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A single-objective, multi-period optimization model of an alternative maritime fuel supply chain network in the Port of Amsterdam

TU Delft

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by

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Preface

Green innovations are gaining more ground day by day. Especially in the transport sector nowadays the focus more than ever is on energy savings and the possible use of green alternative fuels. As a student I have seen the focus shifting throughout my studies towards the search for greener alternatives for the maritime industry. I was eager to do my part in this energy transition. During a lecture Klaas Visser talked about a hydrogen carrier with high potential to play an important role as a future maritime fuel: Sodium Borohydrate (NaBH4). This research, under the H2SHIPS project, sparked my interest and so I decided to join the project and examine corresponding infrastructure set-ups for alternative fuels.

It took a while to find out how my research could contribute the most to the current H2SHIPS research, within the broader perspective of current scientific research on alternative fuel infrastructures. For this reason an extensive literature review was written to evaluate the options for modelling an alternative fuel supply chain. This quickly led to a more mathematical approach of the problem, something with which I am not very familiar with as a Marine Technology student. Luckily one of my favourite mottoes of a childhood hero is the following:

> *"I have never tried that before, so I think I should definitely be able to do that."*
> - Pippi Longstocking

So in good spirits I started on my ambitious project. It was not easy, especially when Covid-19 hit our society and working from home became the new standard. This made it difficult to contact friends and colleagues and to discuss the progress of my research and its content. When writing this preface however I can proudly claim that I was able to overcome all obstacles and that I am very pleased with the resulting thesis which lies before you. It was a great and interesting project in which I learned a lot.

I could not have finished this project on my own, and I want to thank everyone who has helped me in this process: First of all my supervisor, Klaas Visser. Thank you for guiding me throughout this process and thank you for the feedback-sessions on Skype, which always took longer than expected as we both like to chatter a lot. Linked to this I would like to thank everyone working on the H2SHIPS project that has informed me and has tried to include me in the project even though we never met in person. I would like to give special thanks to Dingena Schott from TU Delft and Jan Egbertsen from Port of Amsterdam, for the educational conversations on interesting topics regarding my thesis. Furthermore I owe thanks to Guusje Scheijen, Wessel de Zeeuw and Bilge Atasoy for helping out a maritime student with all her questions about mathematical notations. I have learned a lot from it. Lastly I would like to give a warm thank you to two people dear to my heart: Thank you Pauline Roos and Roland Günther for all the support and much needed distraction throughout this whole process. It has certainly been an exciting journey!

D.M.D. Roos
Delft, December 2020

Abstract

To reduce the CO2 emissions of the maritime industry, several alternative fuels are being researched to possibly achieve this goal. The absence of an infrastructure for alternative fuels in the current port environment is one of the barriers towards implementation of these high potential fuels. The goal of this thesis project was to create an optimization model which can provide more insight into the initial sizing, phased growth and corresponding cost of an infrastructure needed for maritime transport using different forms of alternative fuels. The corresponding main research question is:

"How do the port refueling infrastructures of sodium borohydrate, liquid hydrogen and gaseous hydrogen compare to each other with respect to costs and supply chain set-up in terms of where, when, and at what sizes to build up the production, storage, distribution and refueling facilities?"

To answer this research question a single-objective multi-period mathematical optimisation model (Mixed Integer Programming) has been created for the port refueling environment. The most important model innovations are the inclusion of a maritime refueling convention and the possibility to model less conventional alternative fuels such as sodium borohydrate (NaBH4). Furthermore, input for the model has been gathered from several sources. Next, some parameters of the model have been varied to research their effect on the total alternative fuel infrastructure.

As a result it has been found that the gaseous hydrogen infrastructure is the cheapest with respect to facility capital costs and facility operating costs, but was the most expensive when looking at transportation of the fuel within the port. The liquefied hydrogen was the cheapest with respect to fuel transportation, but scored average on facility capital cost. Furthermore it is the most expensive infrastructure with respect to facility operating cost. The NaBH4-infrastructure is the most expensive infrastructure when looking at the facility capital cost, but scores average on facility operating cost and transportation cost. Overall the gaseous hydrogen infrastructure was the cheapest infrastructure, followed by liquefied hydrogen. The NaBH4-infrastructure turned out to be the most expensive with the current input.

The input parameters for NaBH4 are still very uncertain at this stage as the production of this fuel on a large scale is still at a low Technology Readiness Level and there is still unfamiliarity with large scale storage and transport of the substance. A reduction in the corresponding cost parameters would lead to the NaBH4-infrastructure becoming more competitive with a liquefied hydrogen infrastructure. The input used in the model should thus be further researched to reduce the corresponding uncertainties.

While the current model focuses on optimising the infrastructure from a cost perspective, it must be taken into account that other factors also influence the favouring of certain alternative fuels, such as safety, policy, public acceptance and the preference for certain fuels from the perspective of the maritime users. In future research the expansion of the model towards a multi-objective model should be evaluated.

List of Abbreviations

BHF	Back-haul Factor
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent
DP	Dynamic Programming
ECA	Emission Control Area
FCC	Facility Capital Cost
FOC	Facility Operating Cost
FP	Fuzzy Programming
GH2	Compressed Hydrogen
GHG	Greenhouse Gas
GIS	Geographic Information System
H2	Hydrogen
H2O	Water
HSC	Hydrogen Supply Chain
HSCN	Hydrogen Supply Chain Network
HSCND	Hydrogen Supply Chain Network Design
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LCOH	Levelised Cost Of Hydrogen
LH2	Liquefied Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LP	Linear Programming
MDO	Marine Diesel Oil
Mg	Magnesium
MgBr2	Magnesium Bromide
MgH2	Magnesium Hydride
MGO	Marine Gas oil
MgO	Magnesium Oxide
MILP	Mixed Integer Linear Programming
NaBH4	Sodium Borohydrate
NaBO2	Sodium Metaborate
NOx	Nitrogen oxides
NWE	North-Western Europe
PCC	Production Capital Cost
PEM	Proton-exchange Membrane
PF	Penetration Factor
PM	Particulate Matter
RD	Rijksdriehoek
RO	Robust Optimisation
SA	Scenario Analysis
SAA	Sample Average Approximation
SC	Supply Chain
SCC	Storage Capital Cost
SOx	Sulfur oxides
SP	Stochastic Programming
STS	Ship-to-Ship
TCC	Transportation Capital Cost
TOC	Transportation Operating Cost
TRL	Technology Readiness Level
TTS	Truck-to-Ship
UPC	Unit Production Cost
WER	Weight-to-Energy ratio

Contents

1

Introduction

Shipping has a substantial influence on the global anthropogenic CO2 emissions: According to the latest IMO greenhouse gas study [85], on average shipping accounted for ±3.1% of annual global CO2 emissions between 2007 and 2012 and ±2.8% of annual greenhouse gases on a CO2e basis. Additionally, shipping contributes to about 15% and 13% of global NOx and SOx emissions respectively.

