support tool is to aid in the development of a zero-emission inner-city cargo vessel. This vessel is a small inland cargo vessel developed to sail the canals of Amsterdam. Because no purpose build cargo vessels are developed jet, it is helpful to design the vessel with the aid of a digital design tool in which several different design choices can be made quickly. The goal is to come up with a direction from where the final design process will start. Different designs are compared on a financial level where all costs are calculated towards a cost price per rollable container transported. An overview of the different parts of the decision support tool can be found in Appendix A.

7.1. Cost calculation

The costs are used to compare different design options and to compare the possibility of using water-based transport to other ways of transport. For this research only the cost directly related to the vessel are included. The reason for this is that the additional costs include to many uncertainties and is very dependent on the number of vessels that are operated by a company. The costs are split up in the following categories as can be seen below [74]. The costs calculated in this paragraph are largely based on assumptions and desk research, and results should therefore be taken as indicative.

- Capital expenses (CAPEX) the cost for building and financing the vessel
- Operating expenses (OPEX) the costs to operate the vessel
- Voyage expenses (VOYEX) the voyage related costs

Each category is elaborated below with the related formulas to calculate the costs for the inner-city cargo vessel. The formulas are included in the model.

Capital expenses

The capital expenses are the costs related to the build of the vessel. By using the formula [7-1], the capital expenses per year are calculated.

$$C_{capital} = \frac{C_{build}}{lifetime} + \frac{C_{batteries}}{lifetime} + \frac{C_{fuel\ cell}}{lifetime} \qquad [7\text{-}1]$$

This formula does not consider a possible residual value for the vessel and does not include upgrades to the vessel in the future. The total build costs are calculated using the following formula, see formula [7-2].

$$C_{build} = C_{hull} + C_{engineering} + C_{installations} + C_{propulsion} \qquad [7\text{-}2]$$

The build costs are based on the open-source project: “rondvaartboot van de toekomst” [75]. Here the build cost is split up in hull cost, engineering cost, installations and propulsions. Because this vessel is also propelled by an electric motor and has a similar size and power the cost will be in the same range. Also, the engineering costs are expected to not differ a lot. To calculate the cost of the hull a representative value for each ton of hull weight is used. Based om the document this result in an approximation of the hull cost with a value of 25000 €/ton hull weight.

The fuel cell costs are included separate to account for a different lifetime for the fuel cell and hydrogen storage. The lifetime for the fuel cell is set at 10 years but can be changed in the model. To calculate the costs of the fuel cell and storage tanks the Interreg study on H2SHIPS [76] is used. The values used in this document are converted to a price per kWh fuel cell and a price per kg of hydrogen storage. The hydrogen will be stored in tanks under a pressure of 350bar. The cost is calculated by multiplying the power and weight by the values that can be found below.

- Fuel cell cost 1500 €/kWh
- Storage 1250 €/kg for hydrogen in storage tanks at 350 bar.

The lifetime for the battery pack is calculated by using formula [7-3]. This formula considers the number of charge cycles made each year and the number of cycles the battery pack can make. A lithium battery pack can have around 3000 cycles before it needs replacing [70].

$$Lifetime = \frac{\#\ charges\ per\ day * Sailing\ days\ per\ year}{\#\ cycles\ battery\ pack} \qquad [7\text{-}3]$$

Operating expenses

The operating expense for the vessel is calculated using formula [7-4]. Because only the direct costs associated with the vessel are included, and the overhead is not considered for the container cost calculation, only the employee cost of the captain are included. The captain costs are obtained by multiplying the hours the vessel is operational by the hourly pay of €30.-. The maintenance cost are set at €10,000.- per year. The insurance cost on a yearly basis is set at 2% of the newbuild cost of the vessel [23].

$$C_{operating} = C_{maintenance} + C_{captain} + C_{insurance} \qquad [7\text{-}4]$$

Voyage expenses

The voyage expenses include the voyage related costs and are calculated using formula [7-5].

$$C_{voyage} = C_{hydrogen} + C_{electricity} + C_{harbour} + C_{cargo\ handling} \qquad [7\text{-}5]$$

The hydrogen costs are based on the percental amount of energy that needs to come from the fuel cell. The cost for 1 kWh of hydrogen is calculated by multiplying the price for one kg of hydrogen by the energy density of hydrogen. A fuel cell efficiency of 55% is used. The base cost for 1 kg of hydrogen is €8.- [76].

The total electricity cost is calculated by multiplying the required amount of electricity by the cost of €0.12 per kWh. A charge efficiency of 95% is used to account for the loss of energy while charging and discharging the batteries [70].

Both the harbour cost and load and unload cost are not considered. The cost for these categories is unknown and will vary based in the hub used.

Container cost

The container cost is calculated by dividing the total yearly costs by the total number of containers transported during a year. This is the cost for the operator to operate its vessel. The container costs are reduced by taking on return cargo at a price that is included in the input list. It is expected that the cost that the operator can ask for return cargo will be lower than that of the cargo going towards the city centre. It is also expected that only a limited return load will be available.

7.2. Design

The decision support tool needs to include all the main design aspects. To make sure all aspects are included, a look is taken to the way vessels are designed in general. The development of a vessel generally starts with a design concept that is based on the requirements of the owner combined with the rules and regulations that are in place. From here, the designers will follow a so-called design spiral, see figure 9. Each time they complete a circle, they will take the design one step deeper resulting after a few alterations in the final design.

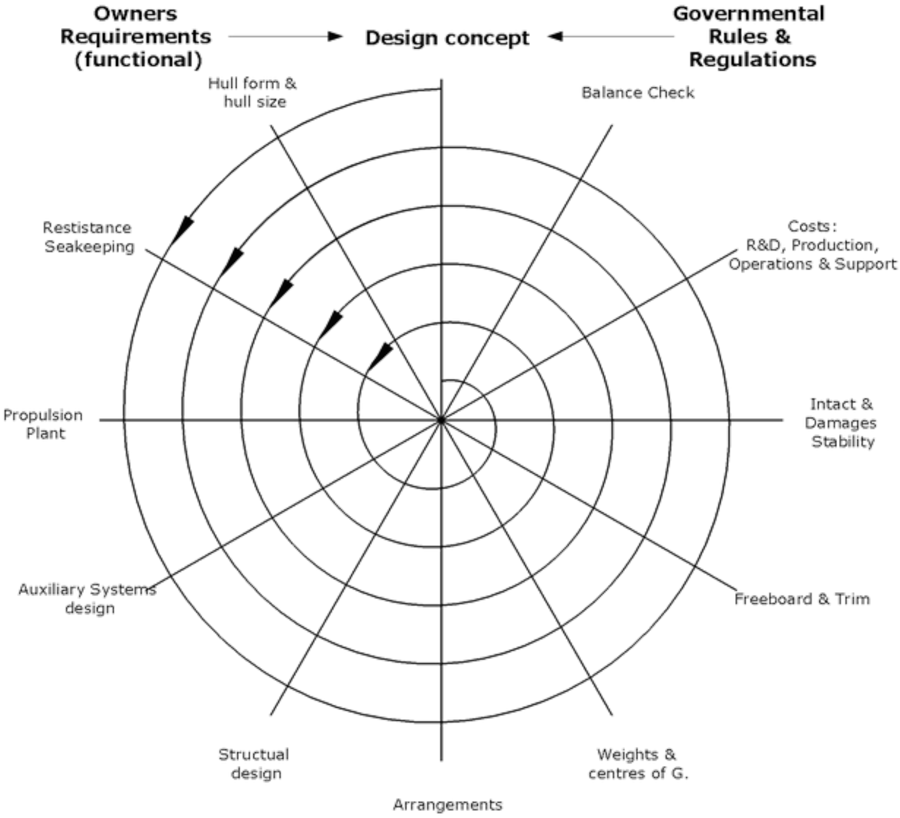


Figure 9, Design spiral [62]

The logistical purpose of the vessel combined with the restrictions and regulations in Amsterdam will serve as a starting point for the design concept. From there, the design spiral will start and a set of design requirements will follow.

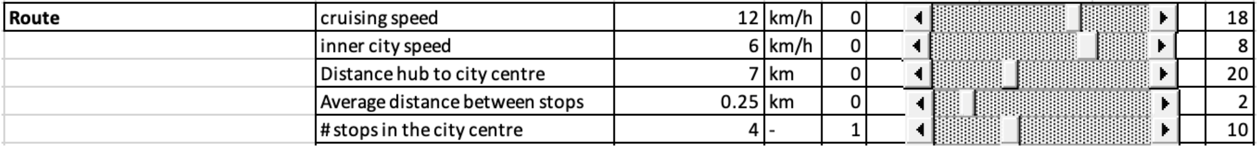
The design requirements and the logistical profile of the vessel are included in the decision support tool. In the following paragraphs, the design requirements and the logistical profile are explained in relation to the model. The hull form & hull size are explained in paragraph 7.4 about the hull form and weight. In this paragraph also the weight of the vessel is included. Resistance is added in the model based on the method from Holtrop and Mennen [63] and is described together with the propulsion system in paragraph 7.5. The auxiliary systems are only included as set power consumptions and weights because a detailed system is not needed during this stage of the design. The same holds for a structural design that is very dependent on rules and regulations. A general arrangement is included in the hull form. Seakeeping is not included in the model; a sufficiently high enough freeboard is expected to be enough for this vessel that will only sail on inland waterways. A stability calculation is included mainly to check the possibility of a liftable deck and can be found in paragraph 7.6.

7.3. Logistical profile

For the model, simplified logistical inputs are used. There is no complete model of the different load and unload locations in the city with the distance between because these locations are not yet known. Instead of this detailed information a more general input of requirements is used for the model. This makes use of several unload locations in the city with a set distance between them. Also, there is a fixed value for the distance from the hub to the city centre. By changing the number of unload locations and the distance between them, different scenarios can be modelled without knowing the exact details in real life. This is enough to give a first indication of the performance of the vessel.

The main input for the logistics information is the route information. The input is changed by moving the sliders on the dashboard as can be seen in table 1. The speed, number of stops and distances all have impact on the number of trips that can be sailed each day.

Table 1, route information input [own]



Route	cruising speed	12	km/h	0		18
	inner city speed	6	km/h	0		8
	Distance hub to city centre	7	km	0		20
	Average distance between stops	0.25	km	0		2
	# stops in the city centre	4	-	1		10

Other logistical information includes the possibility of taking on board a return load that can be changed between 0 and 100 percent of the cargo capacity. While a return load of 100 percent is very unlikely a small return flow can reduce the cost price of each container resulting in lower costs for the customer. The return flow can contain of trash, parcels or other goods that now generally require a separate transporter to pick them up.

Because there is a possibility for additional power requirement to handle or refrigerate the cargo an extra input is added. For now, this value is set at 4.5 kW for each hour of operating time.

7.4. Hull form and weight

The hull form is simplified as a square barge with a separate forepeak. Because of aesthetic reasons the forepeak is not blunt but has a more traditional point. In the model the dimensions of the vessel are a function of the number of containers carried in the hold. The forepeak has a length of 4 meter to accommodate enough room for the wheelhouse from which the captain can sail the vessel. The side decks of the vessel have a fixed width of 40 centimetre to accommodate for the construction of the hull. This width is chosen so that the operator will be able to walk on the side decks from front to aft. The aft deck has a fixed length of 0.5 meter. This is seen as the minimum space needed for the handling for ropes when mooring. These design choices result in the following general arrangement of the vessel as seen in figure 10.

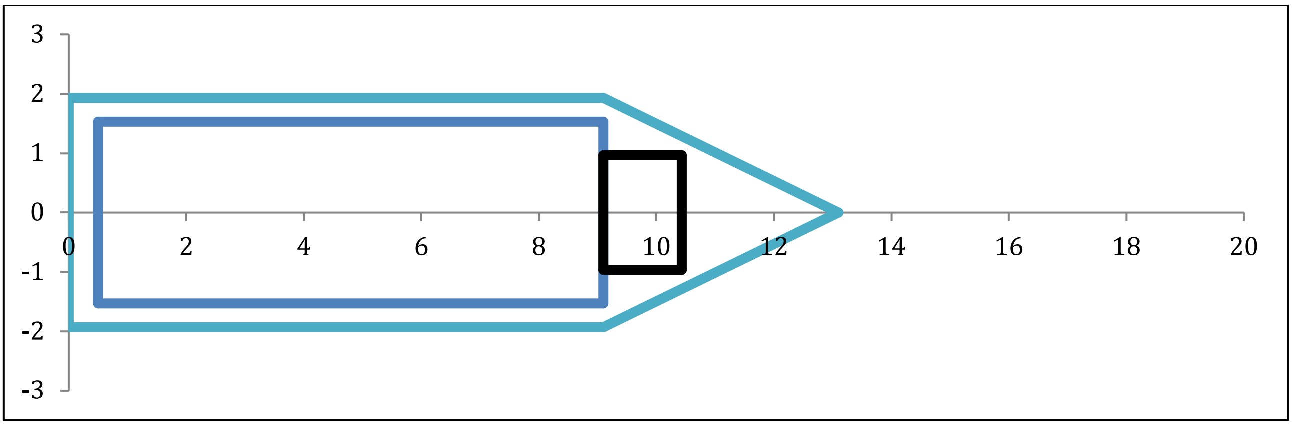


Figure 10, Vessel 4 containers wide and 10 containers long. (Dark blue=cargo hold) (Black=wheelhouse) [own]

The weight of the vessel is estimated using the method developed by Watson [81]. In this method the lightweight of a vessel is calculated using the equipment number of a vessel. The equipment number of a vessel depends on the main dimensions of both the hull and the superstructure. The equipment number (E) can be calculated using formula [7-6]. The values $l_{1,2}$ and $h_{1,2}$ are the length and height of the superstructures of the vessel.

$$E = L(B+T) + 0.85L(D-T) + 0.85[(l_1.h_1) + 0.75(l_2.h_2)] \qquad [7\text{-}6]$$

After calculating the equipment number the lightweight (W) is calculated using formula [7-7]. This formula uses a parameter K which depends on the type of vessel. E. van Hassel [23] used for this parameter a value of 0.019 after he found that the K-value for container vessels would result in an overestimation of the weight of inland vessels. Because the inner-city cargo vessel also is an inland vessel the same value of K is used in the model.

$$W_{si} = K.E^{1.36} \qquad [7\text{-}7]$$

The weight of the vessel is validated using the known weight of a tour boat sailing in the city centre of Amsterdam. When the cargo vessel is scaled to the dimensions of a tour boat that is roughly 18 by 4 meters the weight of the hull excluding the battery pack is 14 ton. Compared to the hull weight of the tour boat of 13.2 ton this is very similar. The added weight is mainly contributed by the addition of a liftable deck for the cargo vessel.

7.5. Propulsion

The main requirement for the propulsion system is that it needs to be free from any harmful emissions. This presents two options for the propulsion of this inner-city cargo vessel. The first option is to use electricity for the propulsion of the vessel. The second option is to use hydrogen as a fuel for the propulsion of the vessel. The energy in the hydrogen can be transformed into propulsive energy in two different ways. By using a fuel cell to convert the energy into electricity or by using a more traditional internal combustion engine fuelled by hydrogen. Because the main propulsion will be electrical and the first function for the hydrogen will be that of a range extender, a fuel cell will be used in case of a hydrogen-electric propelled vessel.

For the modelling of the propulsion system the document “an approximate power prediction method” by Holtrop and Mennen [63] is used. This method starts with a resistance prediction using the following formula, see formula [7-8]. In which the frictional resistance is calculated using the ITTC-1957 fiction formula.

$$R_{\text{total}} = R_F(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \quad [7\text{-}8]$$

To account for the added resistance in the shallow canals a shallow water correction can be added to the total resistance as formulated by Holtrop and Mennen. The shallow water correction method of Karpov is used [64]. This method results in the following formula, see formula [7-9].

$$\mathrm{R}_{\text{ondiep}} = \frac{1}{2} \,.\, \rho.\, \mathrm{S} \,.\, ((\mathrm{C_f}+\mathrm{C_a}).\mathrm{V_1}^2 + \mathrm{C_r}.\mathrm{V_2}^2) \quad [7\text{-}9]$$

This formula contains three different coefficients namely the friction correlation coefficient Cf, the correlation coefficient Ca and the rest resistance coefficient at deep water Cr. The different speeds V1 and V2 are based on the speed of the vessel (V). These speeds are calculated using the following formulas [7-10] in which the terms α* and α** come from figure 11. Here the terms for alfa are based on the Froude depth number of the vessel and the H/T ratio of the water depth and the vessel draft. The Froude depth number is calculated using formula [7-11].

$$\mathrm{V_1} = \frac{\mathrm{V}}{\alpha^*} \quad [7\text{-}10]$$

$$\mathrm{V_2} = \frac{\mathrm{V}}{\alpha^{**}}$$

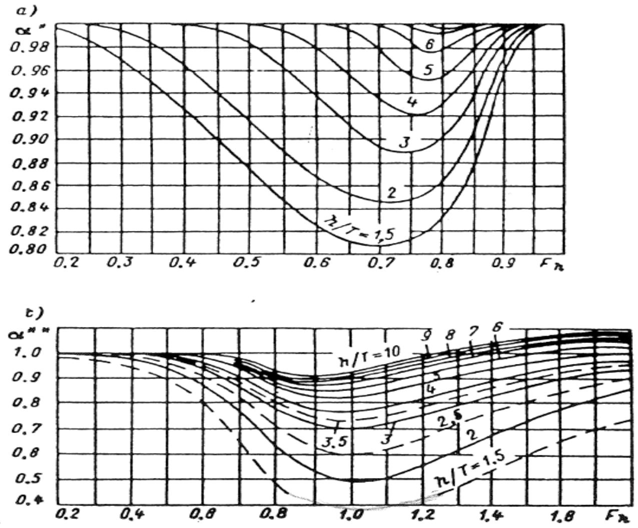


Figure 11, correction lines for the speed [64]

$$Fnh = \frac{V}{\sqrt{g.h}} \qquad [7\text{-}11]$$

After calculating the resistance of the vessel, the required brake power can be calculated. This is the power that needs to be delivered by the engine to propel the vessel at the given speed. This conversion includes several different efficiencies from the several converters as can be seen in figure 12. The biggest loss in the propulsion system is that of the propellor. In general, the open water efficiency for the propellor lies in the range of 30% for inland ships and 70% for frigates [65]. Because of this an open water efficiency of 40% is taken for the vessel. The overall electro motor efficiency including the transformers is taken as 91% as found in the research of Arnaldo Jose Perin [82]. The hull, relative rotative and shaft efficiencies are 103%, 101% and 99.5% respectively in accordance with the values given in the book: “Design of propulsion and electric power generation systems”.

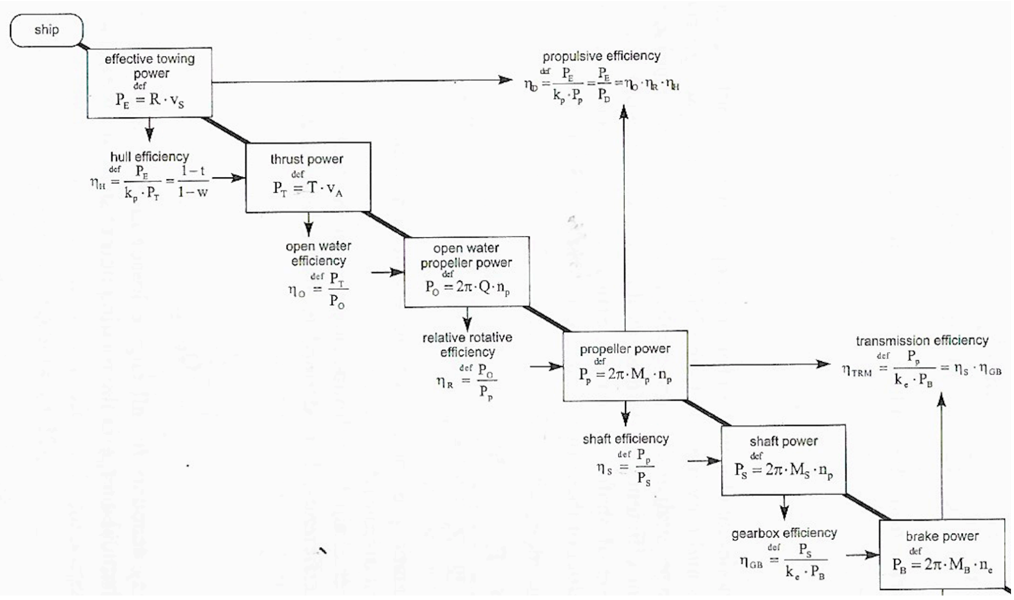


Figure 12, From resistance to installed engine power [65]

For manoeuvring in the canal's additional bow and stern thrusters will be installed. To account for the power consumption of these thruster an additional power requirement is added. This added power requirement is an additional input variable that during this stage of the research is set at 2 kW, but this value can be changed in the inputs.