In addition to this these maritime CO2 emissions are expected to increase significantly in the future: In the period before 2050 an increase of 50% to 250% is expected, depending on future economic and energy developments. Reducing these shipping emissions will have a great impact on global emissions, and thus is something to strive for to limit further climate change. Improving vessel efficiency only will not lead to enough energy savings to achieve a downward trend [37]. Only the use of alternative fuels could lead to enough (and eventually a 100%) greenhouse gas reduction. Using hydrogen as a fuel could be a solution to change the fuel mix and consequently reduce CO2 emissions and possibly NOx and SOx emissions, depending on the power system used (fuel cells, ICE, etc.).

The H2SHIPS project [6] focuses on inland waterway transport in North-Western Europe (NWE), which shows large potential to achieve emissions reduction. Currently almost 100% of the inland fleet uses gasoil as a fuel [13], emitting significant quantities of CO2, NOx, PM and SO2. H2SHIPS aims to develop a blueprint for hydrogen fuel adoption in NWE, as hydrogen advances towards market maturity. Hydrogen as an energy carrier is attractive due to several reasons: Most notably, it can be produced from many different energy sources, including renewable energy such that CO2 emissions are reduced [39]. Moreover, hydrogen improves the travelling range of vehicles compared to batteries [86]. Additionally using hydrogen as a fuel would lead to a more secure energy provision in the future as the transport sector will become less dependent on fossil fuels [29].

The absence of an infrastructure for alternative fuels has been identified as one of the barriers towards implementation of such fuels [37]. This thesis research is inspired by the H2SHIPS project and will focus on creating a model which simulates the development of an hydrogen refueling infrastructure in a port environment. The model is designed as modular as possible such that it can model infrastructures for different alternative fuels and for different ports by simply changing the input of the model. Hydrogen supply chain design models have been made before (as will be discussed in the literature review: chapters 2 and 3), but have not yet incorporated the modularity for modelling different (non-conventional) fuels, and have only focused thus far on automotive refueling infrastructures. The model created in this thesis thus contains two major model innovations: (1) Being able to design infrastructures for several alternative fuels, and (2) designing a refueling infrastructure in a port environment. The background, characteristics and additional challenges of both these innovations will be discussed in paragraph 1.1.

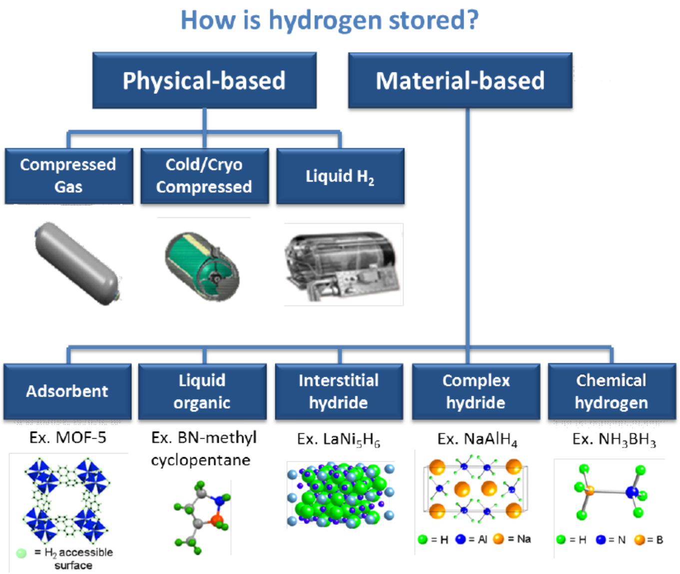


Figure 1.1: Hydrogen storage methods [7]

1.1. Background

In this chapter background information is given as a lead up to the eventual model. For this, first hydrogen carrier characteristics are discussed as well as the workings of NaBH4, in paragraph 1.1.1. Next the features of a port refueling infrastructure and its differences with an automotive infrastructure are discussed in paragraph 1.1.2.

1.1.1. Hydrogen and Hydrogen Carriers as a Fuel

The first major model innovation in this thesis will be the modular build-up of the hydrogen carrier used. Hydrogen has the highest gravimetric density (the amount of energy per mass) compared to other fuels [7]. The drawback however is that the volumetric density (the amount of energy per volume) of hydrogen is very low. In an attempt to store hydrogen in a more compact form to enable its use in the transportation sector there are different storage methods of hydrogen (see also figure 1.1). Each storage method has its advantages and disadvantages. The storage methods on which will be focused in this thesis are compressed gaseous hydrogen (GH2), liquid hydrogen (LH2) and the alternative hydrogen carrier sodium borohydride (NaBH4). NaBH4 is considered as it is selected as a fuel for the H2SHIPS project demonstrator of Port of Amsterdam currently being built. A comparison between NaBH4, liquid and compressed hydrogen will be given in this paragraph. Note that the infrastructure model is not limited to these three hydrogen fuels.

Liquid or compressed hydrogen

Hydrogen as an energy carrier is seen as a pivotal element in the transition to a future low-carbon energy system as it is lightweight, abundantly available and its oxidation product is water which is favourable from an environmental point of view [84]. However storage of hydrogen is a point of attention: the volumetric density is extremely low. For hydrogen fuels to be applicable for use in the transportation sector it should be compact, light, safe and its containment on board should be affordable [84].

By either compressing or liquefying hydrogen the volume of the fuel decreases significantly. However, in comparison to currently used fossil fuels the volume is still notably higher, as shown in figure 1.2. Typical values of the pressures used for compressed hydrogen are 350 and 700 bar. However, for maritime applications the pressures usually are limited to 300 bars. The use of high-pressure vessels brings along a considerable risk. To contain the hydrogen safely at this pressure large, heavy tanks are required which is not beneficial keeping in mind space and weight restrictions for vehicles. Liquefying hydrogen leads to a higher volumetric density with respect to compressed hydrogen. The hydrogen is then cooled to a temperature of -253 °C, which requires energy to do so and part of the stored gas

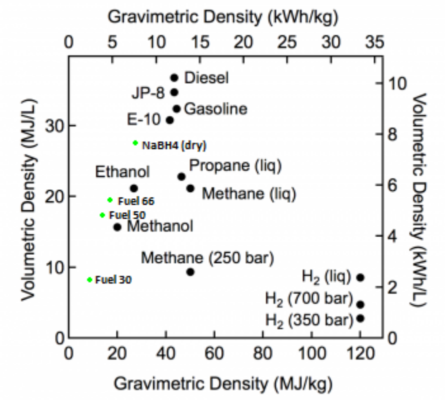


Figure 1.2: Gravimetric and volumetric densities of various fuels based on lower heating values [7]. The green dots have been added to the figure.

will boil off [84], such that the overall efficiency of the system is low. Additionally cost and size of the storage tanks are still relatively high, especially when compared to conventional fossil fuels. Both hydrogen liquefaction and compression present a safety risk to the system as hydrogen is a flammable substance in combination with air [79].