The main propulsive power will be delivered by an electric motor. By combining the electric motor with a battery pack, with or without a hydrogen powered fuel cell, it will provide a system that is free from harmful emissions. The option where the battery is combined with the fuel cell is called the fuel cell hybrid, see figure 13.

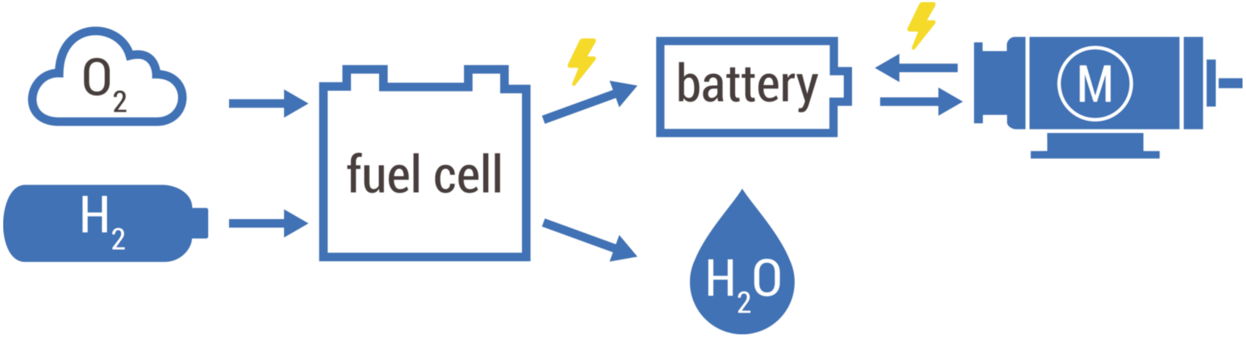


Figure 13, fuel cell hybrid system [66]

7.4.1 Fuel cells

Fuel cells are electrochemical cells that are used to convert the chemical energy of a fuel combined with an oxidizing agent into electrical energy. This is done through a pair of redox reactions. The main difference between fuel cells and batteries is that fuel cells require a constant flow of fuel and oxygen where the reactant of a battery generally are already present within the battery [67]. A fuel cell contains of both an anode and a cathode that are separate by an electrolyte, see figure 14. The flow of the fuel will pass on the anode side while the flow of air passes on the cathode side. When passing through the fuel cell the different flows react resulting in a flow of electrons that can be used in other electrical appliances like electro motors or that can be stored in a battery. The hydrogen used by the fuel cells will be stored as a compressed gas in separate tanks. The number of tanks required is dependent of the amount of hydrogen that is required to sail a specific sailing profile.

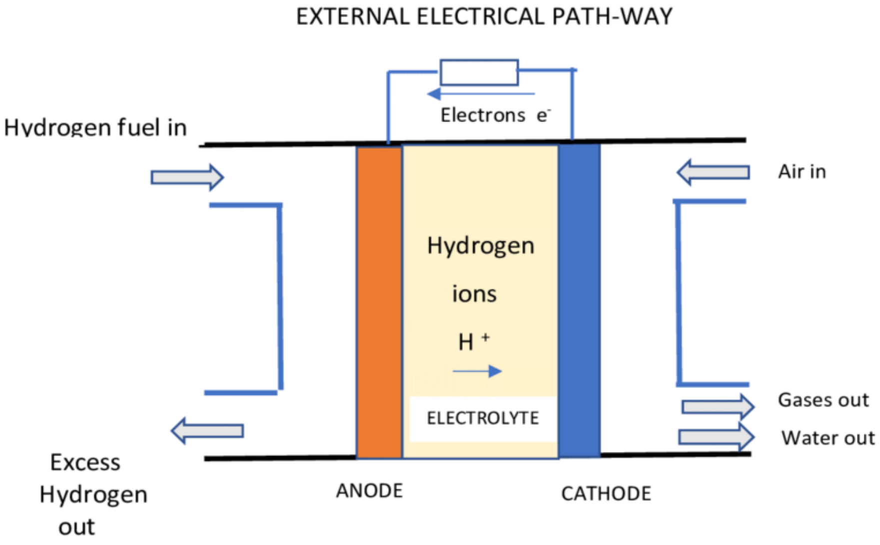


Figure 14, diagram of a fuel cell [68]

The European maritime safety agency distinguishes 7 different potential types of fuel cells to be used in the maritime sector. A brief explanation of these different types is given in the document: "Study of the use of fuel cells in shipping" [67]. Based on 11 parameters which include costs, lifetime, technological maturity, emissions and safety, they came up with the 3 most promising technologies. These are: the Proton exchange membrane fuel cell (PEMFC), the High temperature PEM fuel cell (HT-PEM) and the Solid oxide fuel cell (SOFC).

Proton exchange membrane fuel cell (PEMFC)
An PEM fuel cell can only be powered by hydrogen. The electrodes used are platinum based and the electrolyte is a humidified polymer membrane [67]. PEM fuel cells have already been used in a lot of applications like cars and passenger ships with power levels ranging from 12-60kW. This fits within the power levels required for the inner-city cargo vessel. The efficiency of these type of fuel cells is moderate ranging from 50-60%.

High temperature PEM fuel cell (HT-PEM)
The main difference between a PEM fuel cell and a high temperature PEM fuel cell is their operation temperature. Because the high temperature PEM fuel cell has a lower power density and is not able to cold start this option is less suitable to be used in the proposed concept

Solid oxide fuel cell (SOFC)
Compared to the previous fuel cells the solid oxide fuel cell operates at a lot higher temperature in the range of 500 to 1000 degrees centigrade. A SO fuel cell uses a porous ceramic material as the electrolyte and an anode of a nickel alloy and a cathode of a lanthanum strontium manganite. SO fuel cells are generally used on shore in large scale power production plans making it not a suitable for the inner city cargo vessel.

Fuel cell used
For the inner-city cargo vessel, a normal PEM fuel cell will be used as a range extender. This because of its higher power density. Also, the poisoning of the catalyst by carbon monoxides and Sulphur is less of a problem because pure hydrogen will be used as the fuel. The high number of applications of PEM fuel cells means that the technology is ready to be implemented. The SWIMH2 water taxi concept in Rotterdam developed in cooperation with Enviu also makes use of a PEM fuel cell [69]. The hydrogen will be stored as a pressurized gas at a pressure of 350 bar.

7.4.2 Batteries

The batteries on board are necessary to store the required energy needed by the vessel in case of a fully battery powered vessel and to compensate for the varying power consumption in case of a fuel cell hybrid vessel. When researching the possibility of an electric tour boat on the canals of Amsterdam TNO [70] researched two different types of battery. The Lithium-ion battery and the more traditional lead acid batteries. Lithium-ion technology batteries have a high charge and discharge efficiency of around 95%. This is a lot higher than that of a lead acid battery which is around 70%. Although not an important factor for batteries that are in daily use, the self-discharge of lithium-ion batteries is lower compared to lead acid batteries (around 1% per month vs 5% per month) [70].

Based on the TNO report the most suitable lithium-ion battery to use on board of the vessel is a LFP battery. This is a Lithium Iron Phosphate battery that is also used in other sectors like automotive. Tesla announced that they will use LFP batteries in all their standard range cars despite their lower energy-density compared to the current batteries [71]. The reasons why LFP batteries are used is because these batteries are significantly cheaper, and they are more stable which makes them safer. The most important parameters of both types are summarized in table 2. It is important to note that the values used can differ depending on the manufacturer of the batteries used.

Table 2, comparison Lithium and Lead-acid [70]

	Price (B)	Max discharge*	Lifecycles	Energy density	Charge speed	Charge discharge efficiency
	[€/kWh]	[%]	[-]	[kg/kWh]	[c]	[%]
Lithium (LFP)	250	80	3000	10	2	95
Lead-acid	140	80	1500	30	0.1-0.3	70

*Depends strongly on the depth of discharge and battery quality

The following advantages and disadvantages for both the lead acid and lithium-ion batteries can be found in table 3.

Table 3, Advantages and disadvantages battery types [72]

Type of battery	**Advantages**	**Disadvantages**
Lead acid	Inexpensive Lead is easily recyclable Low discharge	Short life cycle Cycle life is affected by depth of charge Low energy density
Lithium ion	Very high efficiency Very low discharge Low maintenance	Very high cost Life cycle reduces by deep discharge Need special overcharge protection circuit

Following on the information above, lithium-ion batteries will be used for the inner-city cargo vessel. Their more complicated electronics and higher costs are compensated by the higher number of cycles before replacing and their lower weight. The high charge rate also gives the possibility to charge the battery during the day while docked for loading and unloading.

7.6. Stability

Because there is a requirement of a (partly) liftable deck for easy loading and unloading a static stability check is done. This is because the raised deck full of cargo has a negative effect on the stability of the vessel. By making sure there is enough static stability the vessel will not capsize while the deck is raised. This will limit the amount of deck that can be raised at once.

In order to check the static stability of the vessel with a lifted deck the metacentre value GM with a raised deck is calculated. The metacentric height is point M in figure 15 and the points G, B and K are the centre of gravity, centre of buoyance and the keel. When the vessel heels the centre of buoyancy moves to the side as seen on the right side of the figure. The vertical force from this point passes through the metacentre resulting in a righting moment. When M lies above G this righting moment will counterbalance the moment of the gravitational force resulting in a upright vessel.

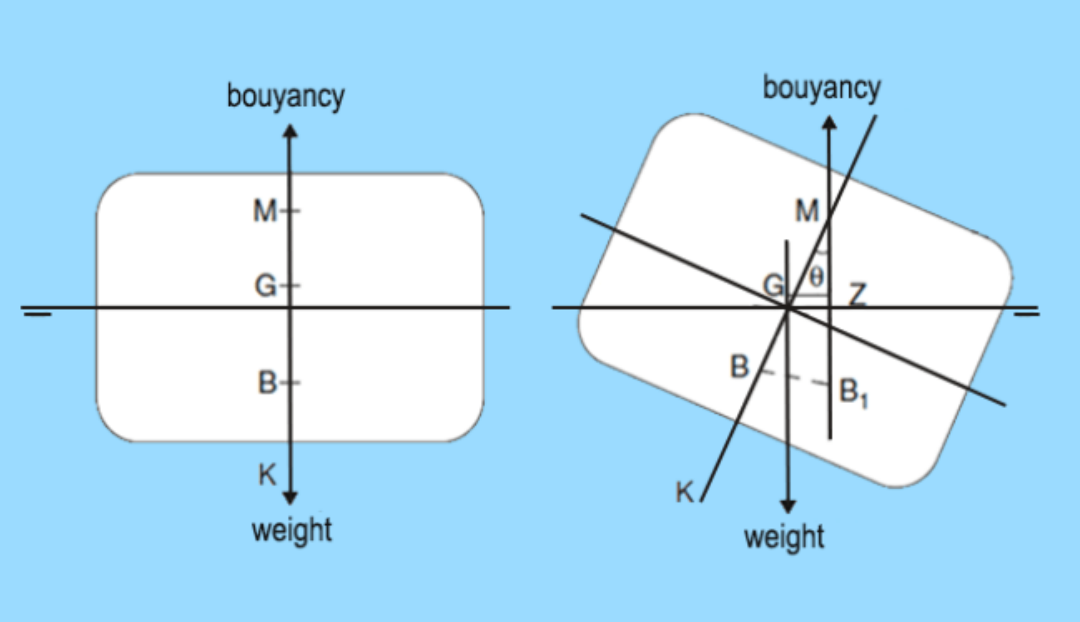


Figure 15, metacentric height [73]

The value of GM is calculated using the following formula's [7-12], [7-13] and [7-14]. A positive value of GM means the ship is stable and a negative value of GM means the ship is unstable. When the value of GM is 0 the vessel is neutrally stable. The raised deck will result in the highest value of KG. Because KM is a fixed value for each design, this will result in the lowest value of GM. Because of this the value of GM in the model is only calculated for the situation where the deck is raised.

$$GM = KM - KG \tag{7-12}$$

$$KM = KB + BM \tag{7-13}$$

$$BM = \frac{I}{\nabla} \tag{7-14}$$

7.7. Dashboard of the decision support tool

The model can be used by only using the dashboard. Here the most important variables can be changed why looking at different output variables like the costs for each container. When a more detailed insight into the calculation is required, the corresponding tab can be consulted. Here it is also possible to change less important variables when necessary.

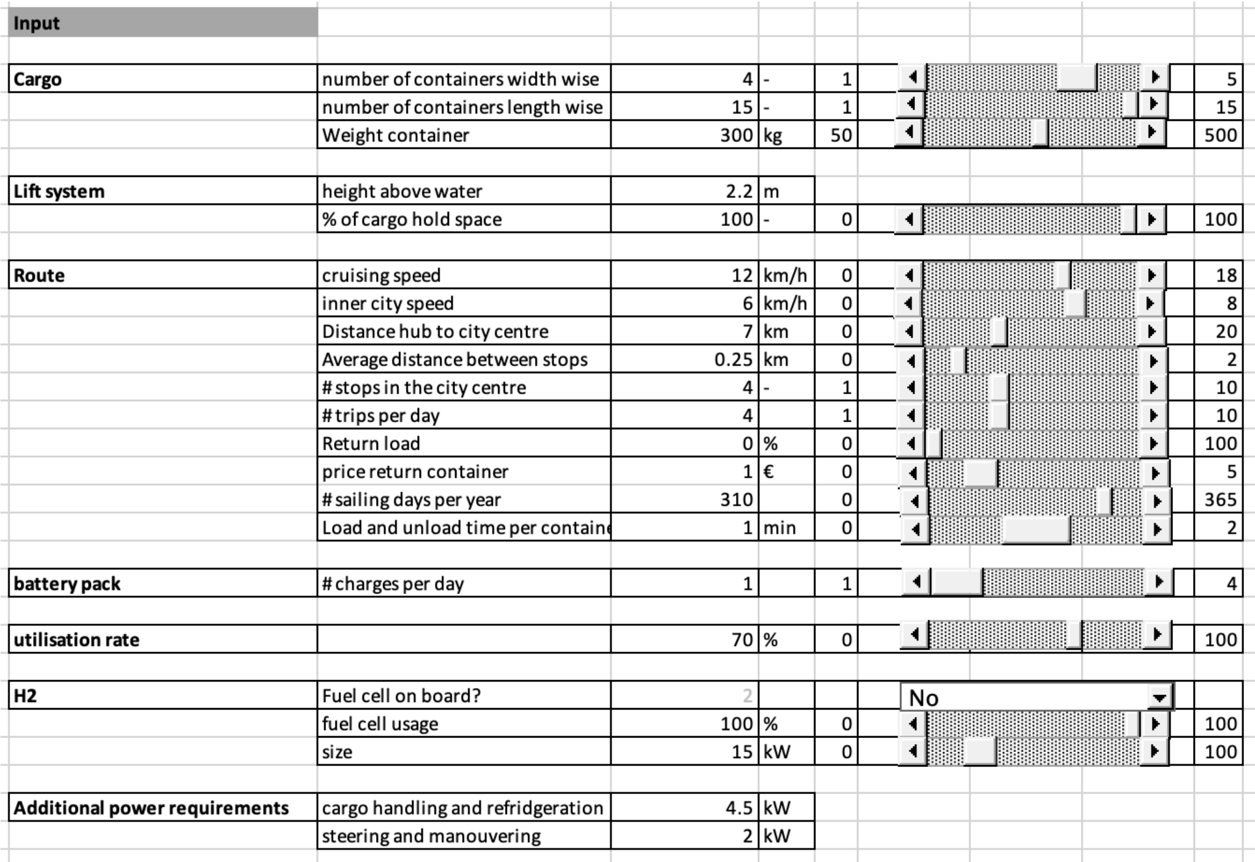
The dashboard contains the most important input and output variables. All variables are combines in one tab so quick changes can be made while observing the outcome. This makes it possible to quickly try out different possibilities or configurations.

7.7.1 Input

The input values to use in the model will follow from the initial requirements as set up by the owner or potential customer. These initial requirements generally include the number and average weight of the containers, and the information about the route and drop off locations.

This section includes all the variable input variables, see figure 16. Different input variables can be altered by using the sliders. The slides are set at a given range, but other values can by tested by filling in these values manually.

A drop-down menu is used to change between a vessel with or without a fuel cell on board. When choosing a fuel cell as a range extender the amount of electricity produced by the fuel cell can be altered using the slider below.

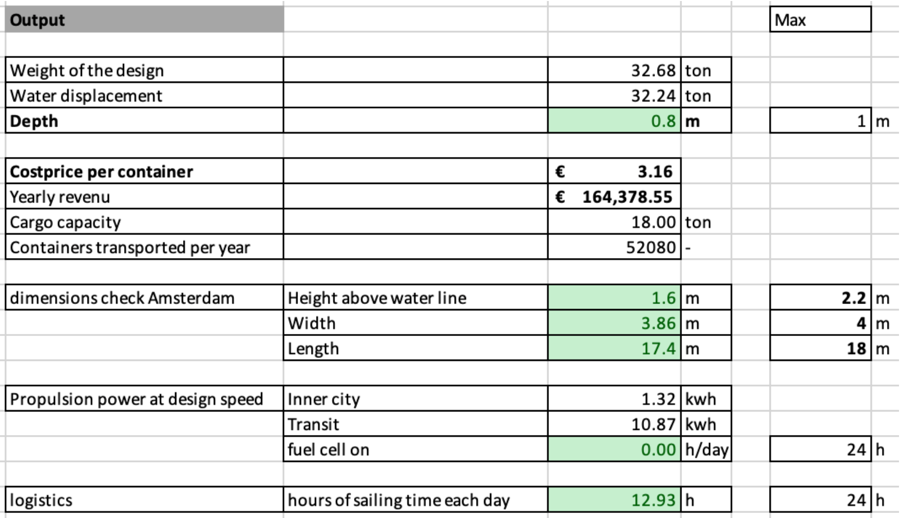


Input						
Cargo	number of containers width wise	4	-	1		5
	number of containers length wise	15	-	1		15
	Weight container	300	kg	50		500
Lift system	height above water	2.2	m			
	% of cargo hold space	100	-	0		100
Route	cruising speed	12	km/h	0		18
	inner city speed	6	km/h	0		8
	Distance hub to city centre	7	km	0		20
	Average distance between stops	0.25	km	0		2
	# stops in the city centre	4	-	1		10
	# trips per day	4		1		10
	Return load	0	%	0		100
	price return container	1	€	0		5
	# sailing days per year	310		0		365
	Load and unload time per containe	1	min	0		2
battery pack	# charges per day	1		1		4
utilisation rate		70	%	0		100
H2	Fuel cell on board?	2			No	
	fuel cell usage	100	%	0		100
	size	15	kW	0		100
Additional power requirements	cargo handling and refridgeration	4.5	kW			
	steering and manouvering	2	kW			

Figure 16, Input variables decision support tool

7.7.1 Output

This part includes the main output parameters, see figure 17. The most important variable is the cost price per containers. By changing the input values the cost price will also change. Also, a figure of the vessel is included, as found in figure 10. Here the hull can be seen in light blue and the cargo hold in dark blue. The black part is the wheelhouse for the captain.