Sodium borohydride (NaBH4)

Apart from physical-based hydrogen storage methods such as compressed or liquid hydrogen, material-based storage options exist. One of these storage options is sodium borohydride (NaBH4), a hydrogen carrier in which hydrogen is chemically stored. NaBH4 has a relatively large hydrogen fraction compared to other materials: It has a gravimetric hydrogen storage capacity of 10.8 wt% looking only at the NaBH4 molecule [77], yet during the reaction of NaBH4 with H20 the hydrogen of the water molecule is also released. This leads to a gravimetric density of the overall storage method being 21.6 wt%, making it a fairly compact material to store hydrogen. The use of NaBH4 is also advantageous with respect to safety as it is stable and can be stored under atmospheric conditions. Using NaBH4 as a fuel can be very promising for the maritime industry as the H20 required for the reaction of NaBH4 can be extracted from the surrounding water. However, there are still many unknowns regarding its applications on-board of a ship.

The working principle of NaBH4 is as follows: Hydrogen is released by hydrolysis of NaBH4 as shown in equation (1.1):

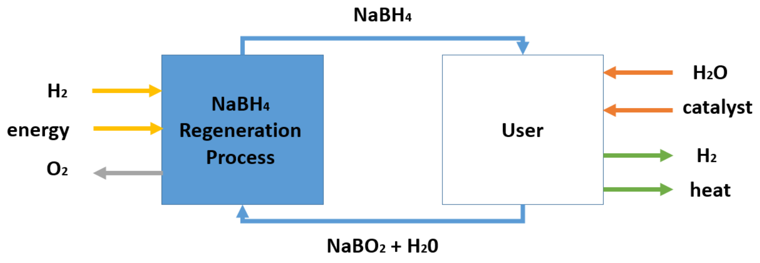
$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 \tag{1.1}$$

The reaction is exothermic (heat is released). Part of this heat can be reused to heat up the reactor to speed up the hydrolysis. The remaining heat can be used otherwise, for example for on-board heating systems. The reaction is slow under normal circumstances, such that acid, catalysts or a high temperature are needed to speed up the process.

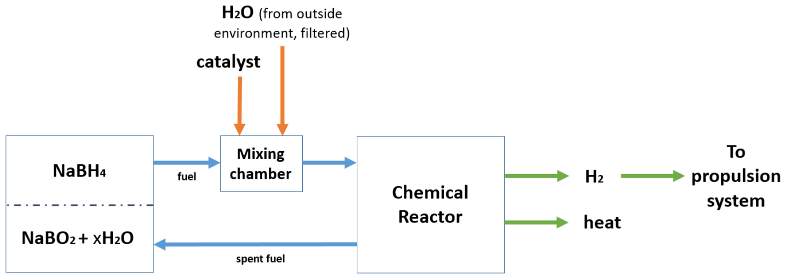
In figure 1.3a the (circular) production and use of NaBH4 is shown schematically. NaBH4 is provided to the user which, via equation (1.1), extracts the hydrogen from the fuel to use as an energy source. The spent fuel is called sodium metaborate (NaBO2) and is received back from the user. This spent fuel can then be regenerated to NaBH4 following the process as described in equation (1.2)[28]. For the total system to be completely free of emissions the energy used to regenerate the spent fuel needs to come from a sustainable source (e.g. wind or solar power).

$$NaBO_2 \bullet 2H_2O + 4MgH_2 \rightarrow NaBH_4 + 4MgO + 4H_2 \tag{1.2}$$

In figure 1.3b an overview is shown of the proposed fuel handling system on board of a vessel. NaBH4 is stored in a tank either in solid form or dissolved (as will be discussed later in this paragraph).



(a) Circular use of sodium borohydride as a hydrogen carrier [4]



(b) Overview of the fuel handling on board for maritime user

Figure 1.3: Overview of sodium borohydride production and usage

It is then transported to the mixing chamber where both a catalyst and H2O are added to it. The advantage of using NaBH4 on board of a ship specifically is the great availability of water, which can be extracted from the environment and filtered to use in the process. This means that the water needed for the reaction does not all have to be carried along on board on beforehand. Next, reaction (1.1) takes place in the reactor and the resulting hydrogen is separated from the sodium metaborate. The hydrogen is used in the propulsion system, for example in a fuel cell to generate electricity. The spent fuel is stored in a tank and needs to be offloaded from the ship to be re-used in the regeneration process as shown in figure 1.3a.

NaBH4 fuel can be delivered in multiple forms: The fuels generally considered are dry fuel (powder or crystals), fuel 30, fuel 50 and fuel 66. The fuel number indicates the weight percentage of NaBH4 in the water-NaBH4 solution. Their properties are displayed in table 1.1. The difference between the fuels is the amount of water added to it. Essentially the more water the fuel contains the better the sodium borohydride is dissolved, evading the problem of NaBH4 solids precipitating in tanks and pipes, clogging the system. The downturn of using more water to dissolve NaBH4 is that the volumetric energy density decreases significantly, making it more difficult to meet targets for the transportation sector [35]. Using dry fuel (NaBH4 as a solid) is a more compact way of storing energy, where water needs to be added to the fuel before the fuel enters the chemical reactor to obtain the right solution required for the chemical reaction. However using a solid form of a fuel adds difficulties in handling the fuel. The benefit lies in the fact that ships, in contrast to automotive users, can use the surrounding water from the environment to filter it and add it to the fuel in the mixing chamber.

What type of fuel is used on board of a vessel depends on the design and mission requirements of the ship. A trade-off should be made per vessel between ease of fuel handling on the one hand and volumetric energy density and stability of the fuel on the other hand. For the maritime industry the most important fuel characteristics to consider are its volumetric density, the safety on board the vessel with respect to the fuel used and the fuel transportability.

An important difference when using conventional fossil fuels, liquid or compressed hydrogen for propulsion, is the fact that the product of the NaBH4 reaction is not only hydrogen but also spent fuel NaBO2.

This product has a low solubility, leading to problems with crystallisation in the reactor and pipes. This can be solved by either heating the solution to a certain temperature or by adding more water to the system, decreasing the overall volumetric density of the system. This however enables the spent fuel solution to be pumped, such that it can be transported from ship to quay adequately. Most importantly for this research the port refueling infrastructure should take into account the extra spent fuel flow through the infrastructure which will be necessary to sustainably use NaBH4. Not only do ships have to load fuel (which is similar to the current situation), they also require offloading of their spent fuel. The implementation of this spent fuel flow into the model is explained in chapter 4.

Fuel	kg/kg_H2	L/kg_H2	kWh/kg	kWh/L	Advantages	Disadvantages
Fuel 30	15.63	15.47	2.13	2.17	Easy fuel handling, No extra water	Needs NaOH to stabilise
Fuel 50	7.18	9.19	3.55	4.84	Easy fuel handling, More dense	Needs NaOH to stabilise, Requires acid solution or water mixing chamber, Requires circulation in the tank
Fuel 66	5.97	6.90	4.69	5.87	Easy fuel handling, More dense	Needs NaOH to stabilise, Needs water mixing chamber, Requires circulation in the tank
Dry fuel	4.69	4.38	7.10	7.60	Very dense, No stabilizer needed, No decay over time	Fuel handling is difficult, Needs water mixing chamber, Humidity could make the substance sticky

Table 1.1: Overview of the properties of different types of NaBH4 fuels, provided in the thesis of Dennis Lensing [56]. Calculations are based on 1 kg of H_2 and a lower heating value of 33 kWh.

Comparison NaBH4 vs LH2/GH2

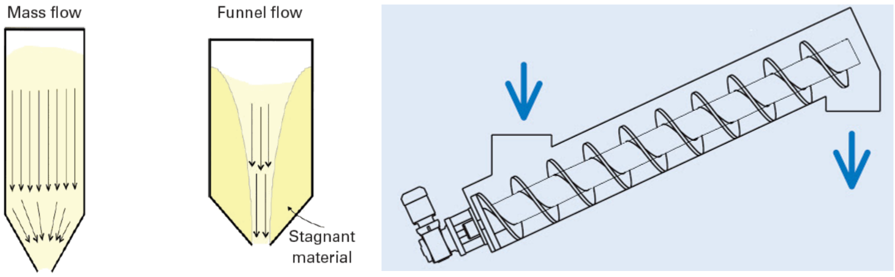
A comparison of gravimetric and volumetric density of several fuel types including liquid hydrogen, compressed hydrogen and different NaBH4 fuels is shown in figure 1.2. Liquid and compressed hydrogen are both more researched fuel options than a material-based storage of hydrogen such as NaBH4. This results in their TRL, Technology Readiness Level, being relatively high. These types of hydrogen however have the disadvantage of a low volumetric density making them less attractive for application in the transportation sector. Additionally the safety of these fuels is a concern: The release of hydrogen, the ignition of hydrogen and its explosion risks could be a problem. Cryogenic and pressurised storage are both riskier ways of storing hydrogen. This makes their certification complex and it certainly complicates their adoption in a port environment.

The storage of hydrogen in chemical hydrides such as NaBH4 have the potential to greatly increase the volumetric density of the fuel. It is however still in an experimental phase with a low TRL. It does have great potential for the application in the maritime industry by improving the safety of the system and to better the energy density of the fuel. Safety of storage is of special importance in a densely occupied port environment which harbours a lot of different industries and products in this area. Additionally the certification process of this technology is expected to be less complicated than for example LH2 or GH2 due to reduced safety risks. The potential of NaBH4 as a hydrogen carrier is greater in the maritime industry compared to its automotive counterpart, as the surrounding water can be used in the fuel system such that it doesn't need to be brought along on a trip. This makes NaBH4 a high potential fuel to reduce CO2 emissions in the maritime industry.

Implications of NaBH4 usage in the hydrogen supply chain

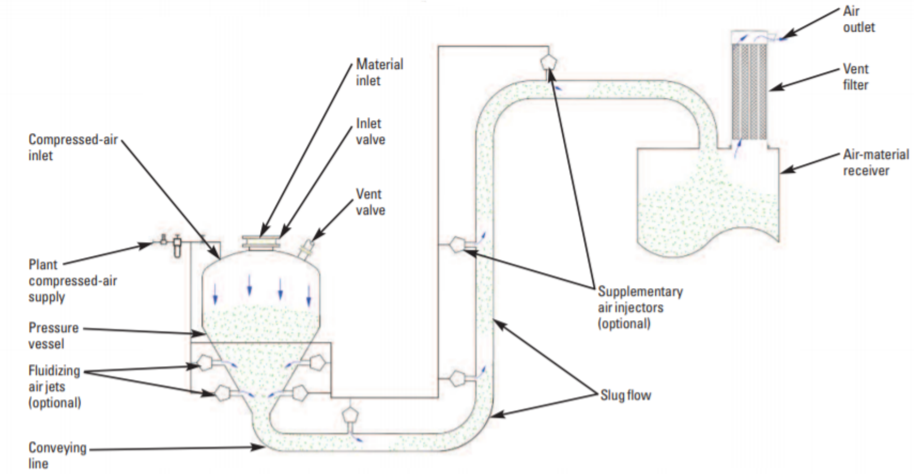
The delivery of NaBH4 as a fuel to ships has its implications for the supply chain and the corresponding infrastructure. The challenge is to be able to incorporate these implications in the infrastructure model. The NaBH4 supply chain design differs from other supply chains (LH2, GH2 or common fossil fuels) in multiple ways:

The first challenge of this different fuel type is the fact that it could be in either a solid or liquid state, depending on the (spent) fuel types used. A supply chain must be designed which is adapted to the transportation and storage of both solid as well as liquid material and its corresponding behavior. Different possibilities for transshipping solids [53] are shown in figure 1.4.



(a) Gravity driven solids transport [65]

(b) Screw conveyor [11]



(c) Pneumatic conveyor [73]

Figure 1.4: Several examples of solids transport technologies

The second challenge of implementing NaBH4 in the supply chain is the incorporation of a spent fuel flow which needs to be offloaded from the users to the quay and further transported to the regeneration plant. This adds complexity to the logistical process of the supply chain. Among other things it influences the number of refueling trucks or barges required. In the model design this extra flow should be implemented in a smart way to limit model complexity as far as possible. How this is implemented into the model is explained in chapter 4.

1.1.2. Port Refueling Infrastructures

The second major model innovation in this thesis is the modelling of a maritime refueling infrastructure, which differs in several aspects from a (more researched) automotive refueling infrastructure. In this chapter maritime characteristics and the sector's distinction from the automotive industry with an effect on the hydrogen infrastructure will be discussed. These distinctions consist of two points, being (1) the different refueling convention, and (2) the different expected adoption rate of an alternative fuel. The adoption of hydrogen in the maritime sector is expected to follow an S-shaped curve (as shown in figure 1.5), similar to most new technologies. Mosgaard et al. conclude [68] that the maritime industry has a lower adoption speed than its land-based transportation counterpart when it comes to adoption of energy renovations. Whether this will also be the case for the maritime transition towards cleaner fuels is a key question. This depends on many factors (as will also be discussed in this chapter) but amongst other things the regulations can play a big role in this transition, stimulating uptake of alternative fuels.