Output				Max	
Weight of the design		32.68	ton		
Water displacement		32.24	ton		
Depth		0.8	**m**	1	m
Costprice per container		**€ 3.16**			
Yearly revenu		**€ 164,378.55**			
Cargo capacity		18.00	ton		
Containers transported per year		52080	-		
dimensions check Amsterdam	Height above water line	1.6	m	**2.2**	m
	Width	3.86	m	**4**	m
	Length	17.4	m	**18**	m
Propulsion power at design speed	Inner city	1.32	kwh		
	Transit	10.87	kwh		
	fuel cell on	0.00	h/day	24	h
logistics	hours of sailing time each day	12.93	h	24	h

Figure 17, Output variables decision support tool

Weight

The weight of the vessel gives an indication of the size of the vessel. Because the depth of the vessel is one of the input variables of the model this needs to be changed so that the displacement of the hull and the weight of the vessel including cargo are matched. When there is a big different between the water displacement and the weight the other calculations become inaccurate.

Cost price per container

This is the most important output value. By changing the input variables, the cost for each container will change. By making sure the cost price per container is as low as possible while considering the limitations the vessel will become more profitable. Also, the expected revenue of the vessel is given. As stated before the model does not take into account a profit margin but only looks at the cost price. A distribution of all the costs is included at the output by including the graph below, see figure 18.

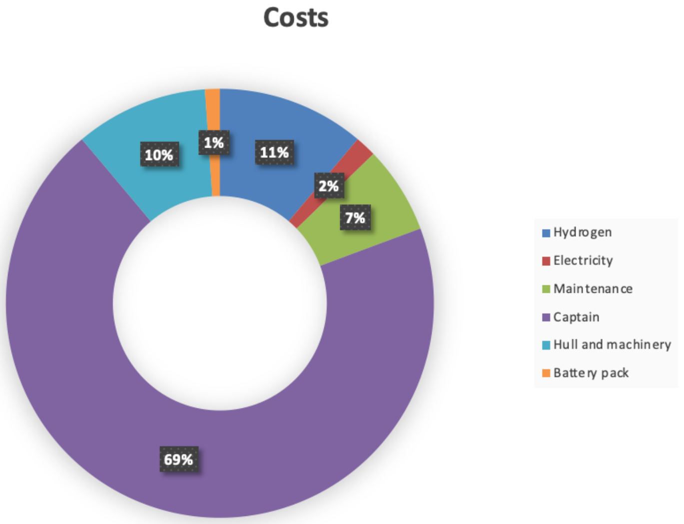


Figure 18, cost distribution output

Dimensions
The dimensions of the vessel are one of the limitations found in the city centre of Amsterdam. To check whether the vessel will be able to sail on the canals of Amsterdam, the dimensions of the vessel need to be smaller than the maximum values as given on the output page.

Propulsion power
The main parameters of the propulsion system are given. This includes the minimal installed power to sail at the required speed. The size of the battery pack and hydrogen system to make sure enough energy is on board to meet power demand are also output values. When the hours the fuel cell needs to be operational exceeds the number of hours the vessel is sailing a bigger fuel cell needs to be included or the percentage amount of energy produced by hydrogen needs to be lowered.

Hours sailing
The number of hours the boat is sailing is depending on the number of trips and the duration of these trips. The model does not limit the number of hours the vessel is allowed to be operational because it may be beneficial to sail an extra trip during a day. By sailing an additional trip during a day, the cost price per container could reduce a considerable amount. A manual check needs to be performed to check whether the vessel does not exceed an operational time of more that 24 hours per day. When this is the case, the vessel needs to shorten its trip time or limit the number of trips made each day.

7.8. Conclusion

Chapter 7 includes an overview of all the different aspects that are included in the decision support tool. The tool serves as a framework for the next chapter where several different aspects are analysed. By combining the results of these two chapters the following sub question will be answered at the end of chapter 8:

> How can a decision support tool be supportive to generate a concept design for a vessel as a last mile solution in the inner city of Amsterdam?

8 Case study and sensitivity analysis

The case study as used as the starting point for the analyses is given by Enviu. Based on their first insight, Enviu came with a vessel to transport cargo on the canals of Amsterdam. This base case study will be elaborated on in the first paragraph. After implementing the case study in the model, a sensitivity analysis is done on the size of the vessel by changing the number of containers transported. Based on these analyses an additional design is formulated from where a more detailed sensitivity analyses is done to acquire general rules of thumb for the design of inner-city cargo vessels. Each of them investigates a different relationship between different design considerations like speed, distances, costs etc.

8.1. Case study

The case study is based on the initial idea from Enviu. Enviu came up with the idea of a zero-emission logistical solution for urban waters. They did some research partly based on the proposed hydrogen drive water taxi sailing in Rotterdam.

The initial idea from Enviu is to build a boat made of polyethylene with a cargo capacity of 28 rollable containers. Because of the preference to build a scalable and environmentally friendly the build material is changed from polyethylene to steel for this research. A steel hull can easily be adapted to a different design while this would require an entirely different building mould for other materials. Also, the weight penalty is not as much of a problem because the vessel would otherwise require ballast to sail at a large depth to ensure that it can sail underneath bridges. A render used for promotional purposes can be seen in figure 19.

Figure 19, Portago vessel concept [77]

The propulsion of the vessel needs to be free of any harmful emissions. Because of this Enviu included an electric propulsion with the use of a fuel cell for additional range. In the first concept the fuel cell has a power of 95kW and a hydrogen storage of 15kg of compressed hydrogen. Additionally, there is a 40kW battery pack, but the vessel would only be fuelled by hydrogen.

The initial range requirements are:

- Average return fare distance 15 km
- Total distance per 12 hours 60-90 km
- Average speed 8 km/h
- Return fares per boat per day 4 (12-hour slot)

Based on the initial requirements more input variables are needed for the model. These variables are formulated in consultation with Enviu. In total 4 stops with 250 meters in between need to be supplied. The distance from the hub to the city centre is 7 km and an initial utilisation rate of 70% is used. In the initial calculation no return cargo is considered. A complete overview of the input parameters can be found in Appendix B.

Outcome

The concept of the vessel is designed with the help of the decision support tool and the input values from above. The tool contains all the main design parameters and calculates the cost price per container. The vessel has a length of 10.52 meter and is 3.86 meters wide, see figure 20. For the utilization rate a value of 70% is used. The main output parameters are summarised in table 4.

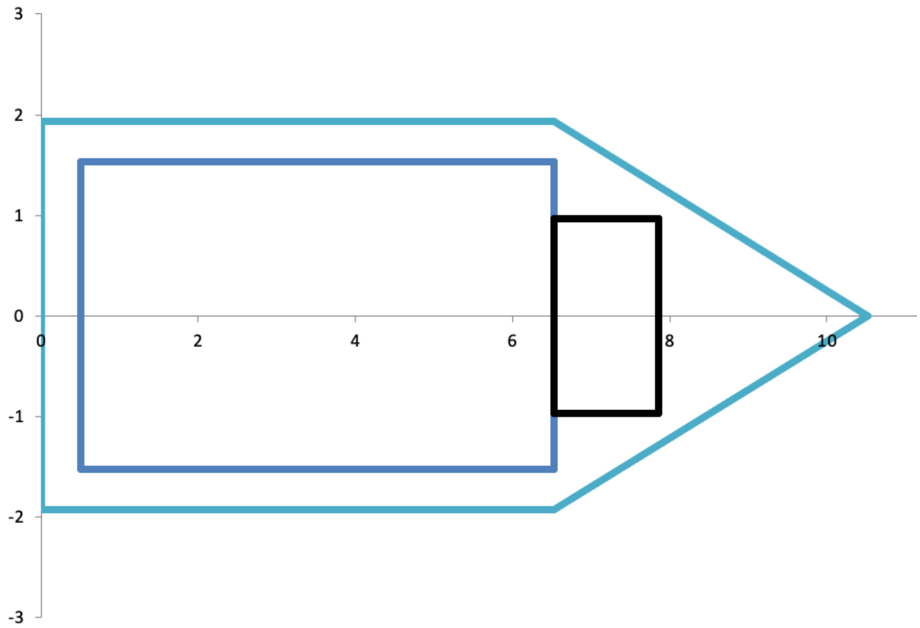


Figure 20, Vessel layout case study

Table 4, output parameters

PARAMETER	VALUE	UNIT
LENGTH	10.52	M
WIDTH	3.86	M
DEPTH	0.72	M
WEIGHT	17.61	Ton
CONTAINER CAPACITY	28	-
CARGO CAPACITY	8.40	Ton
PROPULSION POWER	3.50	kW
SAIL TIME PER DAY	13.5	hours

The design results in a cost price per container of €7.73. The is based on 300 sailing days per year. The total cost price per container is calculated by dividing the total costs per year by the total number of containers transported. The total yearly revenue is €186,950.21 and there are 23,520 containers transported. A breakdown of all the yearly cost can be found in figure 21. The biggest cost is the captain cost accounting for €121,500.00 of the total costs. An increase in the total number of containers transported in necessary to reduce the total cost per container. This way the captain costs are spread out over a larger number of containers.

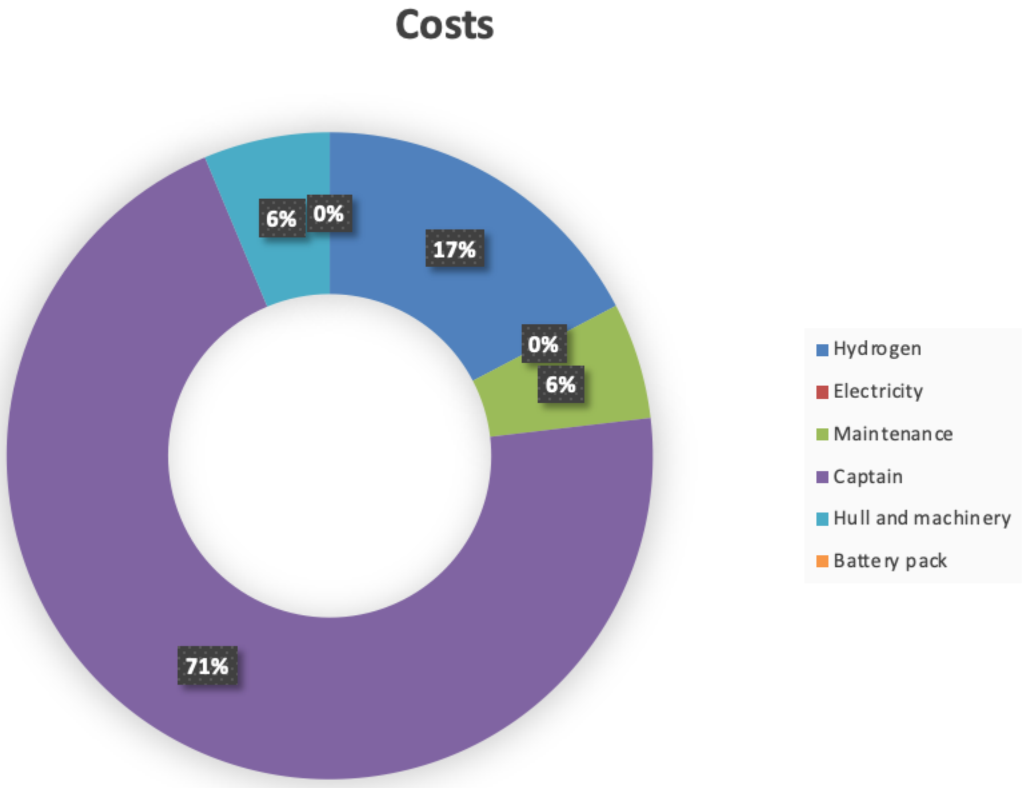


Figure 21, yearly costs case study

8.2. Sensitivity analysis

Starting with the case study, a sensitivity analysis for various designs and input parameters is done by comparing the design requirements with the cost price per container. By doing so general rules of thumb for the development of these new inner city cargo vessels are found. The analysis starts with a size analysis where the influence of size on the overall cost per container is evaluated. Following a comparable analysis is done considering the influence of speed on the costs. After these several different logistical aspects are considered like the utilisation rate, distance to city centre and number of stops in the city centre. In the end, an analysis is done on the costs relating to different energy sources like electricity of hydrogen.

8.2.1 Size analysis.

Following this first design, the size of the vessel is analyses. Because the captain cost turned out to be the biggest contribution to the overall cost an increase in the number of containers transported would be beneficial. This analysis is done by varying the number of containers length wise between 1 and 15 for the different widths of 1 till 5 containers wide, see figure 22.

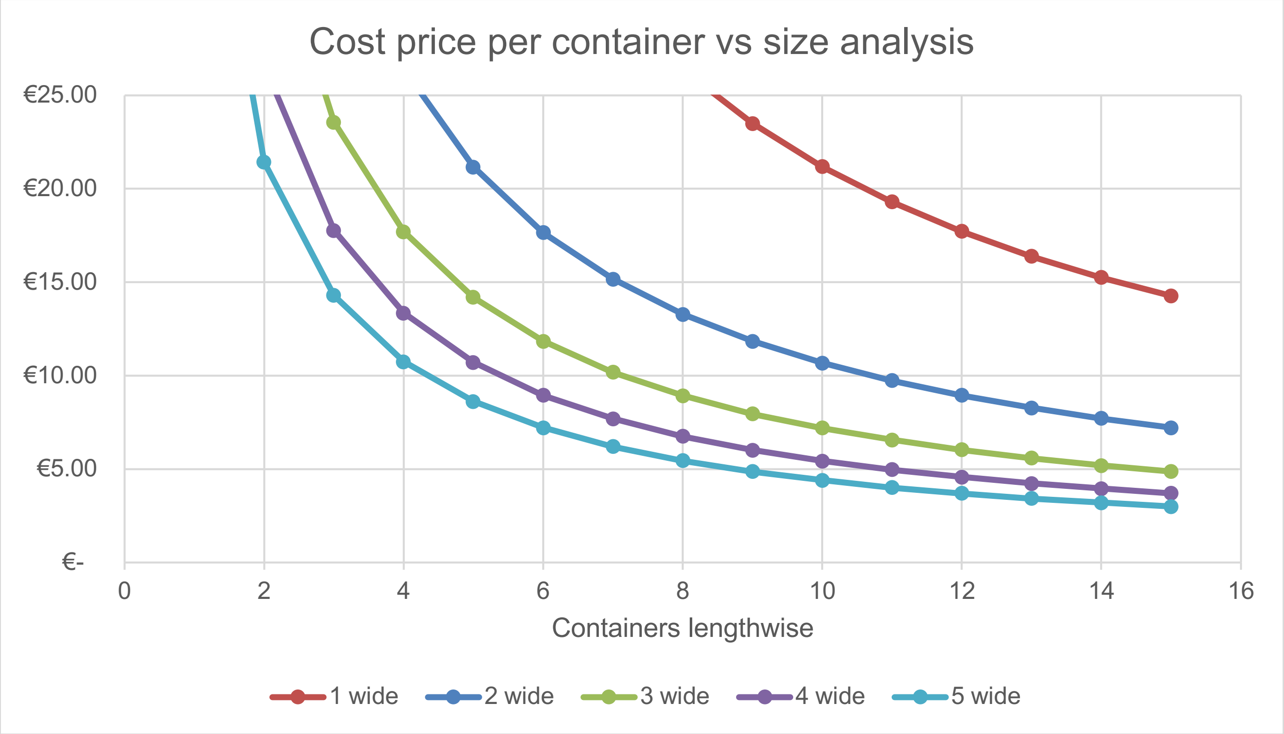


Figure 22, cost price per container for various sizes

When the vessel can carry more containers the cost price per container gets lower. The increase in size and power consumption is counterbalanced by a higher decrease in captain cost. This shows that it is beneficial to use a vessel that can carry as much containers as possible although it will be limited by the demand for containerised transport. To be able to supply most of the inner-city canals, it was found from literature that the vessel should fit within the requirements of section B and C of figure 6. This results in a vessel with a maximum width of 4 meters and a maximum length of 18 meter. This corresponds with a vessel that carries 15 containers lengthwise and 4 containers width wise. These dimensions will be used in the following analyses.

8.2.2 Speed analysis.

The speed of the vessel affects the resistance of the vessel. By using different speeds as input for the model the resistance at these different speeds can be calculated. The insight generated by this analysis is than used to study the influence on the cost price. Also, the correlation between cruising speed and total trip time is added because shorter trips means that more trips can be made during a delivery window.

Transit speed vs resistance

The first speeds analysis figure studies the relation between the speed of the vessel and the resistance at different speeds. For both lines the vessel is 4 containers wide and 10 or 15 containers long. Both a longer and a shorter vessel are used as input to further investigate the impact length has on the resistance and thus overall cost.

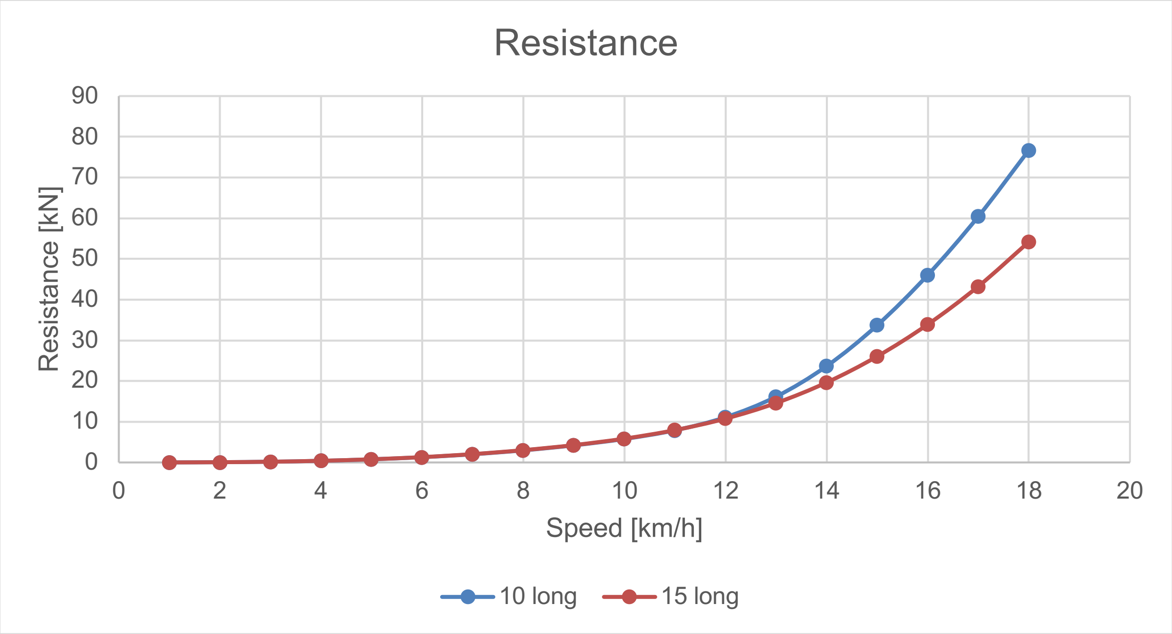


Figure 23, Vessel resistance at different speeds

When increasing the speed, the resistance of the vessel will also increase as can be seen in figure xx. Because resistance increased with the power 3 it shows that it would be beneficial to not sail a lot faster than 12 km/h. This figure also shows that an increase in length of the vessel results in a lower resistance. This again shows that it would be more beneficial to build a bigger vessel although the difference is very small at lower speeds.

To check this theory a comparison is made between a vessel with a capacity of 56 containers sailing half full and a vessel of 28 containers sailing full. This results in the following cost price per container, table 5. A larger vessel sailing at only part of its capacity will not result in an increase in cost price per container compared to the smaller vessel. This also has the advantage that when more cargo is available the vessel has the capacity to carry these additional containers to increase the income and lower the cost price per container. Both vessels sail at 6 km/h in the inner city and 12 km/h on the transit route. For this calculation they sail fully electric with 4 stops in the city centre.