Ships in general

Maritime vehicles possess several characteristics which significantly change their needs from an infrastructural point of view when compared to automotive vehicles. Firstly, the lifetime of ships is gen-

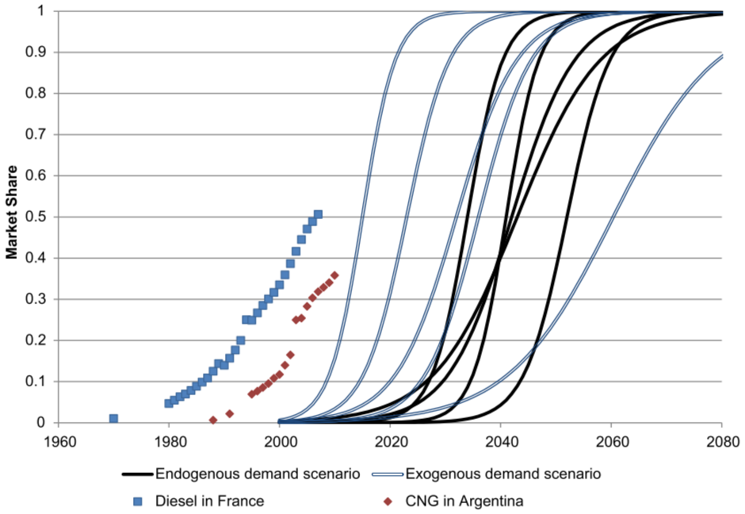


Figure 1.5: S-curves used by different studies modelling the market share of hydrogen in an automotive environment. Additionally two historical analogies are displayed for comparison [15].

erally longer than road-transport vehicles. Due to this longer lifetime, the opportunity arises to retrofit existing vessels, thus enabling already existing vessels to sail on hydrogen instead of regular marine diesel oil [68]. This might ease the uptake of NaBH4 and thus can influence the adoption rate of hydrogen as a fuel positively as many vessels will be able to qualify for adoption of alternative fuels.

Secondly, in contrast to the aerospace and automotive industry where products are built in large quantities, the maritime industry usually builds unique products. As it happens sister ships might also differ from each other considerably. Building a prototype to test the effectiveness of a new innovation for a specific ship, such as sailing on an alternative fuel, is thus not really an option in this sector. This means that the earlier adoption (the very first part of the S-curve) might lag behind the automotive industry. The uniqueness of every vessel could however have a positive effect on the later adoption of a new technology, when this is beyond demonstrator level: Due to avoidance of series production proven technologies are more easily implemented. This might lead to faster implementation of a new technology in the second part of the S-curve.

Refueling infrastructure in ports

Due to maritime user characteristics, the refueling infrastructure in ports regarding bunkering properties is also distinct: In a port environment, apart from ships visiting bunkering stations, tanker trucks or barges deliver (pre-ordered) fuel from the storage facility to the users. Due to this set-up vessels do not need to navigate towards a refueling station, which would often take a lot of effort and time and which would increase the number of manoeuvres inside the port perimeter.

This particular port set-up leads to a significantly different model regarding fuel transportation compared to automotive HSCNs (Hydrogen Supply Chain Networks). In short an extra stage (the tanker barges/trucks moving to the end users) needs to be modelled. This means there will be two transportation flows: the first flow being the delivery of fuel to restock refueling stations, the second flow being the delivery of fuel directly to users. This direct delivery to users adds significant complexity to the models. The availability of these delivery barges/trucks and their maximum capacity need to be incorporated into the model. The model will try to minimise the number of miles traveled by the barges/trucks delivering the fuel to cut costs. An elaboration on incorporating these characteristics mathematically in the infrastructure model is given chapter 4.

Regulations and the Netherlands

Regulations can either stimulate or restrain innovation in a sector. Creating the right regulatory circumstances could accelerate the adoption of an alternative fuel such as hydrogen (either in gaseous, liquid or solid state). The innovations in fuel efficiencies in the maritime transport sector lag behind the automotive sector due to the absence of strict maritime environmental regulations [71] [40]. However, political pressure could trigger the maritime industry into banning ships with high emissions [60] and thus stimulate adoption of cleaner alternative fuels. For example, the further development of Emission Control Areas (ECAs) could promote this adoption of alternative fuels. It is expected that these regulations will develop even further once viable alternative fuels are available in the maritime sector [41].

The Netherlands is the biggest supplier of maritime fuels in Europe. From this position the Netherlands could seize the opportunity of becoming a leader in alternative (low-carbon) fuels for the maritime sector [5]. Being in this position could speed up regulations concerning alternative fuels. Additionally the Dutch state is a shipowner herself as well. In this role the state could promote research and development of sustainability in the maritime sector [5]. These factors might lead to a higher adoption rate of hydrogen fuels in the Netherlands specifically. Of course the pressure to lower CO2-emissions also comes from other directions apart from the government: industry, society, the European Union and supply chain operators all strive for lower CO2-emissions.

Ship owner considerations

Ship owners are mostly commercial instead of recreational: they behave differently from recreational users as they are driven by making profit on their vessels. The business case of sustainable solutions on ships is currently not profitable as the cost of innovation is yet too high [5]. This limits the adoption rate of new technologies significantly. Even if suppliers are willing to sell their components needed for sustainable maritime operations at a low price, the installation of these components can still be expensive [68], such that testing of new technologies is costly and only develops at a slow rate. Due to the high capital costs involved in ship ownership, there is inertia which slows down the implementation of cleaner technologies even when both the economic and environmental conditions are advantageous, due to the risk of implementing a new technology of which the outcome is uncertain [68].

Mosgaard et al. [68] conclude that the uncertainty of these projects originates in both the technical aspect (how will the new technology actually perform on board the vessel?) as well as the operational aspect (how will the crew apply the new technology?). Looking at the crew however one might also say that, due to their professionalism (especially when comparing them to recreational automotive users) a lower threshold of switching to an alternative fuel could be expected.

Apart from the general risk aversion which limits the adoption rate of a new technology, both the seagoing vessels as well as the inland shipping vessels are internationally oriented. This means that (inter)national sea and inland ports collectively would need to supply these vessels with alternative fuel should they adopt the new fuel type. This means that in the long run not only national ports will have to enable the supply of an alternative fuel, but international ports as well. Alternatively the fuel needs to be easily/cheaply deliverable to other ports. This affects the view on the modelling scale needed in a port environment in contrast to an automotive environment.

Conclusion

It is clear that the introduction of an alternative fuel into the maritime sector is a complex undertaking and that it needs to overcome several hurdles such as a (current) lack of (inter)national regulations regarding CO2-emissions and the high costs associated with technological innovations. On the other hand, some maritime characteristics actually promote the implementation of new technologies, such as the presence of professional crews, the absence of series production and the possibility of retro-fitting ships. The adoption rate which will be used in this thesis will be discussed in paragraph 5.1.3.

More importantly, the development of a hydrogen infrastructure in a port environment can stimulate the user uptake of maritime hydrogen-based fuels. A port is a hub for many industries and transportation modes, requiring power to execute their tasks, and is thus an ideal starting point for an hydrogen infrastructure focused on the transportation sector. Implementing a hydrogen infrastructure in an area densely occupied by users could stimulate possible hydrogen users in the uptake of a new type of fuel [60].

1.2. Problem Definition

Having elaborated more on the characteristics of hydrogen carriers and port environments in previous chapter 1.1, the knowledge gap and research problem will be identified in this paragraph.

An adequate hydrogen infrastructure is not yet available on a large scale, which is seen as one of the biggest barriers of implementation of hydrogen as a fuel [57]. A leading Dutch example is the termination of the Nemo H2 project, due to the lack of a viable hydrogen supply chain [89]. Currently researchers are working on many different ways of producing, storing and transporting hydrogen fuels. Therein the transportability, safety and volumetric density are the most important criteria for maritime users regarding the alternative fuel adopted. The challenge is to select the best configuration of these different technologies into a hydrogen fuel supply chain, such that demand is met at predefined optimal conditions (such as lowest cost or minimal environmental impact).

The design of such an infrastructure is complex. The cost of installing its components is high and once constructed, modifications to it will be difficult and expensive. It is therefore important to thoroughly evaluate all options and to make a well considered decision on the infrastructure to be built. Additionally, as the lifetime of an infrastructure is very long, yet the usage profile of it will be dynamic over the years to come, it must be taken into account how such an infrastructure will function in different scenarios. It can thus be difficult to determine the best overall solution to the problem throughout time. Moreover, ship bunker requirements on the one hand and port logistic requirements on the other (think about aspects such as safety, energy density and environmental impact) should be met by the infrastructure. Lastly, there will be some uncertainty in modelling interdependencies between infrastructure components and users, as a full scale hydrogen supply chain has not been built before in a port environment.

In short, an adequate infrastructure is required to facilitate the adoption of alternative fuels and ensure the continuation of (hydrogen) projects, yet infrastructure design is a complex undertaking. Consequently, a tool is needed to aid in the design of hydrogen refueling infrastructures in port environments. The goal of this thesis project is thus to create an optimization model which can provide more insight into the initial sizing, phased growth and corresponding cost of an infrastructure needed for maritime transport using different forms of alternative fuels. This model can then be used to evaluate the growth and scalability of such an infrastructure and to model different scenarios (e.g. varying the number of users of the network or the projected costs) and identify value drivers and innovation needs. Information provided by this model could then be used by stakeholders, institutions and companies to more clearly determine their role in the green energy transition of maritime transport and set up their investment and research strategy accordingly. Additionally, by using the model a robustness analysis can be made, which is important to limit the risk of the infrastructure being poorly dimensioned.

The H2SHIPS project includes the development of a NaBH4 driven vessel as a demonstrator project for the Port of Amsterdam. Resulting from this development the configuration of a corresponding fuel supply chain should be researched. For this research mathematical optimisation is used, which is seen as a systematic decision making process [36], simulating the selection of the best infrastructure configuration. Hydrogen Supply Chain Network Design is a popular field using mathematical optimisation, with most research focusing on the automotive sector combined with liquefied or compressed hydrogen fuel (this will be discussed further in Part I: Literature Review). Translating this model type to a port environment using sodium borohydride (NaBH4), liquid hydrogen (LH2) or compressed hydrogen (GH2) as an energy carrier leads to two important model innovations:

1. The challenge is to create a model structure which can be used for different fuels (NaBH4, LH2, GH2, and others) depending on the input supplied. Up until now no papers have been found tackling the HSCND (Hydrogen Supply Chain Network Design) problem for **alternative fuels** like chemical hydrides such as NaBH4. Yet these hydrogen carriers are very promising for the maritime transport sector specifically due to the abundance of available surrounding water which is used in the chemical process of releasing the hydrogen. Using NaBH4 will change the model structure significantly because of its characteristics as discussed in paragraph 1.1.1.

2. The focus of the H2Ships project is on **maritime users**, which differ in several aspects from their widely researched automotive counterpart (as discussed in paragraph 1.1.2). This will affect the demand and adoption rate of hydrogen fuel in the port environment. Additionally, focusing on a port environment results in a different modelling scale: the boundaries of the model are set within the port perimeter. Moreover the components of the supply chain are different in a port due to a different refueling convention.

1.3. Research question

In this paragraph the research question of this thesis and corresponding sub-questions will be discussed. Additionally the scope of this research will be defined.

As discussed in paragraph 1.2 the goal of this thesis is to create a model as a decision support tool for the strategic planning of the hydrogen supply chain in a port environment, to explore the scalability of such an infrastructure. Correspondingly the following research question is devised:

How do the port refueling infrastructures of sodium borohydrate, liquid hydrogen and gaseous hydrogen compare to each other with respect to costs and supply chain set-up in terms of where, when, and at what sizes to build up the production, storage, distribution and refueling facilities?

The eventual model will be designed in such a way that with different inputs also other fuel types and port locations can be evaluated. Several sub-questions are designed to provide answers leading up to the main research question:

- What type of model and model characteristics should be chosen to simulate a port infrastructure? (discussed in the literature review: chapters 2 and 3)
- What model design should be used in order to keep it as modular as possible? (discussed in chapter 4: Mathematical Model)
    - For different demand scenarios.
    - For NaBH4, LH2, GH2, but also other fuels.
    - For Port of Amsterdam, but also other ports.
- What data should be used as input for the model? (discussed in chapter 5)

Scope

This thesis will research hydrogen infrastructure development within the H2SHIPS project. Because of this it will use the Port of Amsterdam as port input, as this will be home to one of the demonstrators currently being developed within the H2SHIPS project. This hydrogen powered port authority vessel will use NaBH4 as a hydrogen carrier. Because of this the fuels researched in this thesis are NaBH4, but also LH2 and GH2 as these are the prevailing forms of current hydrogen fuels. This makes the comparison between these fuels interesting. Note that the model is set up in a modular way such that other fuels (and also other ports) could also be researched using the same model.

DNV-GL defines three barriers for alternative fuel implementation [37]: (1) cost, (2) availability and infrastructure and (3) onboard storage. This thesis will focus on the hydrogen refueling infrastructure components (the second barrier) (production, storage and refueling facilities and the transportation of fuel) and their cost (the first barrier). For the onboard use (the third barrier mentioned by DNV-GL) and storage of hydrogen and NaBH4 in particular a reference is made to the thesis work of D. Lensing [56].

The hydrogen infrastructure can be designed on a strategical, tactical, or operational level. For the port infrastructure specifically the strategical level takes into account planning for decades concerning the purchase and dimensioning of components. The tactical level allocates these available resources to its tasks over multiple years, and the operational level treats day to day planning and daily demand fluctuations. As the product of this thesis will be a conceptual model and the focus is on infrastructure components and their allocation, the strategical and tactical level will be treated and the operational level will be out of scope for this research.