Table 5, Cost price per container for different utilisation rates [Own]

CONTAINER CAPACITY [-]	AVERAGE UTILISATION RATE [%]	COST PRICE PER CONTAINER
56	50%	€4.31
28	100%	€4.15

Speed vs cost price
Following for the speed vs resistance analysis a speed vs cost price per container graph is made, see figure 24. This shows that vessels that sail very slow will rapidly increase the cost price per container. When the overall cost price per container is low because of the high number of containers transported the line keeps on dropping until the maximum speed used in this analysis. But in case of a smaller vessel like a vessel that is only 10 containers long a favourable speed can be found within the range of the graph.

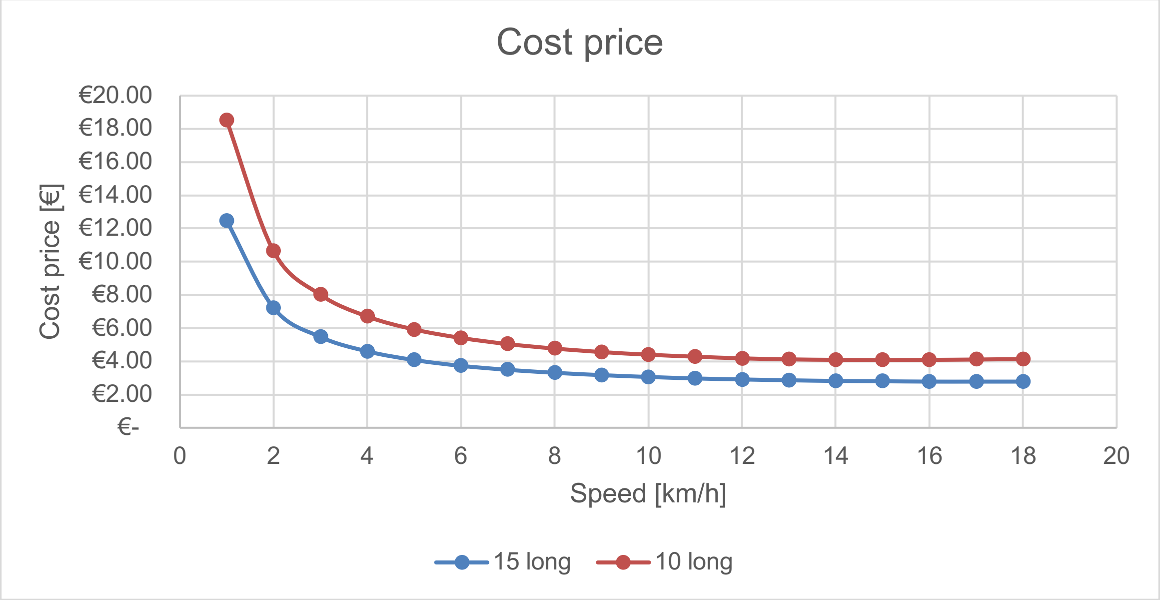


Figure 24, cost price per container for different speeds

Transit speed vs trip time
From figure 25 is concluded that by sailing at a higher speed, the total trip time deduces. This makes it possible to increase the number of trips a vessel can sail each day during the preferred time frame. When sailing at transit speed lower than 6 km/h an additional 1 km/h faster will decrease the trip time with more than half an hour per time step. When sailing faster this effect becomes smaller for each additional speed step. This figure is made for a vessel 4 wide, 15 long and sailing fully electric. It makes 4 stops; transit distance is 7 kilometres, and the inner-city speed is 6 km/h.

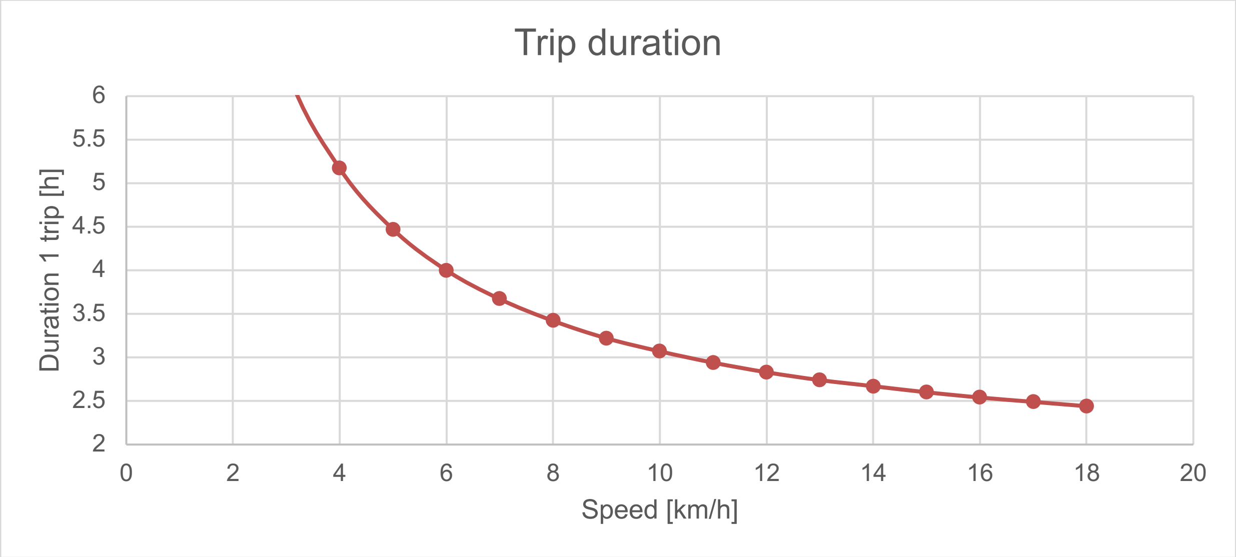


Figure 25, Trip duration based on speed

8.2.3 Logistical considerations

For the different logistical considerations different analyses are made. Al considerations are compared to their influence on the cost price. By using this information different prices can be calculated for different customers in the future. Following from the previous analysis for all figures a vessel that is 15 containers long and 4 containers wide is used. This vessel will sail at an inner-city speed of 6 km/h and a transit speed of 12 km/h.

Utilization rate vs cost price

The influence of the utilisation rate on the cost price per container is very high when the vessel is sailing a very low capacity, as seen in figure 26. An increase in the utilization rate of the vessel will lead to a decrease of the cost price per container. This effect becomes smaller for each increase. When sailing at 50% capacity the cost price will only decrease a small amount for each step. This figure shows it is important to use a vessel that sails at more than 20% capacity and preferable at an even higher utilisation rate. This graph can also be used to check the break-even capacity when a fixed price per container is used. In this graph the cost is calculated for a vessel sailing fully electric.

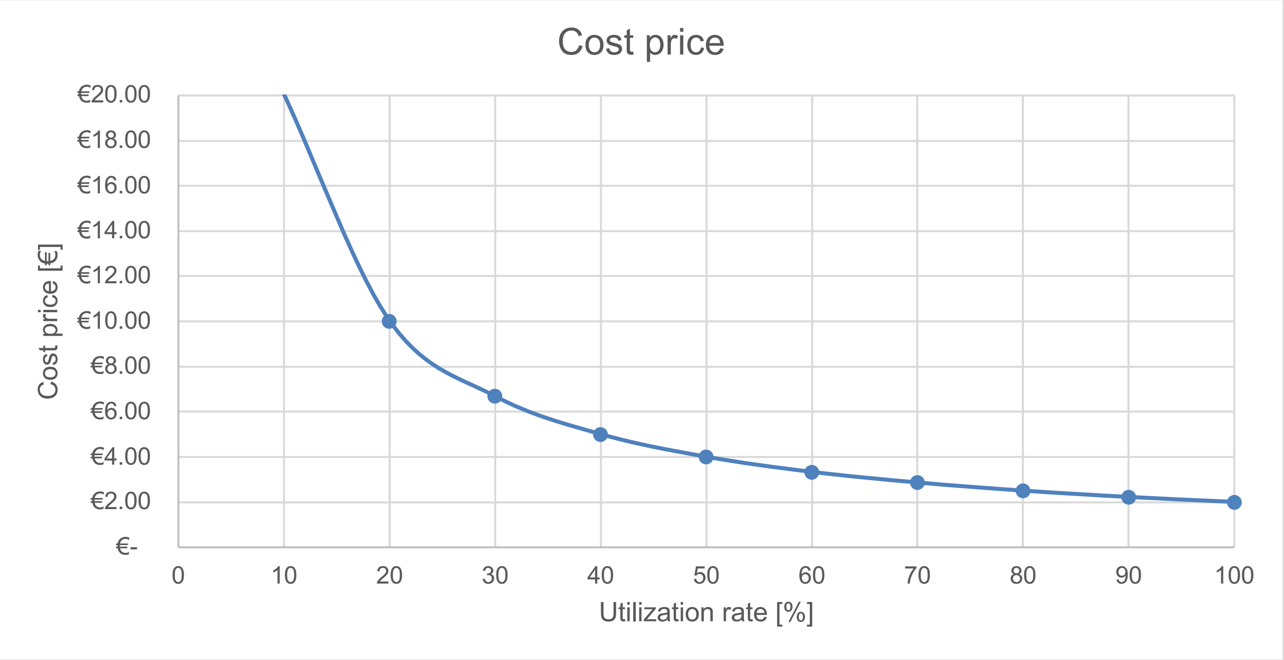


Figure 26, Cost price per container for different utilisation rates

Distance to centre vs cost price

When the hub of located far away from the city centre the cost price per container will increase as can be seen in figure 27. Each additional kilometre the vessel needs to sail between the city centre and the hub the cost price per container increases with roughly €0.18. It is important to have the hub located as near to the city centre as possible. Also, a larger means that less trips can be made decreasing the cost price even further for the hubs located closer to the city centre.

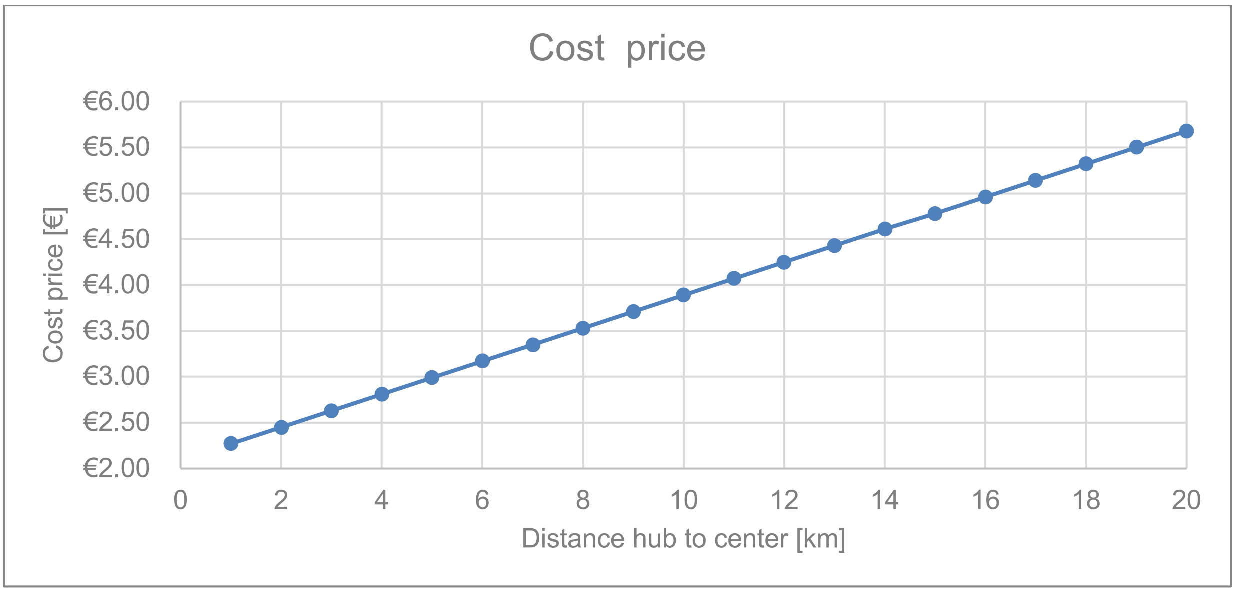


Figure 27, Cost price per container for different hub locations

Number of stops vs cost price

A similar correlation as above can be seen in figure 28 for the influence on the cost price per container for the different number of stops. Each additional stop will result in an increase of the cost price per container of €0.25. This also means that a higher cost price for a hub located further from the city centre can be compensated by reducing the number of stops. Because a decrease in stops will reduced the cost it is important to bundle the cargo as much as possible. Larger customers would be favourable to reduce the costs per container. For this consideration the stopping time at each location is the same and independent of the number of containers unloaded at the stop.

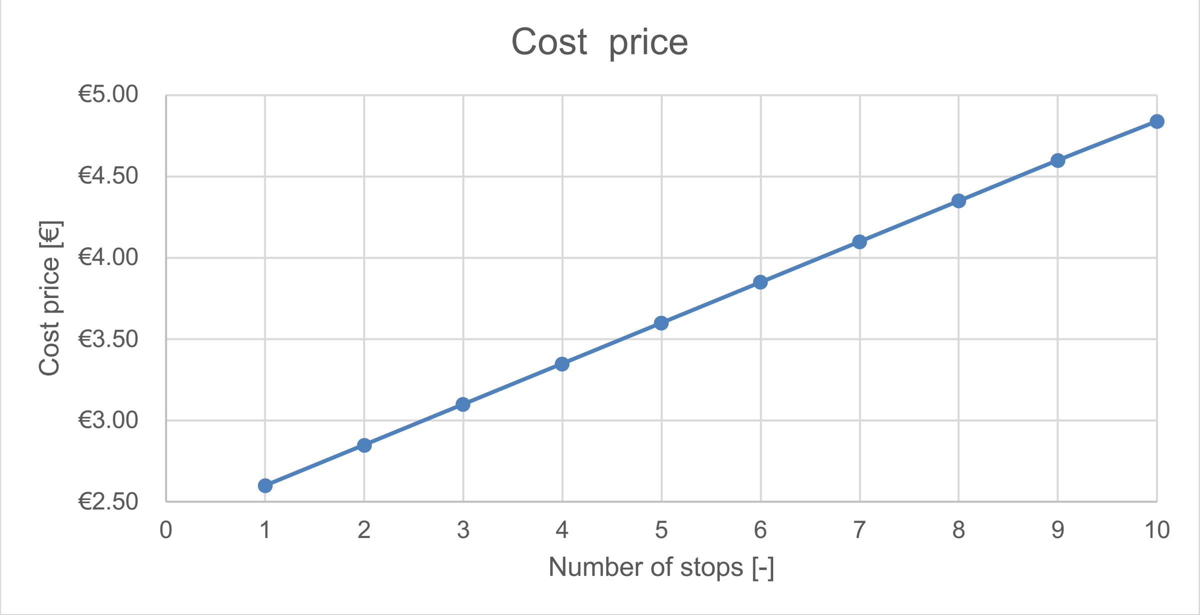


Figure 28, Cost price per container for different number of stops

Return cargo

By taking on board additional paid return cargo, besides the empty rollable containers, the cost per container will reduce. This return cargo brings in additional income while the costs stay the same. Because the cost price per container is a function of the cost that can now be reduces by the additional income the overall cost price will reduce with an increase of return cargo as also can be seen in figure 29. The effect becomes bigger when the price for each return container is bigger as can be seen for a price of €2.00 per container compared to €1.00. This eventually even results in an equal cost price per container when 40% return load at a price of €2.00 is taken on board. Although the graph goes from 0 to 100% return load it is expected that only a limited return load will be available. But what the figure does show is the positive effect on the cost price per container the addition of return cargo has.

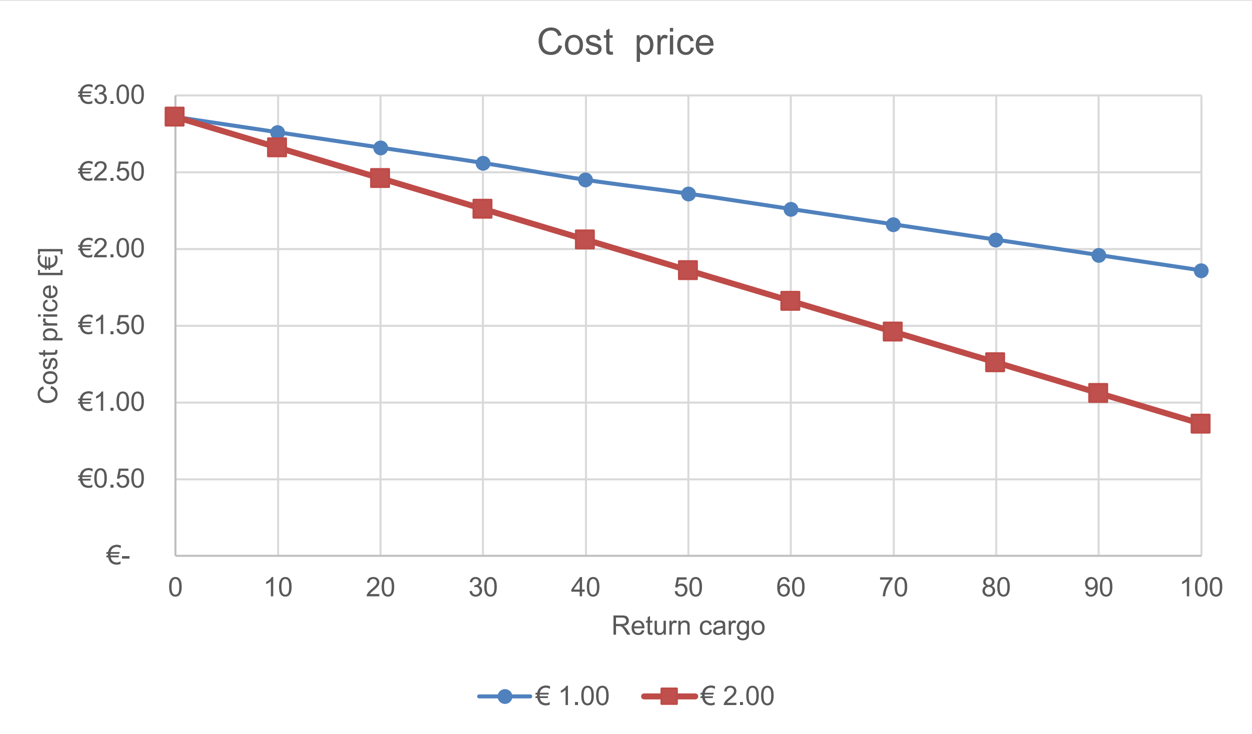


Figure 29, effect of return cargo on the cost price per container.

Number of sailing days per year

The number of sailing days per year has only a limited effect on the cost price per container. When sailing for 300 days per year 10 additional days will only result in a price change that is less than 1 percent for the cost price per container. As expected, it is favourable to sail as many days as possible but once the vessel can sail roughly 300 days per year the influence of additional days for the cost price per container is limited.

Stability vs lifting deck

The last analysis is more of a design aspect than a logistical aspect. This is the influence of the lifting deck on the static stability of the vessel. To be able to load and unload the vessel faster than a truck the proposal is to make a big part if not all the deck liftable at once. By doing so the containers can directly be loaded and unloaded without additional container movements. For this analysis the liftable deck needs to move 2.2 meter above the waterline. As can be seen in figure 30, the analysis is done for designs varying in width from 3 to 5 containers wide. The wider the vessel is the more stable the vessel is. For the vessel 3 containers wide a 100% liftable deck result is a negative GM value which is not possible. This means for a vessel 3 containers wide only part of the deck can be made liftable. For a vessel of 4 of 5 containers wide it is possible to lift the entire deck according to the calculations. More detailed designs need to be made to check whether this is also the case considering difference is container weights. For now, it is advised to take a margin when deciding the amount of deck that is liftable resulting in roughly 50% of the deck being liftable when 4 containers wide and 100% when 5 containers wide.