1.4. Thesis Outline

The structure of this thesis report is as follows: Part I consist of the literature review (chapters 2 and 3), in which the most relevant studies concerning hydrogen infrastructure modelling are gathered in order to provide an overview and analysis of the current model types being used, their scope and assumptions and to identify trends within the field of Hydrogen Supply Chain Network Design (HSCND).

Next, chapter 4 formally describes the complete mathematical model used for the refueling infrastructure design of this thesis. In chapter 5 the input used as a base case for the model and the corresponding assumptions are discussed. Additionally, the model requires thorough verification in order to justify its usability. This verification process is described in chapter 6.

The results of the model (the infrastructure costs and dimensions for different fuel types) are discussed in chapter 7. A discussion of the results and the model approach is provided in chapter 8. This report is then concluded by a conclusion (chapter 9) and recommendations for future research (chapter 10).

I

Literature Review

2

Theoretical Framework: Reviews

Hydrogen supply chain network design (HSCND) is a trending topic in research of the last decade. Several literature reviews of these HSCND-models will be evaluated in this chapter as they provide a clear overview of past research in this area. These reviews provide reasons for using certain modelling techniques (Linear Programming, Dynamic Programming and Geographic Information Systems), different ways of classifying these models and recommendations for future studies. In addition to these literature reviews, the 2006 paper of Almansoori and Shah [19] will be discussed. This paper is regarded as the seminal paper of this branch of research and is used as a basis for many other models, being the simplest form of modelling the hydrogen supply chain (HSC). An overview of the structure and vocabulary used in this chapter and chapter 3 is schematised in figure 2.1.

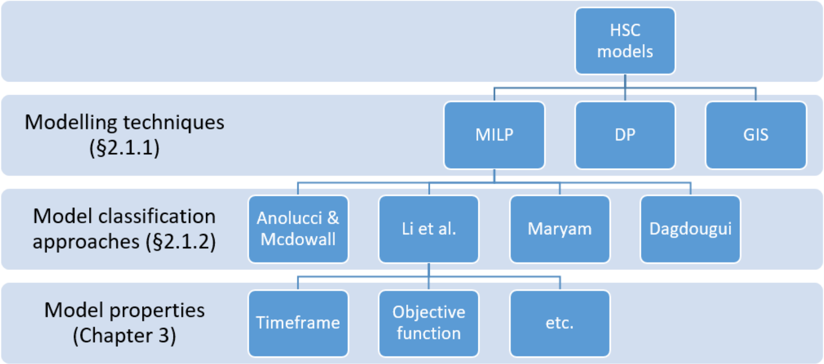


Figure 2.1: Labelling of model subdivision

2.1. Literature Reviews on the HSCND

Four major literature reviews on the topic of HSCND can be identified. They are listed in chronological order below:

- 2012: Dagdougui [29], 35 citations in Scopus
- 2013: Agnolucci and McDowall [15], 38 citations in Scopus
- 2017: Maryam [64], 5 citations in Scopus
- 2019: Li et al. [57], 5 citations in Scopus

These papers are used as a basis to identify modelling techniques regarding the HSCND. These techniques will be discussed in paragraph 2.1.1. The literature reviews also use different classifications of HSC optimization models, which will be discussed in paragraph 2.1.2. Recommendations for future studies described by the literature reviews are discussed in paragraph 2.1.3.

2.1.1. Introduction to modelling techniques

HSCND is a popular topic in scientific research, in which various modelling techniques can be identified. The three most relevant modelling techniques are Mixed Integer Linear Programming (MILP), Dynamic Programming (DP) and using a Geographic Information System (GIS). Dagdougui [29] already concluded that hydrogen supply chain (HSC) models are mainly focusing on mathematical optimization as this is seen as the most effective approach to the problem. MILP and DP are both optimisation models analysing the optimal configuration of a HSC. A GIS is used to model the spatial or geographical aspects of the optimisation model.

Mixed Integer Linear Programming models aim to find the optimum value of an objective function by finding the best combination of decision variables, whilst meeting predefined constraints [36]. In the case of the HSC this can be translated as the optimal configuration of the supply chain according to a predefined objective (for example minimizing the costs). The strength of Linear Programming models is that they can cope with complicated systems (many decision variables, inter-dependencies and constraints) [64]. These models are able to identify when, where, at what sizes and with which technologies the hydrogen infrastructure should develop [57]. Linear programming provides a good base for decision making in an infrastructure lay-out as complex decisions and interdependencies between components can be represented mathematically [36].

Dynamic Programming, like MILP, attempts to find the optimal solution to a problem. It focuses on multistage decision processes, where multiple decisions need to be made over both space and time [25]. The DP-approach is mostly used when a specific string of information is relevant to the problem. This string will then be followed through time using backward calculation. From end-time T_n the model recursively works back to the starting point T_0 where the optimal sequence of configuration of the supply chain is found [59]. A predefined rule will be constantly applied to this string (e.g. minimise the cost). Bellman [25] states that DP models have the danger of needing to store a large data set. Researchers using DP models also recognise this problem of dimensionality [58]. To reduce the size of the set of feasible solutions a DP model is often simplified by adding multiple constraints [15].

Geographic Information Systems are systems that add a geographical dimension to the overall model [61], possibly including information on the spatial distribution of a population, availability of resources, etc. [64]. In the case of the HSC, GIS is used in two different ways [57]: The first is to use GIS to link geographic constraints to the optimisation model, thus using it as input. This is the case for studies such as Ball [23] and Johnson [48]. The second use of GIS is to map the results from the optimisation model in order to validate these results with real world geographics. These two uses can be combined, such that GIS can be used for both input and validation (as is done by for example De-León Almaraz [34]).

Li et al.[57] conclude that the linear programming (LP) and mixed-integer linear programming (MILP) models are the most commonly used. Very few models use dynamic programming (DP) to research the HSCND. Agnolucci and McDowall [15] state that DP models are relatively simple compared to (MI)LP models. By using MILP one is able to model the optimal configuration of the hydrogen system, instead of assuming this exogenously as is the case with DP models. Thus, MILP models are generally preferred over DP models. Dagdougui [29] only briefly mentions DP as a modelling technique but does not elaborate on its (dis)advantages. Maryam [64] states that the main advantage of MILP models is that they enable a flexible approach to optimising a variety of objectives of the problem. The paper does not explicitly discuss DP-model approaches.

In conclusion, all review papers considered seem to express a preference for MILP techniques to model the HSC, which is unsurprising taking into account its many advantages. MILP can be used when evaluating multiple decision variables, in contrast to DP which is more focused on only one variable throughout time to limit the total feasible solution set of the model. DP follows a given pathway and optimises it, such that the configuration of the hydrogen system is seen as an input. This leads to the decision to adopt the MILP modelling technique, enabling the researcher to also optimise the configuration of the hydrogen supply chain in the port. A GIS will not be necessary in this model, as the port environment only comprises a small geographical scale compared to other models using GIS. The geographic information necessary for the model can thus be entered manually, ensuring computational feasibility of the model.