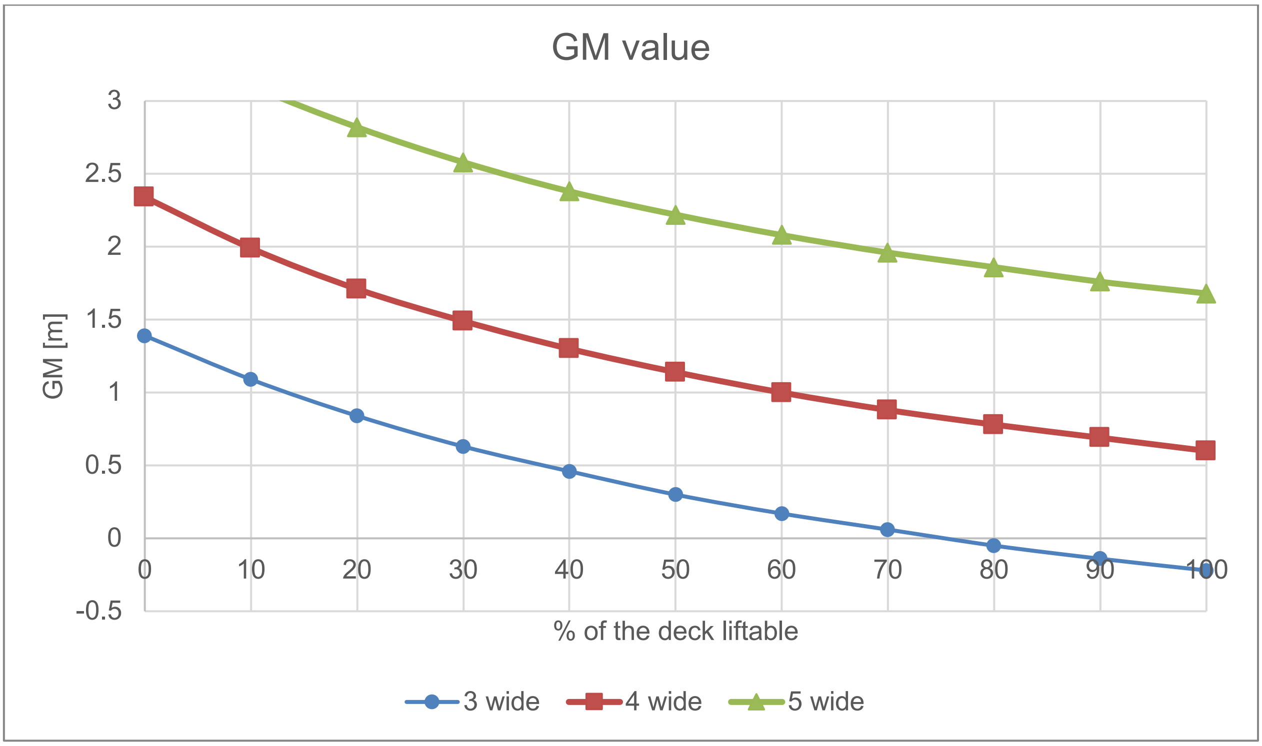


Figure 30, stability of the vessel

8.2.4 Propulsion considerations

When the size and trip considerations are made the cost price per container can be altered by looking at the different propulsion options. Sailing fully electric or using hydrogen will result in different cost prices per container. This is partly because of the higher initial investment and partly because the higher cost per kWh for Hydrogen compared to electricity. Again, the vessels tested are 15 containers long and 4 containers wide. The vessel will sail at an inner-city speed of 6 km/h and a transit speed of 12 km/h while having a utilisation rate of 70%

Percentage Hydrogen vs cost price

The higher the percentage of amount of power produced by the fuel cell the higher the cost price per container becomes as seen in figure 31. This is because the price per kWh for hydrogen in higher than the price for electricity. The cost price per container when sailing on electric only is €2.86 while the cost price per container for an 100% hydrogen propeller vessel is €3.35. This is a total increase of €0.49 per container or an increase in cost price of 17%. These calculations are based on an electricity price of €0.12 per kWh and a hydrogen price of €8.00 per kilogram.

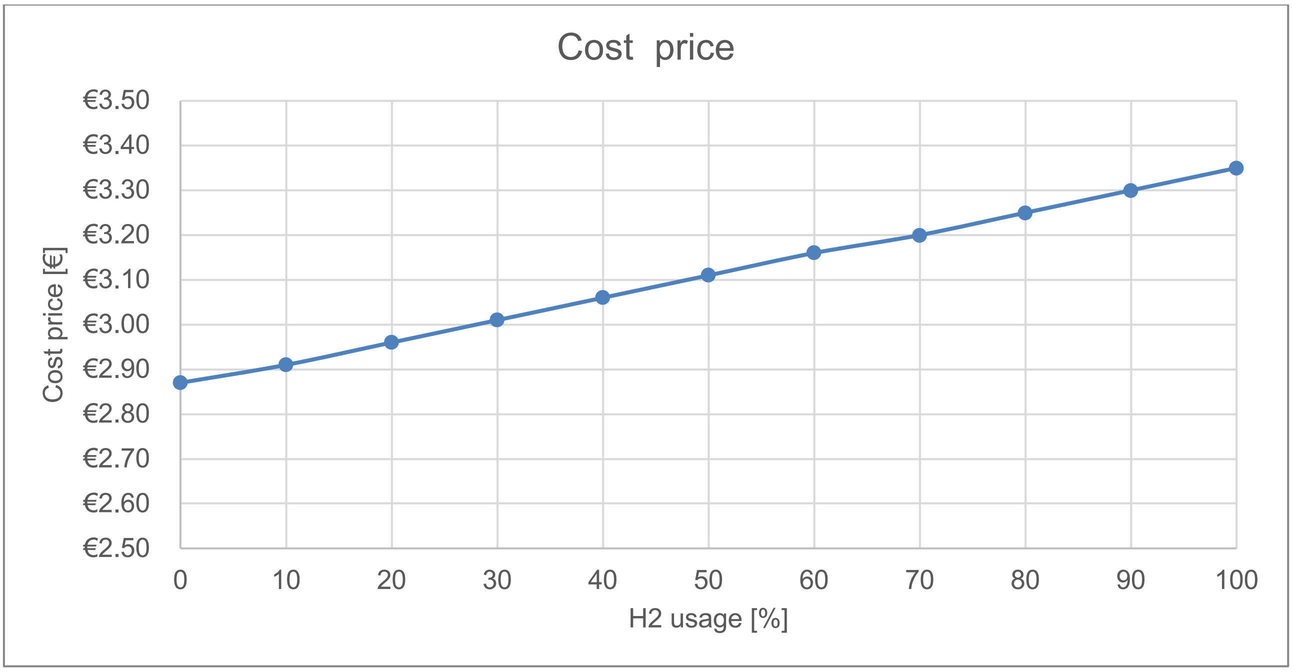


Figure 31, Cost price per container depending on hydrogen usage

Hydrogen price vs cost price

As seen in the figure above a vessel using a fuel cell with hydrogen as a fuel result in a more expensive trip. To check the influence of the hydrogen price on the overall cost an analysis of the hydrogen price is made, see figure 32. This graph includes the cost price per container for all the different hydrogen prices with the blue line. The red line is the cost price per container for the fully electric vessel. The intersection of these two lines lies at an approximate hydrogen price of €2,00 per kilogram. This means that when the price per kWh of electricity stays €0.12 the price of hydrogen needs to be around €2.00 to be competitive. The decision can be made to develop a hydrogen propelled vessel, but the higher cost will result in a higher cost for the customer.

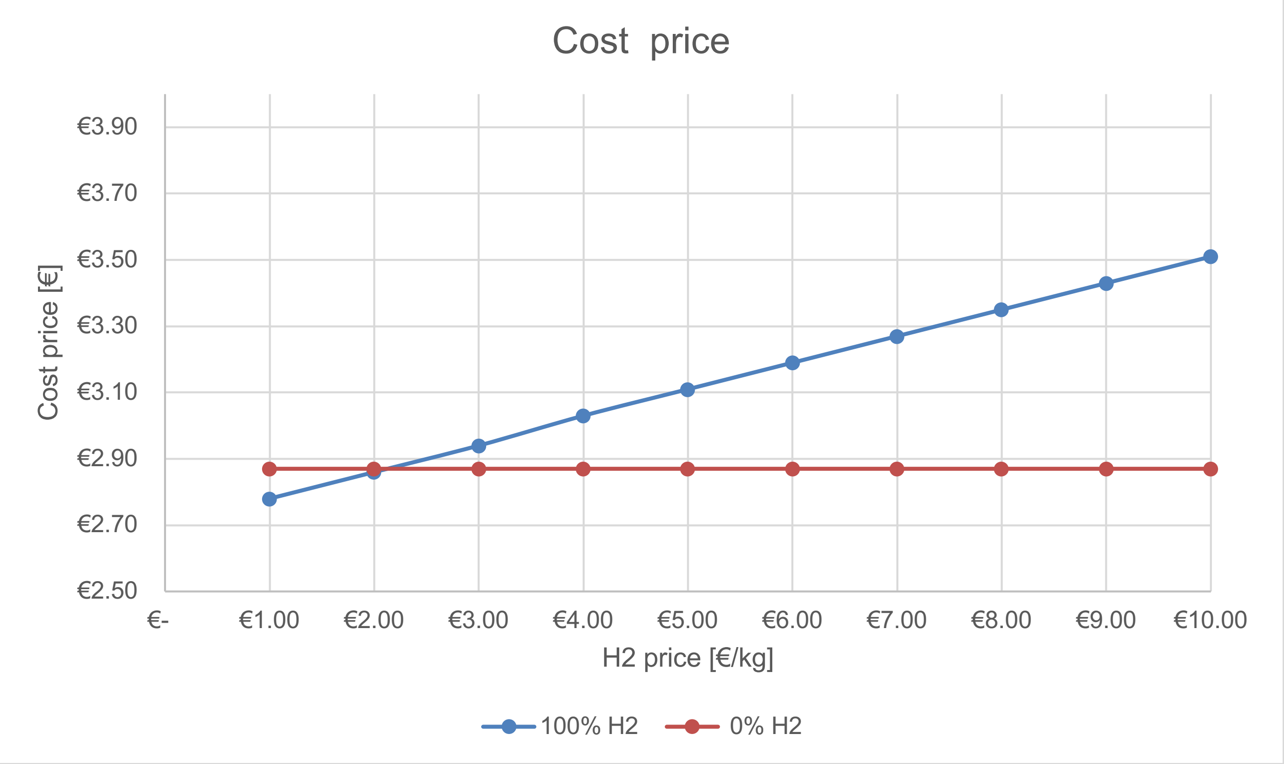
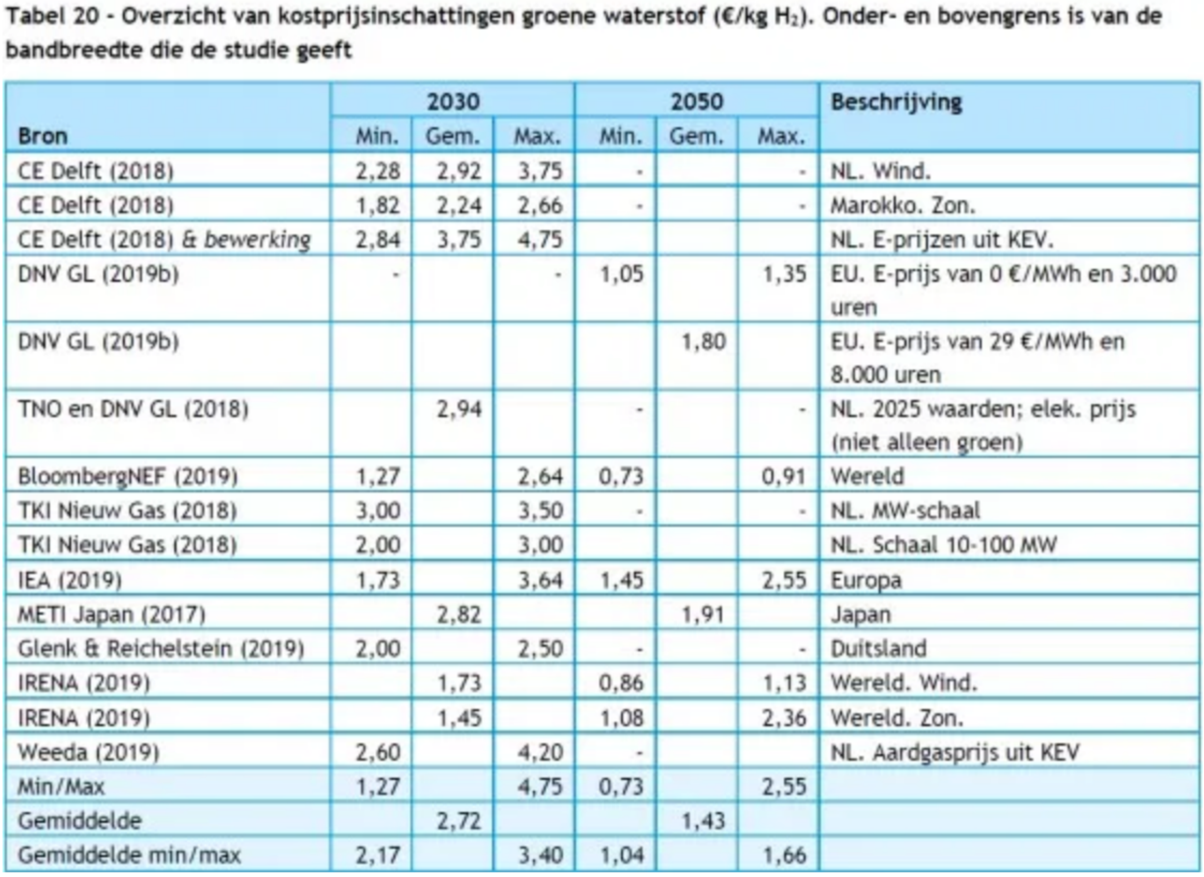


Figure 32, Cost price per container for different hydrogen prices

To test the possibility of hydrogen as a fuel in the future research is done on the price per kilogram of hydrogen in the future. The following prices follow from the “staalkaart waterstof” [78]. For the price of hydrogen, a distinction between the source of the hydrogen is made. Here hydrogen produced from natural gas is classified as grey hydrogen because of the CO2 emission during the production. This type of hydrogen generally has a lower price than the more environmentally friendly green hydrogen produced by electrolysis of water. Without taxes the price for om kilogram of grey hydrogen is roughly €1.50 till €2.00 per kilogram while green hydrogen costs around €15.00 per kilogram now. It is expected that the price of green hydrogen will reduce to around €3.00 per kilogram in 2030. The price for the production of green hydrogen does have a range of €1.27 till €4.75 based on several different studies as seen in table 5. This table is based on a study done by CE Delft and indicates an even further reduction in costs in 2050. Based on these prices it would be preferred to only use electricity as a fuel source in the coming future.

Table 5, Green hydrogen cost per kilogram [79]



Tabel 20 - Overzicht van kostprijsinschattingen groene waterstof (€/kg H_2). Onder- en bovengrens is van de bandbreedte die de studie geeft

	2030			2050			Beschrijving
Bron	Min.	Gem.	Max.	Min.	Gem.	Max.	
CE Delft (2018)	2,28	2,92	3,75	-		-	NL. Wind.
CE Delft (2018)	1,82	2,24	2,66	-		-	Marokko. Zon.
CE Delft (2018) & *bewerking*	2,84	3,75	4,75				NL. E-prijzen uit KEV.
DNV GL (2019b)	-		-	1,05		1,35	EU. E-prijs van 0 €/MWh en 3.000 uren
DNV GL (2019b)					1,80		EU. E-prijs van 29 €/MWh en 8.000 uren
TNO en DNV GL (2018)		2,94		-		-	NL. 2025 waarden; elek. prijs (niet alleen groen)
BloombergNEF (2019)	1,27		2,64	0,73		0,91	Wereld
TKI Nieuw Gas (2018)	3,00		3,50	-		-	NL. MW-schaal
TKI Nieuw Gas (2018)	2,00		3,00				NL. Schaal 10-100 MW
IEA (2019)	1,73		3,64	1,45		2,55	Europa
METI Japan (2017)		2,82			1,91		Japan
Glenk & Reichelstein (2019)	2,00		2,50	-		-	Duitsland
IRENA (2019)		1,73		0,86		1,13	Wereld. Wind.
IRENA (2019)		1,45		1,08		2,36	Wereld. Zon.
Weeda (2019)	2,60		4,20	-			NL. Aardgasprijs uit KEV
Min/Max	1,27		4,75	0,73		2,55	
Gemiddelde		2,72			1,43		
Gemiddelde min/max	2,17		3,40	1,04		1,66	

Captain cost vs cost price

Because the captain cost is the biggest contributing factor in the overall costs an addition analysis on the salary of the captain is made. The salary previously used was €30.00 per hour which resulted in a cost price per container of €2.86, see the red dot in figure 33. By ranging the hourly pay from €10.00 to €40.00 table 6 is obtained which included the cost price per container for the different salaries. This data is used to make figure xx in which the correlation between cost price and salary is given. As expected, a lower salary will result in a lower cost price per container. A reduction of €10.00 in salary will result in a cost price reduction of 23.8%. It is important to reduce the captain cost by reducing the salary of the captain to an acceptable level to reduce the cost price per container. This is only of the important consideration when making the business plan in the future.

Figure 33, cost price per container based on different salaries

Table 6, cost price per container based on different salaries

SALARY [€/HOUR]	COST PRICE PER CONTAINER [€]
€ 10.00	€ 1.51
€ 15.00	€ 1.84
€ 20.00	€ 2.18
€ 25.00	€ 2.52
€ 30.00	€ 2.86
€ 35.00	€ 3.19
€ 40.00	€ 3.53

Another option would be to consider a vessel without a captain to reduce cost. This autonomous vessel would have no captain costs but the system to sail autonomous would mean a bigger initial investment. Also, a different solution would be required for the load and unload operations since the captain would not be available for these tasks. The possibility of an autonomous vessel is not considered in the report but would be interesting to study for future inner city cargo vessels.

Variable load and unload times

In the first version of the model the time spent at the load and unload location was fixed at 15 minutes at every unload location in the city centre and 30 minutes to load at the hub. This time included docking and cargo handling. To account for the different time it would take to load and unload more containers from a bigger ship an additional sensitivity analysis on the load and unload time is made. This analysis is found in figure 34.

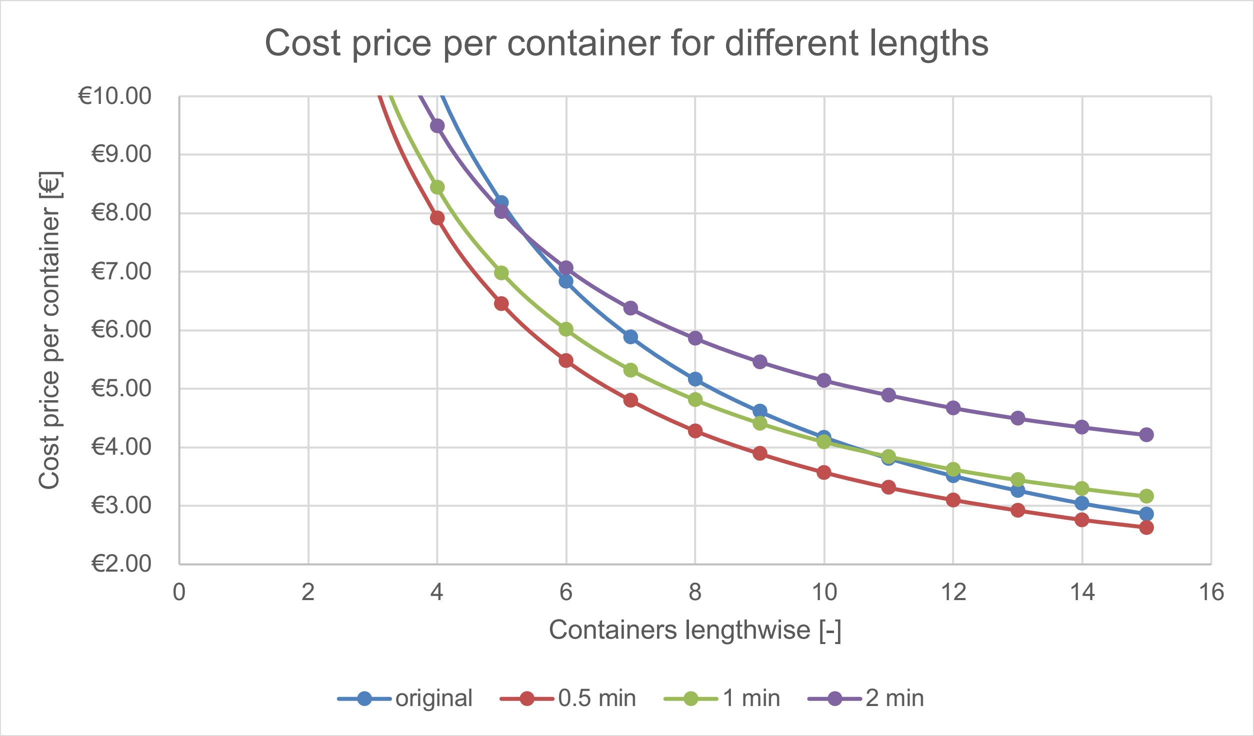


Figure 34, Cost price per container for different vessel lengths

For this analysis the load and unload time are made dependent on the number of containers on board. To dock the vessel a fixed time of 6 minutes us used at both the hub and each city centre drop off location. This time includes manoeuvring and mooring. Additionally, time is added for the movement of each individual container. Because the time this takes is dependent on the load and unload system and this information is not jet known the time is varied from 30 seconds per container to 2 minutes per container. The cost price per container for vessels 4 containers wide with varying lengths of containers is given in figure 34. Here the blue line included the original fixed load and unload time of 15 and 30 minutes. The other lines are the different load and unload times per container. A lower load and unload time will result in a lower overall cost price per container. The main difference between the fixed and variable load and unload time is the moment the line starts to level off at the bigger capacity vessels. This is a more realistic representation of the reality showing there would be a limit to the cost reduction for bigger ships when loading and unloading takes a lot of lime. Within the boundaries a bigger ship will still result in a reduction of cost price per container even with the variable load and unload times.

8.3. Final design

Based on the findings in this report an alternative design is presented. This design is an improvement of the initial design in terms of cost per containers. The model is only a representation of the reality, but the separate conclusions will also be valid for the final design. The main function for this improved design is to function as a starting point in the final design process.

Logistics

This design will be 15 containers long and 4 containers wide following the size analysis, for dimensions see figure 35 and table 7. This size minimalizes the cost per container assumed that Portago will be able to fill the vessel for approximately at least 20% during all trips. Because a market analysis is not part of this research it is assumed that the demand for this higher number of containers is in place. When possible, return cargo should be taken on board even if this is for a lower price per container. This will lead in an overall lower price per container for the containers transported towards the city centre. From this calculation no return cargo is used. For the cost calculation it is assumed that the vessel will need to sail 7 km from hub to the city centre and has 4 drop off location in the centre. When following this the vessel can sail 4 trips within 12 hours a day.

Propulsion

The most economical speeds for the vessel based on the model is the maximum speeds both within the city centre and in transit. This corresponds with a speed of 6 km/h in the city centre and 12 km/h during transit. The vessel will be fully electrically powered and charged once a day. It would be useful to ensure there is enough space available to retrofit a fuel cell in the future when the price of green hydrogen becomes competitive.

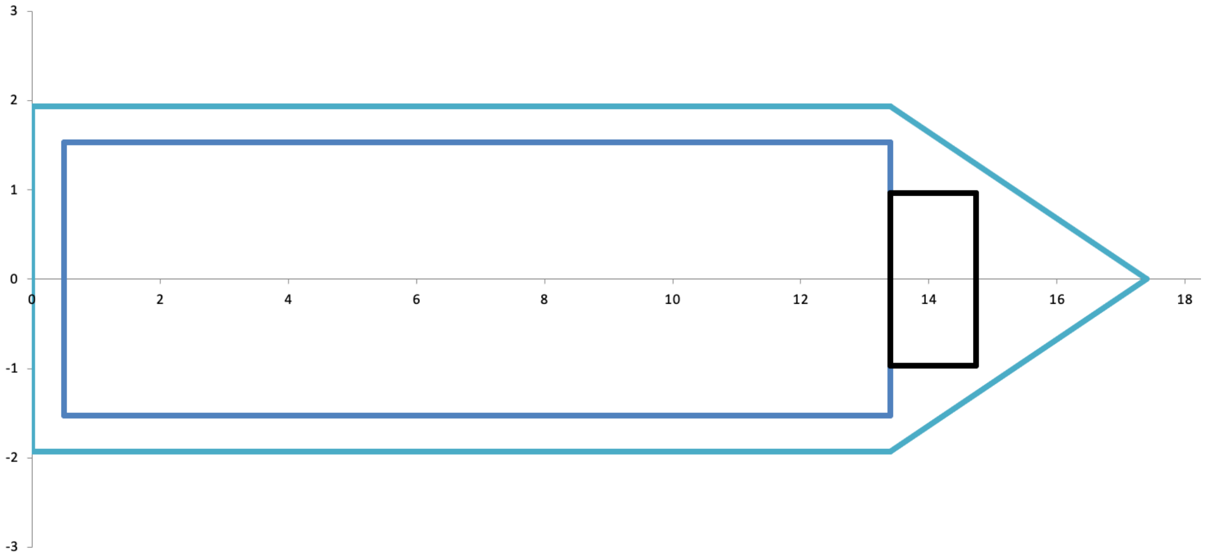


Figure 35, layout final design

Table 7, Dimensions final design

PARAMETER	VALUE	UNIT
LENGTH	17.4	M
WIDTH	3.86	M
DEPTH	0.81	M
WEIGHT	32.59	Ton
CONTAINER CAPACITY	60	-
CARGO CAPACITY	18	Ton
PROPULSION POWER	10.88	kW
SAIL TIME PER DAY	11.33	hours

Cost

The design above will result in a cost price per container of **€2.86**. This price is a lot lower than the price for the initial design which was €7.73. The main improvement is made by scaling up the vessel. The larger vessel had a limited effect on the capital cost while being able to spread out the captain cost over more containers. The new price is only 37% of the initial price which is a very big saving. By reducing the cost, the cost price for the end customer can be lowered but also the profit could be improved.

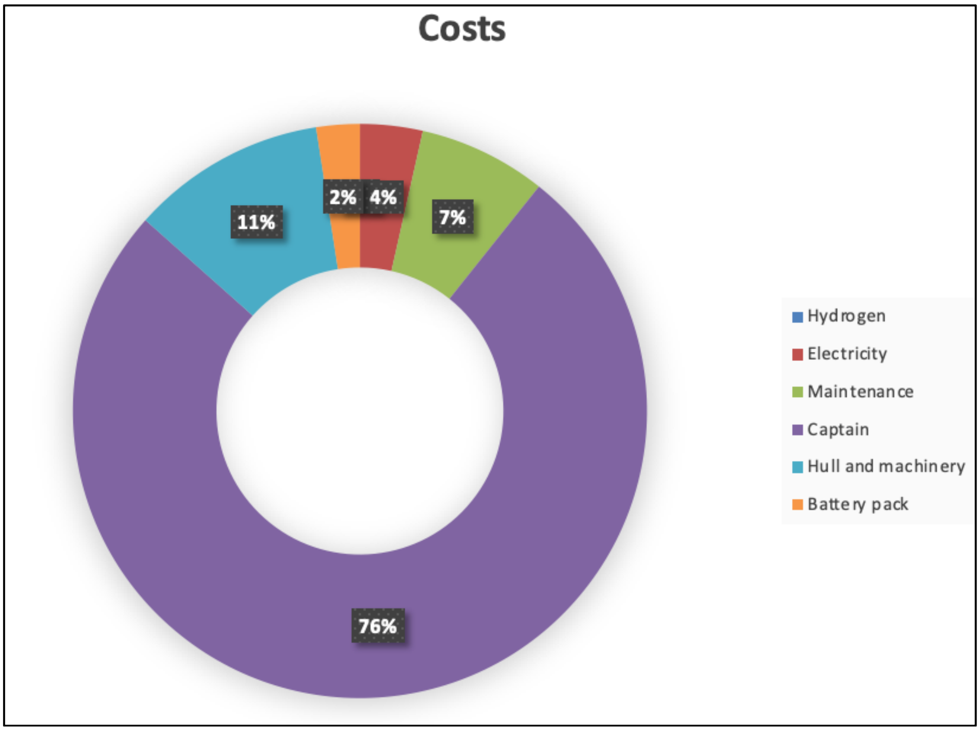


Figure 36, cost categories final design

Based on the design above the total revenue becomes **€148,769.82**. This is less than in the initial design because of a decrease in costs. Still the captain is the most expensive cost category, as can be seen in figure 36. This cost can only be reduced by limiting the number of sailing hours each day. The total number of containers transported per year is increased from 23,520 containers per year to 52,080. This is more than double of the original capacity. This improved design can transport more containers while reducing cost which will result in less nuisances in the city and a bigger profit for Portago.

Hydrogen powered

As a comparison the hydrogen powered design is also added. The municipality of Amsterdam stated that it doesn't have the grid capacity to have all trucks and vessel using electricity as a fuel. The design is like the previous design with the only addition of a fully hydrogen powered propulsion system with a capacity of 15kW. A fuel cell with 15kW of power will be on during less than 8 hours while the total sailing time for the vessel is 11.33 hour.
The addition of a fuel cell results in a higher cost price per container of **€3.35**. Compared to the fully electric design this is an increase of **17.1%**. This is based on the hydrogen cost of €8.00 per kilogram. As described before a reduction in hydrogen cost towards €2.00 per kilo would result in a similar cost price per container. There would be the possibility of a combined system, but the ratio of electricity and hydrogen would need to be determined based on the limitations at the hub from where the vessel sails.
For the distribution of the different costs see figure 37. Compared to figure 36 the addition of a fuel cell adds a big addition cost. The fuel cell and hydrogen storage combined are 21% of the total yearly costs for the hydrogen propelled concept.

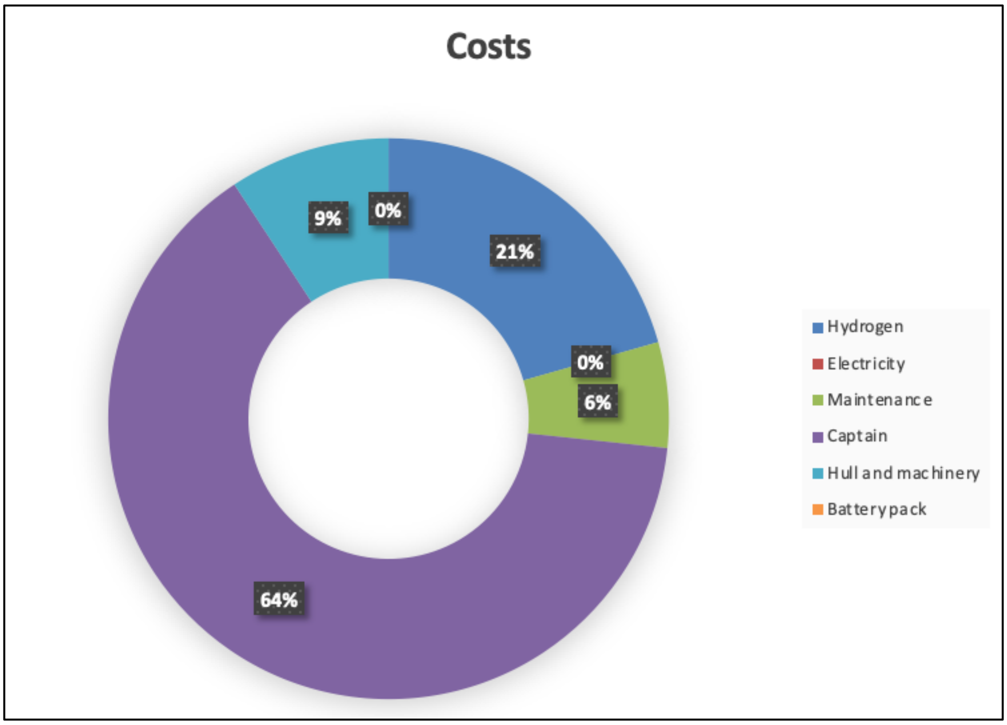


Figure 37, cost categories final design using hydrogen

Comparison trucks

To compare the current road-based transportation system with the water-based transportation it is important to have an indication of the current cost price per containers. Because this cost cannot be found in literature an attempt is made to calculate these costs based on similar assumptions as used for the vessel. The utilisation rate is also set at 70% and the same driver salary is the same at 30.00 €/hour.

For the truck a cost price per kilometre is used. This price is 0.7€/km for an electric truck and 1.00€/km for a diesel truck [80]. Because the truck is used as a last mile solution it will also travel from the new Amsterdam logistics city hub to the city centre of Amsterdam. This distance is roughly 10km depending on the chosen delivery location. The round-trip time is set at 1 hour for the truck to load, drive, unload at destination and drive back.

By combining these inputs, a cost price per container of **€2.51** is calculated for an electric truck and **€2.84** for the diesel-powered truck. Both trucks have a lower cost price per container compared to the cost price per container for the proposed design as calculated in the model. With the note that the model is not the reality but only a model of the real cost the outcome is very similar. A more detailed cost evaluation would be necessary to find the true cost price per container and could be based on a pilot of the Portago project to give a more representative figure.

External costs

For a better understanding of the environmental differences between road based and water based inner city cargo transportation an effort is made to calculate the external cost for both ways of transport. The European Union together with CE Delft have developed the handbook on the external costs of transport. This handbook gives representative values per ton kilometre (tkm) for transport via road, rail and water. The road-based goods transportation is divided in light commercial vehicles (LCV) and heavy goods vehicles (HGV). Because LCV's are used for both passenger and cargo transport the external cost per tkm of cargo could not be calculated so for this category the costs are based on a price per vehicle kilometre (vkm) as can be seen in table 8.

Table 8, Average external costs [83]

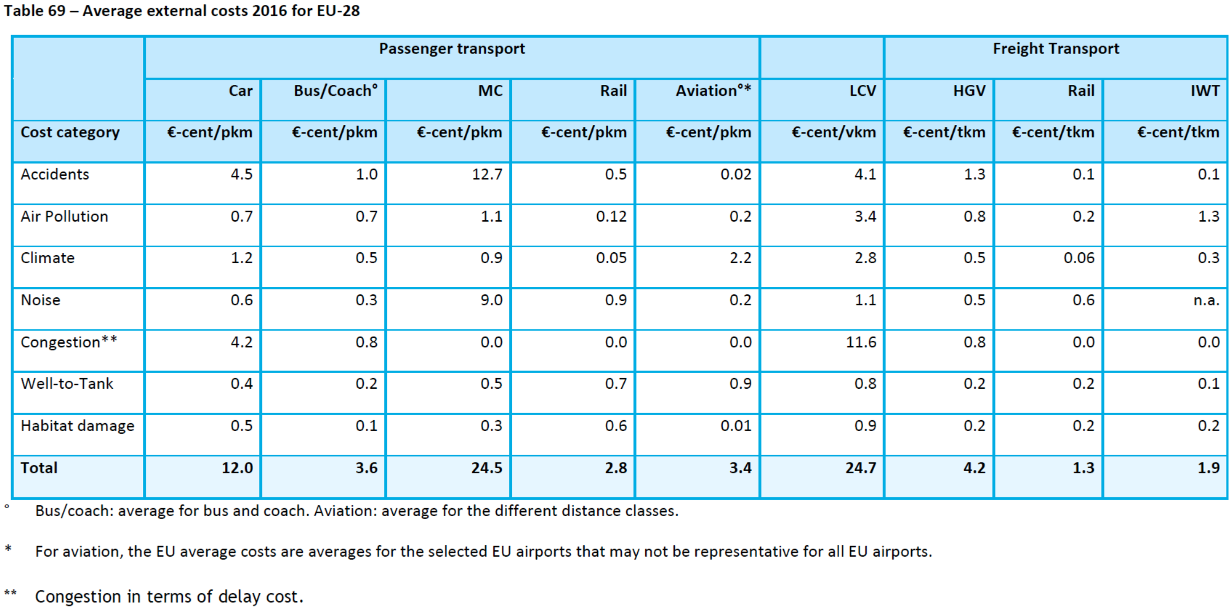


Table 69 – Average external costs 2016 for EU-28

	Passenger transport						Freight Transport		
	Car	Bus/Coach°	MC	Rail	Aviation°*	LCV	HGV	Rail	IWT
Cost category	€-cent/pkm	€-cent/pkm	€-cent/pkm	€-cent/pkm	€-cent/pkm	€-cent/vkm	€-cent/tkm	€-cent/tkm	€-cent/tkm
Accidents	4.5	1.0	12.7	0.5	0.02	4.1	1.3	0.1	0.1
Air Pollution	0.7	0.7	1.1	0.12	0.2	3.4	0.8	0.2	1.3
Climate	1.2	0.5	0.9	0.05	2.2	2.8	0.5	0.06	0.3
Noise	0.6	0.3	9.0	0.9	0.2	1.1	0.5	0.6	n.a.
Congestion**	4.2	0.8	0.0	0.0	0.0	11.6	0.8	0.0	0.0
Well-to-Tank	0.4	0.2	0.5	0.7	0.9	0.8	0.2	0.2	0.1
Habitat damage	0.5	0.1	0.3	0.6	0.01	0.9	0.2	0.2	0.2
Total	**12.0**	**3.6**	**24.5**	**2.8**	**3.4**	**24.7**	**4.2**	**1.3**	**1.9**

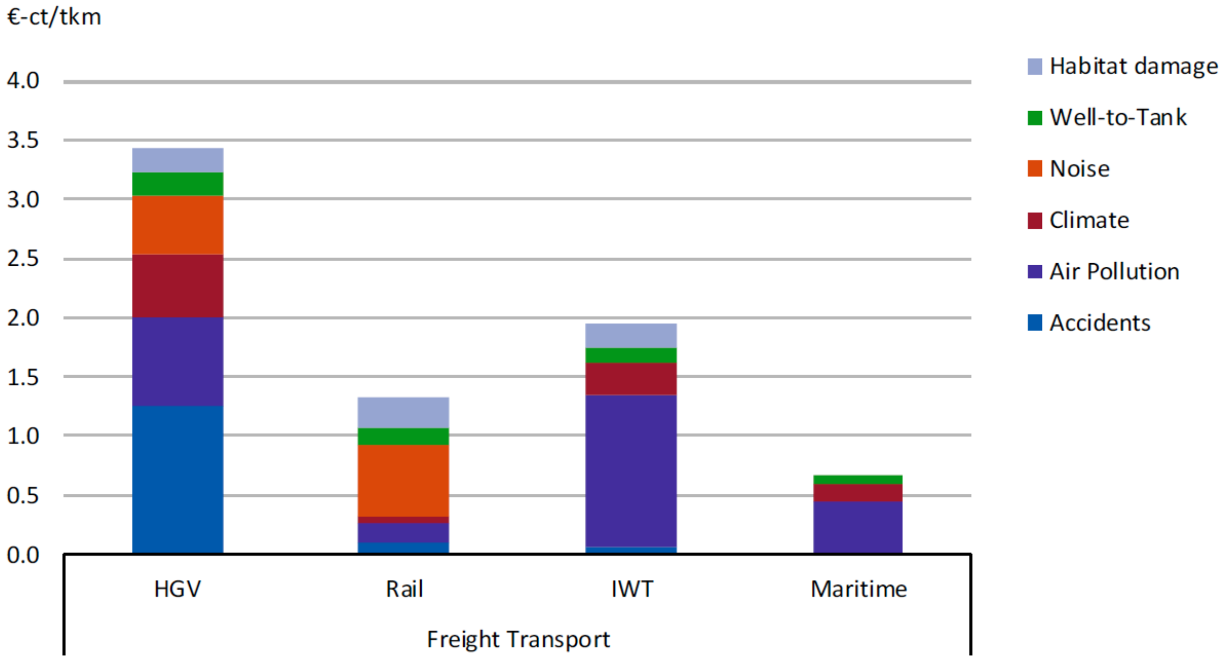
° Bus/coach: average for bus and coach. Aviation: average for the different distance classes.

* For aviation, the EU average costs are averages for the selected EU airports that may not be representative for all EU airports.

** Congestion in terms of delay cost.

Figure 39 gives the cost in €-cent per tkm for the different ways of transport in 2016. This figure also shows the distribution of the total costs over the different categories. The categories considered in the handbook are the external costs for: accidents, air pollution, climate change, noise, congestion, well-to-tank and habitat damage. The external cost for all individual categories can be found in table 8.

Figure 16 - Average external costs 2016 for EU28: freight transport (excluding congestion)



* Maritime: average for selected EU28 ports.

Figure 39, External costs for different categories [83]

Because the external costs are based on the average of all HGV's and inland vessels the values are not representative when used for last mile calculations. The main use for these values is the relation between the different cost with the external costs of HGV's roughly twice that of inland waterway transport. The main contributing factor for inland waterway transport is the external cost for air pollution which will be limited in the presented design which is free from harmful emissions. The biggest contributing factor to the external cost for the HGV's is the cost for accidents which will stay roughly the same even when electric trucks are used. The total cost for air pollution is only 20% of the total cost which will result is a lower reduction of external cost when a more environmentally friendly truck is used. The external costs for HGV's used as last mile solution are therefor expected to be higher that the external cost for water-based transport. A more detailed calculation of the external costs is not part of this research and should be seen as a new research possibility.

8.4. Conclusion

This chapter includes the finding by using the decision support tool. Several different sensitivity analyses are done to find general rules of thumb. Combined with chapter 7 the following sub question can now be answered.

> How can a decision support tool be supportive to generate a concept design for a vessel as a last mile solution in the inner city of Amsterdam?

The decision support tool makes it possible to check various designs in a short time. This results in the figures as seen in the sensitivity analyses where the influence of alle the individual input values is given on some important output parameters. This knowledge is used to propose a different design for the inner-city cargo vessel. Enviu had a first design which functioned as case study from where the analyses were made to end with the improved design. Because the large variety of input variables a lot of different design considerations were made in a short time. The main benefit of the decision support tool is that a lot of different design consideration could be made while consuming limited resources and time. An added benefit is also that the correlations between different design choices become clear while also showing their impact on the final cost price per container. In the end the final design became bigger, and it is suggested to use electricity as a fuel instead of using hydrogen. Also, the decision support tool was able to generate knowledge about several different logistical choices like number of stops and distance to hub. This information is useful when developing the final business plan for Enviu.

9 Conclusion

The main objective of the thesis is to answer the following main question:

"What are the critical aspects for the design concept of a water based inner city transport vessel in the city of Amsterdam to be competitive as a last-mile solution?"

To answer this question, research is done on other transporters used in city logistics and the possibilities for water-based transport in Amsterdam. The answers to all the sub questions can be found in the corresponding chapters. There were several critical aspects for the design concept of a water based inner city transport vessel found during this research. Aspects are seen as critical when a small change results in a significant change in cost price per container. They are split up in aspects related to the logistics, the design and others.

Design
To minimalize the cost price per container, it turned out that it is the best to build the vessel as large as possible while still being allowed on the canals in Amsterdam. This resulted in a vessel with a maximum width of 4 meters and a maximum length of 18 meters. To offset the high captain costs, the vessel should sail at the maximum allowed speed both in the city centre and during transit. There is a most economical speed based on the sensitivity analyses but for the tested case this was faster than the allowed speed.
It is advised to use electricity to power the vessel. Due to the higher initial and higher running costs associated with a hydrogen propelled vessel it is more cost effective to use electricity. However, it would be recommended to consider the option of retrofitting a hydrogen fuelled fuel cell in the future.

Logistics
When possible, the distance from the hub to the city centre should be limited compared to the cost price. Also, the number of stops should be limited. More stops are not a problem but will increase the cost price per container. The vessel should aim to sail at at least 20% of its cargo carrying capacity. If possible, the vessel should take on return cargo even if this would be for a lower price per container.
To load and unload the cargo a liftable deck would be desired. The size of this deck depends on the dimensions of the vessel, the height of the quay and the weight of the containers.

Other
The highest cost for the concept turned out to be the captain cost. By limiting the captain cost price per container could be reduced drastically. This is done by minimalizing the sailing time of the vessel or by reducing the salary of the captain.

Following the research of the different design aspect a new design is proposed to function as a starting point for further development. The proposed design makes use of the maximum allowed dimensions on the canals of Amsterdam. The most cost-effective design would be fully electrically propelled using hydrogen will need to be considered because of the limited grid capacity in Amsterdam. Based on the similar considerations the cost per container for containers transported using the water are roughly the same as containers transported by trucks. Based on the assumptions made in this report the water based inner-city transportation can compete with road-based transportation in trucks.

10 Discussion

This thesis provides a first insight in the possibility of using the canals in Amsterdam for the transportation of cargo in rollable containers. By expanding this research other possibilities and solutions can be provided.

External cost
During this research the external cost are only looked at briefly. Because the data required to calculate the external cost of water based inner city cargo no final cost could be calculated. In the future it would be interesting to calculate the external cost of this concept to be able to compare this way of transport with road-based transport. This could deliver additional motivation for cities to start using the already in place canal system for the transportation of goods instead of using the road network.

Hub function
Another interesting follow up research could be to research the possibility to use the hub as a satellite within the last mile logistics system. Here the vessel would sail from a hub to a location in the city centre where it would moor and function as a smaller satellite hub. This water-based hub can then be used to supply other last mile solutions that have a smaller range or that are capable to also deliver cargo to location further away from the water.

Propulsion systems
This research has limited the possible energy sources to electricity and hydrogen. A more detailed study could provide different insights in all energy sources and could also include a more detailed insight into different fuel cell systems. For this research the hydrogen is stored as a compressed gas, new storage methods could reduce cost or increase safety. A more detailed study in the complete hydrogen system would create more insight in the different possibilities. Because of the big and flat surface of the roof, there is the possibility to add solar panels for additional charging. The addition of solar panels is not included in this study and a detailed study should be performed to check whether the addition of solar panels would be beneficial.

Autonomous
The captain costs are the biggest contributing factor to the overall costs. In some designs the captain costs where 75% of the total costs. To eliminate these costs autonomous vessels could be considered. A future study should test the possibility of an autonomous vessel including the problems that come with these vessels with loading and unloading. In the current design concept, this is done by the captain. Also, the size of the vessel will need to be reconsidered when designing autonomous vessels.

Future design
Following this research which is based on a lot of assumptions the design should be tested in a real-world environment. Based on a pilot project the feasibility and more important the costs for running the vessel will become known. Based on this pilot a better design could be made to be used in the future.

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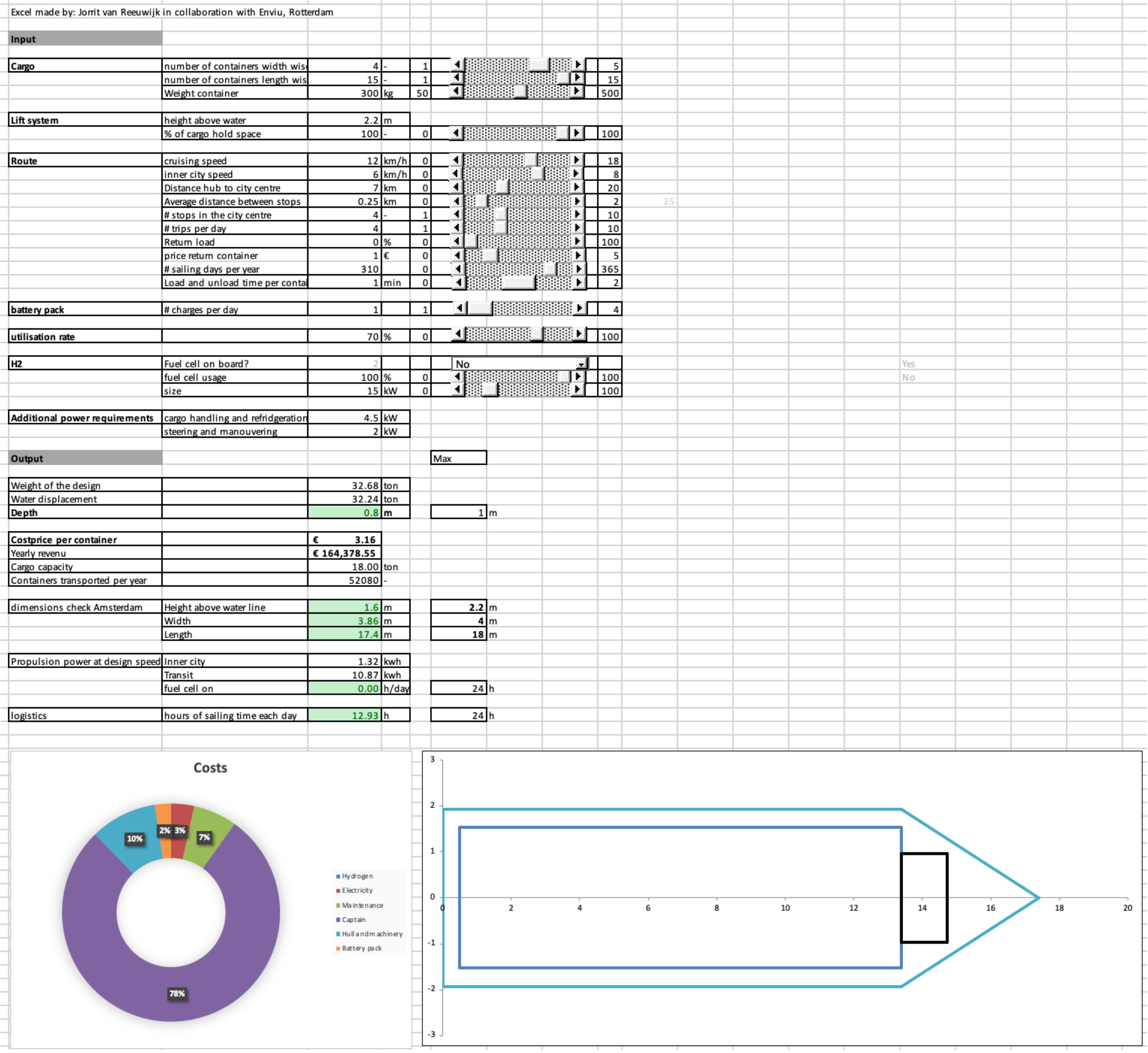
Appendix

Appendix A: Excel

The Excel is made by: Jorrit van Reeuwijk in collaboration with Enviu, Rotterdam

Screenshots of all pages of the Excel model are added individually

Dashboard



Excel made by: Jorrit van Reeuwijk in collaboration with Enviu, Rotterdam

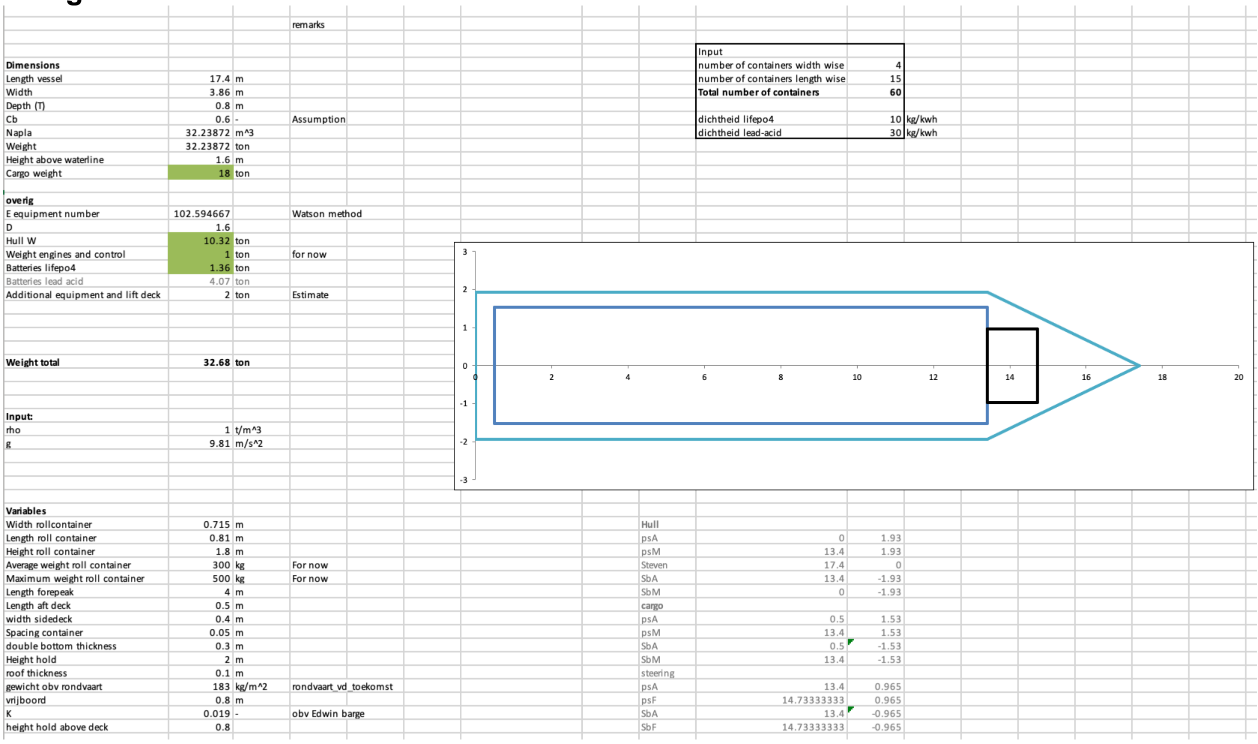
Input

Cargo	number of containers width wis	4	-	1		5
	number of containers length wis	15	-	1		15
	Weight container	300	kg	50		500
Lift system	height above water	2.2	m			
	% of cargo hold space	100	-	0		100
Route	cruising speed	12	km/h	0		18
	inner city speed	6	km/h	0		8
	Distance hub to city centre	7	km	0		20
	Average distance between stops	0.25	km	0		2
	# stops in the city centre	4	-	1		10
	# trips per day	4		1		10
	Return load	0	%	0		100
	price return container	1	€	0		5
	# sailing days per year	310		0		365
	Load and unload time per contai	1	min	0		2
battery pack	# charges per day	1		1		4
utilisation rate		70	%	0		100
H2	Fuel cell on board?	2			No	
	fuel cell usage	100	%	0		100
	size	15	kW	0		100
Additional power requirements	cargo handling and refridgeration	4.5	kW			
	steering and manouvering	2	kW			

Output

				Max	
Weight of the design		32.68	ton		
Water displacement		32.24	ton		
Depth		0.8	**m**	1	m
Costprice per container		**€ 3.16**			
Yearly revenu		**€ 164,378.55**			
Cargo capacity		18.00	ton		
Containers transported per year		52080	-		
dimensions check Amsterdam	Height above water line	1.6	m	**2.2**	m
	Width	3.86	m	**4**	m
	Length	17.4	m	**18**	m
Propulsion power at design speed	Inner city	1.32	kwh		
	Transit	10.87	kwh		
	fuel cell on	0.00	h/day	24	h
logistics	hours of sailing time each day	12.93	h	24	h

Design

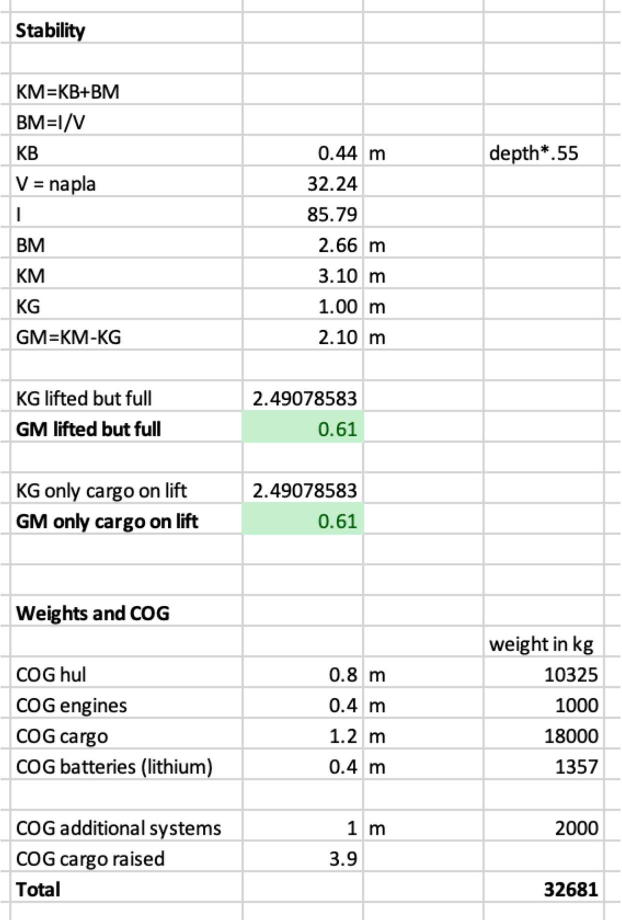


			remarks
Dimensions			
Length vessel	17.4	m	
Width	3.86	m	
Depth (T)	0.8	m	
Cb	0.6	-	Assumption
Napla	32.23872	m^3	
Weight	32.23872	ton	
Height above waterline	1.6	m	
Cargo weight	18	ton	
overig			
E equipment number	102.594667		Watson method
D	1.6		
Hull W	10.32	ton	
Weight engines and control	1	ton	for now
Batteries lifepo4	1.36	ton	
Batteries lead acid	4.07	ton	
Additional equipment and lift deck	2	ton	Estimate
Weight total	**32.68**	**ton**	
Input:			
rho	1	t/m^3	
g	9.81	m/s^2	
Variables			
Width rollcontainer	0.715	m	
Length roll container	0.81	m	
Height roll container	1.8	m	
Average weight roll container	300	kg	For now
Maximum weight roll container	500	kg	For now
Length forepeak	4	m	
Length aft deck	0.5	m	
width sidedeck	0.4	m	
Spacing container	0.05	m	
double bottom thickness	0.3	m	
Height hold	2	m	
roof thickness	0.1	m	
gewicht obv rondvaart	183	kg/m^2	rondvaart_vd_toekomst
vrijboord	0.8	m	
K	0.019	-	obv Edwin barge
height hold above deck	0.8		

Input		
number of containers width wise	4	
number of containers length wise	15	
Total number of containers	**60**	
dichtheid lifepo4	10	kg/kwh
dichtheid lead-acid	30	kg/kwh

Hull		
psA	0	1.93
psM	13.4	1.93
Steven	17.4	0
SbA	13.4	-1.93
SbM	0	-1.93
cargo		
psA	0.5	1.53
psM	13.4	1.53
SbA	0.5	-1.53
SbM	13.4	-1.53
steering		
psA	13.4	0.965
psF	14.73333333	0.965
SbA	13.4	-0.965
SbF	14.73333333	-0.965

Stability calculation



Stability			
KM=KB+BM			
BM=I/V			
KB	0.44	m	depth*.55
V = napla	32.24		
I	85.79		
BM	2.66	m	
KM	3.10	m	
KG	1.00	m	
GM=KM-KG	2.10	m	
KG lifted but full	2.49078583		
GM lifted but full	0.61		
KG only cargo on lift	2.49078583		
GM only cargo on lift	0.61		
Weights and COG			
			weight in kg
COG hul	0.8	m	10325
COG engines	0.4	m	1000
COG cargo	1.2	m	18000
COG batteries (lithium)	0.4	m	1357
COG additional systems	1	m	2000
COG cargo raised	3.9		
Total			**32681**

Logistics

Based on input

Per trip		
Total time sailing at cruising speed	1.17	h
Total time sailing at inner city speed	0.17	h
Number of dockings	4	-
Total time per unload location	0.25	h
Loading time hub	0.5	h
Total time round trip	2.83	h

Per year		
Total time sailing at cruising speed	1446.67	h
Total time sailing at inner city speed	206.67	h
Number of dockings	4960	-
Total time round trips	3513.33	h

Number of trips per day	4	
sailing time per day total	11.33	h
Number of sailing days per year	310	

Costs

power requirement			notes
transit	1446.67	h	
inner city	206.6666667	h	
energy cons per year trans	15571.8	kwh	
energy cons per year inner	271.6	kwh	

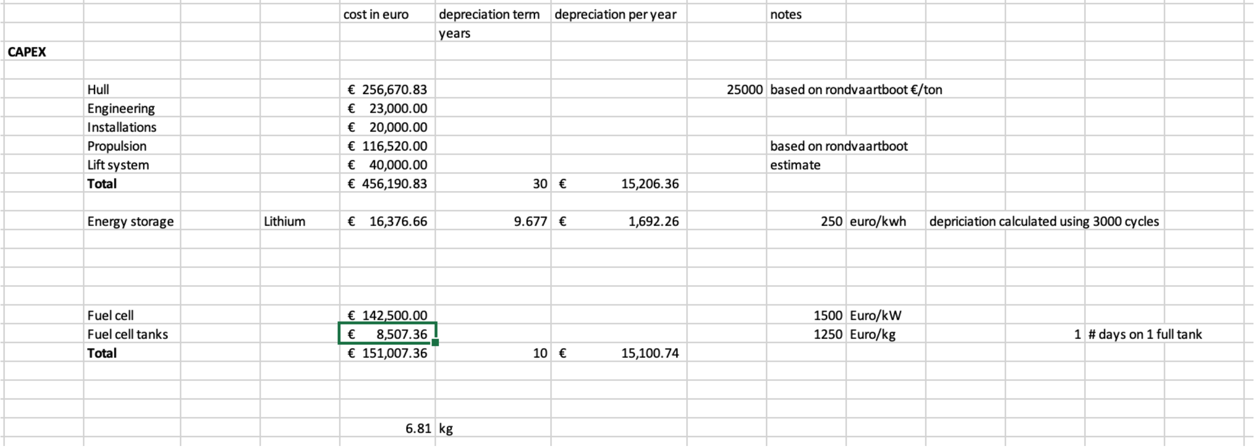
additional power requirements		
refridgeration	15810.00	kwh
steering etc zie TNO	7026.67	kwh
per year	***22836.7***	kwh

total power	38680.1	kwh	per year	
total power H2	35163.7	kwh	per year	
total power batteries	20307.1	kwh	per year	including charge discharge efficiency

VOYEX				
Hydrogen	€	16,878.60		
Electricity	€	2,436.85		
OPEX				
Maintenance	€	10,000.00		
Insurance	€	12,471.50	0.02	2% of build cost
Captain	€	105,400.00		
Depreciation				
Hull and machinery	€	15,206.36		
Battery pack	€	1,692.26		
Fuel cell system and storage	€	15,100.74		
TOTAL	€	164,085.56		
Return containers transported per year		0		
Income return containers	€	-		
Containers transported per year to city		52080		
Costprice per container	**€**	**3.15**		

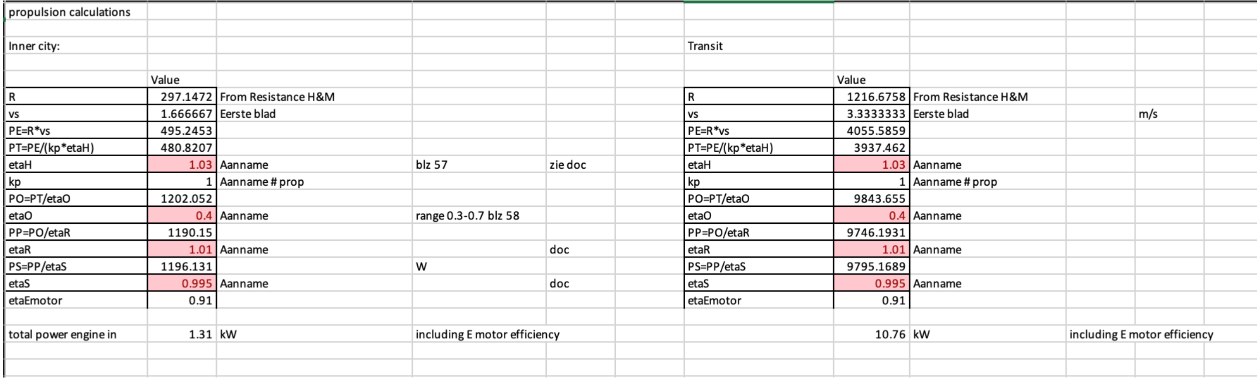
hydrogen	0.06	kg/kwh	
	8	€/kg	
	0.48	€/kwh	
	55	%	PEM Fuel Cell efficiency
Electricity	0.12	€/kwh	TNO (Enviu 0.24)
	95	%	charge discharge efficiency lithium
captain	30	€/hour	

Capex costs



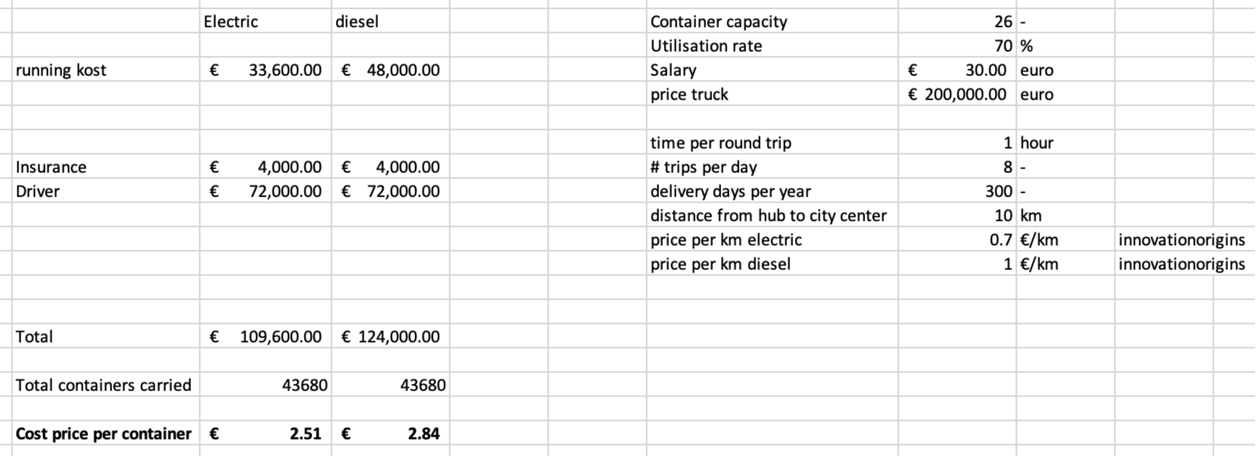
			cost in euro	depreciation term years	depreciation per year		notes				
CAPEX											
	Hull		€ 256,670.83			25000	based on rondvaartboot €/ton				
	Engineering		€ 23,000.00								
	Installations		€ 20,000.00								
	Propulsion		€ 116,520.00				based on rondvaartboot				
	Lift system		€ 40,000.00				estimate				
	Total		€ 456,190.83	30	€ 15,206.36						
	Energy storage	Lithium	€ 16,376.66	9.677	€ 1,692.26		250	euro/kwh	depriciation calculated using 3000 cycles		
	Fuel cell		€ 142,500.00				1500	Euro/kW			
	Fuel cell tanks		€ 8,507.36				1250	Euro/kg		1	# days on 1 full tank
	Total		€ 151,007.36	10	€ 15,100.74						
			6.81	kg							

Propulsion



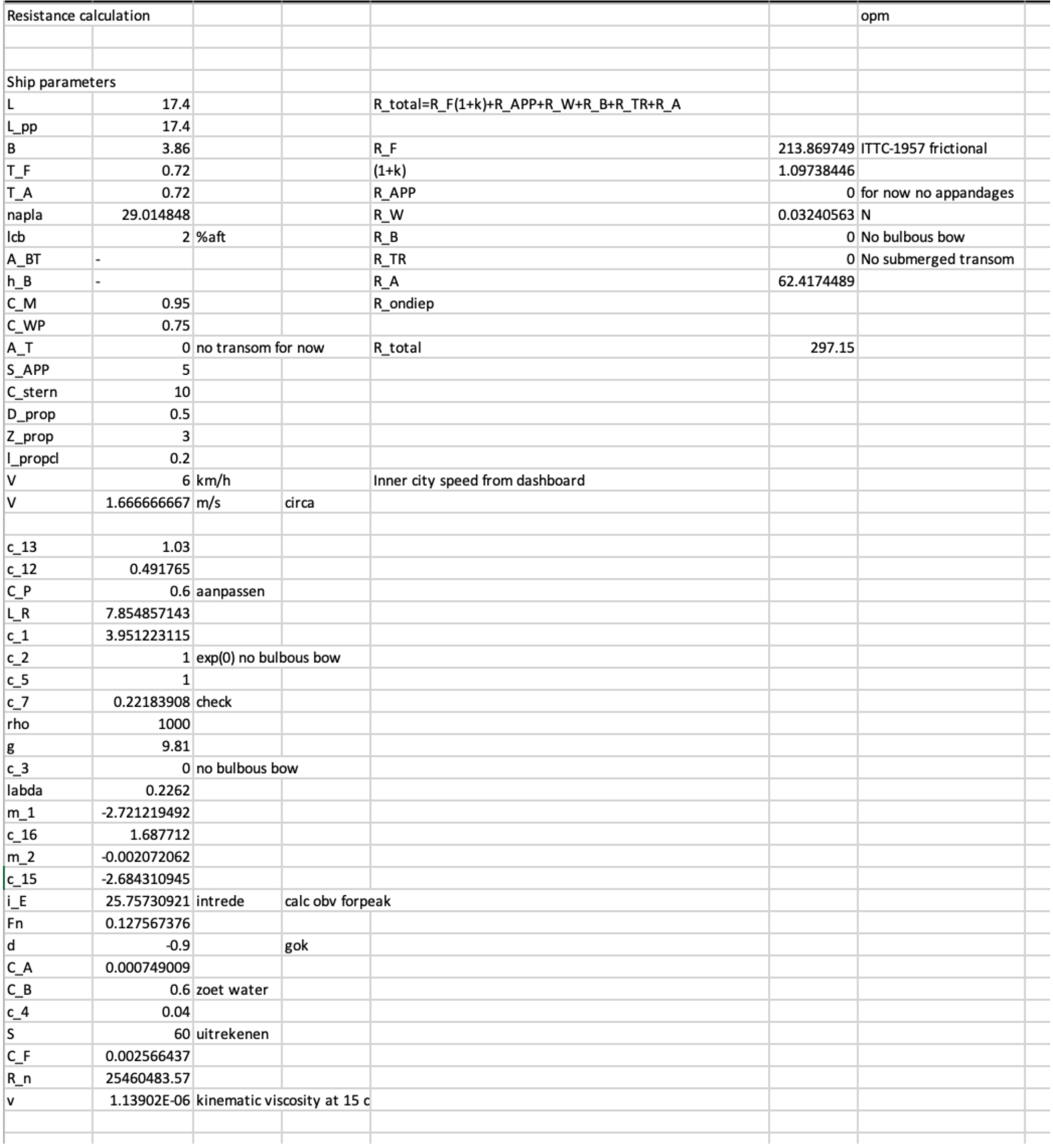
propulsion calculations										
Inner city:					Transit					
	Value					Value				
R	297.1472	From Resistance H&M			R	1216.6758	From Resistance H&M			
vs	1.666667	Eerste blad			vs	3.3333333	Eerste blad		m/s	
PE=R*vs	495.2453				PE=R*vs	4055.5859				
PT=PE/(kp*etaH)	480.8207				PT=PE/(kp*etaH)	3937.462				
etaH	1.03	Aanname	blz 57	zie doc	etaH	1.03	Aanname			
kp	1	Aanname # prop			kp	1	Aanname # prop			
PO=PT/etaO	1202.052				PO=PT/etaO	9843.655				
etaO	0.4	Aanname	range 0.3-0.7 blz 58		etaO	0.4	Aanname			
PP=PO/etaR	1190.15				PP=PO/etaR	9746.1931				
etaR	1.01	Aanname		doc	etaR	1.01	Aanname			
PS=PP/etaS	1196.131		W		PS=PP/etaS	9795.1689				
etaS	0.995	Aanname		doc	etaS	0.995	Aanname			
etaEmotor	0.91				etaEmotor	0.91				
total power engine in	1.31	kW	including E motor efficiency			10.76	kW	including E motor efficiency		

Cost calculation road bases transportation using trucks



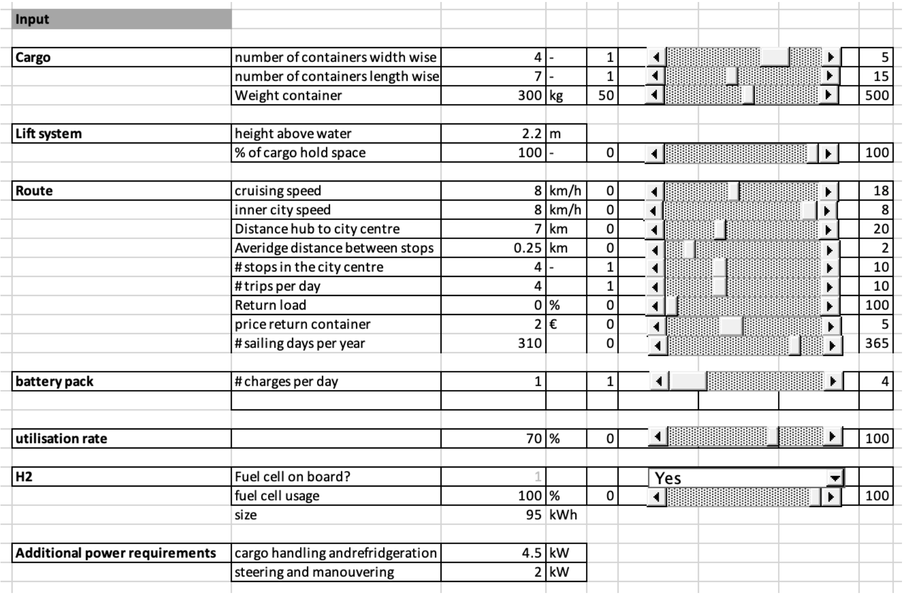
	Electric	diesel				
			Container capacity	26	-	
			Utilisation rate	70	%	
running kost	€ 33,600.00	€ 48,000.00	Salary	€ 30.00	euro	
			price truck	€ 200,000.00	euro	
			time per round trip	1	hour	
Insurance	€ 4,000.00	€ 4,000.00	# trips per day	8	-	
Driver	€ 72,000.00	€ 72,000.00	delivery days per year	300	-	
			distance from hub to city center	10	km	
			price per km electric	0.7	€/km	innovationorigins
			price per km diesel	1	€/km	innovationorigins
Total	€ 109,600.00	€ 124,000.00				
Total containers carried	43680	43680				
Cost price per container	**€ 2.51**	**€ 2.84**				

Resistance calculation inner city speed

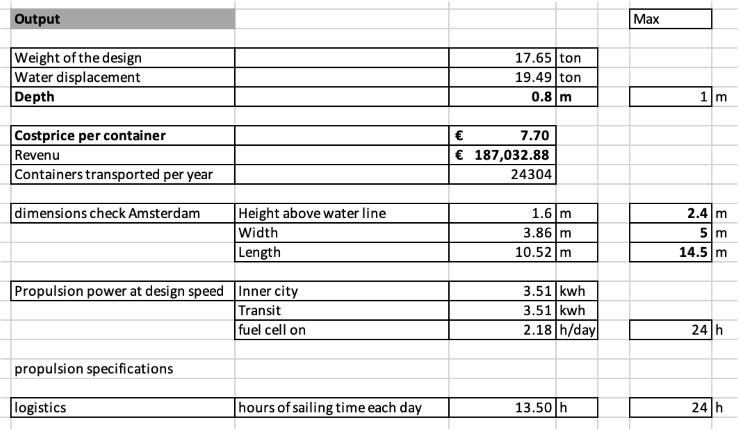


Resistance calculation						opm
Ship parameters						
L	17.4			R_total=R_F(1+k)+R_APP+R_W+R_B+R_TR+R_A		
L_pp	17.4					
B	3.86			R_F	213.869749	ITTC-1957 frictional
T_F	0.72			(1+k)	1.09738446	
T_A	0.72			R_APP	0	for now no appandages
napla	29.014848			R_W	0.03240563	N
lcb	2	%aft		R_B	0	No bulbous bow
A_BT	-			R_TR	0	No submerged transom
h_B	-			R_A	62.4174489	
C_M	0.95			R_ondiep		
C_WP	0.75					
A_T	0	no transom for now		R_total	297.15	
S_APP	5					
C_stern	10					
D_prop	0.5					
Z_prop	3					
l_propcl	0.2					
V	6	km/h		Inner city speed from dashboard		
V	1.666666667	m/s	circa			
c_13	1.03					
c_12	0.491765					
C_P	0.6	aanpassen				
L_R	7.854857143					
c_1	3.951223115					
c_2	1	exp(0) no bulbous bow				
c_5	1					
c_7	0.22183908	check				
rho	1000					
g	9.81					
c_3	0	no bulbous bow				
labda	0.2262					
m_1	-2.721219492					
c_16	1.687712					
m_2	-0.002072062					
c_15	-2.684310945					
i_E	25.75730921	intrede	calc obv forpeak			
Fn	0.127567376					
d	-0.9		gok			
C_A	0.000749009					
C_B	0.6	zoet water				
c_4	0.04					
S	60	uitrekenen				
C_F	0.002566437					
R_n	25460483.57					
v	1.13902E-06	kinematic viscosity at 15 c				

Appendix B
Original case study input and output parameters



Input						
Cargo	number of containers width wise	4	-	1		5
	number of containers length wise	7	-	1		15
	Weight container	300	kg	50		500
Lift system	height above water	2.2	m			
	% of cargo hold space	100	-	0		100
Route	cruising speed	8	km/h	0		18
	inner city speed	8	km/h	0		8
	Distance hub to city centre	7	km	0		20
	Averidge distance between stops	0.25	km	0		2
	# stops in the city centre	4	-	1		10
	# trips per day	4		1		10
	Return load	0	%	0		100
	price return container	2	€	0		5
	# sailing days per year	310		0		365
battery pack	# charges per day	1		1		4
utilisation rate		70	%	0		100
H2	Fuel cell on board?	1			Yes	
	fuel cell usage	100	%	0		100
	size	95	kWh			
Additional power requirements	cargo handling andrefridgeration	4.5	kW			
	steering and manouvering	2	kW			



Output				Max	
Weight of the design		17.65	ton		
Water displacement		19.49	ton		
Depth		**0.8**	**m**	1	m
Costprice per container		**€ 7.70**			
Revenu		**€ 187,032.88**			
Containers transported per year		24304			
dimensions check Amsterdam	Height above water line	1.6	m	**2.4**	m
	Width	3.86	m	**5**	m
	Length	10.52	m	**14.5**	m
Propulsion power at design speed	Inner city	3.51	kwh		
	Transit	3.51	kwh		
	fuel cell on	2.18	h/day	24	h
propulsion specifications					
logistics	hours of sailing time each day	13.50	h	24	h