2.1.2. Model classification approaches

As discussed in paragraph 2.1.1 the MILP modelling technique will be used to model the alternative fuel supply chain for a port environment. There are many approaches to classifying MILP models to be able to evaluate them systematically. Literature reviews use different model classifications, depending on the emphasis of the review. These classifications will be discussed in this paragraph. Next, the most appropriate approach to MILP model classification is selected. Using this classification, model properties will be methodically discussed in chapter 3.

Agnolucci and McDowall [15] identify three model categories based on the HSC spatial scale (e.g. national, regional, local) and subsequently on the supply chain components of the HSC being incorporated in the model. Furthermore they treat uncertainty of inputs separately. This leads to a clear division of models, yet using this categorisation of models lacks an in depth analysis of decisions variables and performance measures used in models. Dagdougui [29], and Maryam [64] (focused on HSCND in the UK only) discuss optimization techniques only partly. The literature reviews do not only discuss mathematical optimization techniques, but also GIS models, transition models and system dynamic approaches. Ref. [15] logically states that this classification type of models is superseded, as some studies have combined an optimisation model with the GIS model. These review set-ups will thus not be used in classifying MILP models in chapter 3.

Li et al.[57], being the most recent literature review in the HSCND subject-area, gives a good insight into the relevant models and model properties currently being implemented to research the HSCND. Having collected papers from 2004 to 2018 on the subject of HSCND, they evaluate the selected models separately with respect to three categories. This approach to classifying model properties is a good way of creating a complete overview of the wide variety of current HSCND models, as it doesn't compartmentalise models but instead explores all distinct properties of models. The classification approach used by Li et al. [57] is as follows:

1. Pre-optimization work: treat methods for data collection for the MILP model
2. System analysis: assess the different supply chain components (feedstock, production method, etc.) modelled
3. Modelling and solution methods: assess different model properties (time-period evaluated, performance measures used, amount of uncertainty incorporated in the model)

HSCND has become a popular topic of research and the current models differentiate themselves from each other in many creative and different ways. For this reason it is considered best to use the classification approach of models as used by Li et al. [57], where there is room to evaluate all different models by classifying properties of the model separately and not by classifying complete models into categories. In chapter 3 different model properties will be discussed more in depth using such a categorisation. Note that only categories of model properties relevant to this research will be discussed.

2.1.3. Recommendations for future studies by review papers

The literature review papers considered in this review propose multiple directions for further research in the field of HSCND, derived from identified knowledge gaps. A selection of the recommendations which are possibly relevant to the research in a port environment are listed below. These include future study directions as well as general recommendations for the model approach:

- **Alternative hydrogen carriers:** Li et al. [57] recommend researching HSCNs based on alternative hydrogen carriers. Many new forms of hydrogen carriers are being developed (for example metal hydrides, chemical hydrides, high surface area carbon sorbents, and liquid-phase hydrocarbons). These carriers show high potential for implementing hydrogen into the energy mix, as discussed in chapter 1.1.1. A corresponding HSCN should be evaluated to provide information on the advantages and disadvantages of using these types of alternative hydrogen carriers. In this thesis this will be done for NaBH4.

- **Different users:** Ref. [57] also briefly mentions the adoption of hydrogen by users other than automotive users. In this thesis an alternative fuel supply chain in a port environment is designed, which would be an example of such different users. A local port supply chain could be beneficial for the overall evolution of the alternative fuel supply chain for three main reasons: **(1)** According to the literature review by Maryam [64] a local hydrogen infrastructure will initiate the use of hydrogen, until the uptake of hydrogen on a more centralised level is seen as viable. Subsequently governments and stakeholders will start to further develop a centralised hydrogen infrastructure. For this reason big users (such as ports) are expected to be the front runners in the hydrogen transition [15]. **(2)** Introduction of a hydrogen infrastructure in an area with high potential demand, such as a port, will reduce the average infrastructure costs as there will be a relatively high demand in a small area. **(3)** Whilst developing a hydrogen infrastructure in a port for maritime transport use one could make use of the current hydrogen usage by industry in the port environment.

- **Modelling uncertainty:** Agnolucci and McDowall [15] stress the fact that uncertainty in hydrogen demand should be accurately modelled. In the time that their review was written, uncertainty modelling of demand was only developed to a limited extent in HSCND. However, the transition rate of hydrogen demand does have a dominant influence on the choice of infrastructure and its corresponding costs [15]. Six years later Li et al. [57] concluded that uncertainty of hydrogen demand has been sufficiently included in several models. However, they recommend further researching uncertainty in inputs such as capital cost, operational uncertainties, government policies and technological evolution. Both Agnolucci and McDowall [15] and Dagdougui [29] stress the importance of assessing the sensitivity of the model outputs to changing hydrogen demand. Therefore, in this thesis chapter 7 assesses the output of the model with respect to changing cost of components and changing demand curves.

- **Discrete facility steps:** Li et al. [57] recommend introducing discrete facility capacity expansion options into multi-period models. This is a more realistic approach to modelling the HSC and will most likely result in lower initial investment costs as the infrastructure is only required to serve the initial demand. When not including capacity expansions in the model a very large infrastructure will be required early on as it assumes the need to suffice for upcoming hydrogen demand. Additionally, including possibilities for expansion are attractive for stakeholders as it can be adapted throughout time to unforeseen changes in demand and policies. Capacity expansions will be modelled in this thesis. The approach for such an expansions is described in chapter 4.4.

- **Performance measures:** Current HSCND models use mainly cost as a performance measure of the designed infrastructure. Other favoured performance measures are safety of the supply chain and the environmental impact of the complete infrastructure. Li et al. [57] suggest additional performance measures that could be explored: The Levelised Cost Of Hydrogen (LCOH), the efficiency of energy use (meant for renewable energy specifically) or the social benefit (in terms of jobs provided).

2.2. Seminal paper: Snapshot model

The 2006 paper written by Almansoori & Shah [19] is regarded in the HSCND research field as the seminal paper on which further research models are based. Their paper gives a full overview of the mathematical model formulation used, such that it is very useful to use as a basic start up of a model. Additionally their assumptions are stated and explained in a clear way. For this reason this paper will be elaborated on more in this paragraph.

A schematic overview of the model of Ref. [19] is shown in figure 2.2. The focus of this model is on production, transport and storage of hydrogen; the location and number of refueling stations is outside the scope of this research. MILP is used as an optimisation tool, solving a steady state problem. This means that the evolution of a hydrogen supply chain through time is not taken into account: the model is only optimised for one specific moment in time (a snapshot). The demand is fixed. The model optimises for HSC cost only. Optimisation of safety or environmental impact are not taken into account. Multi-objective optimisation (which will be discussed in more detail in chapter 3) is a more recent approach to optimisation models in which multiple objectives can be optimised.

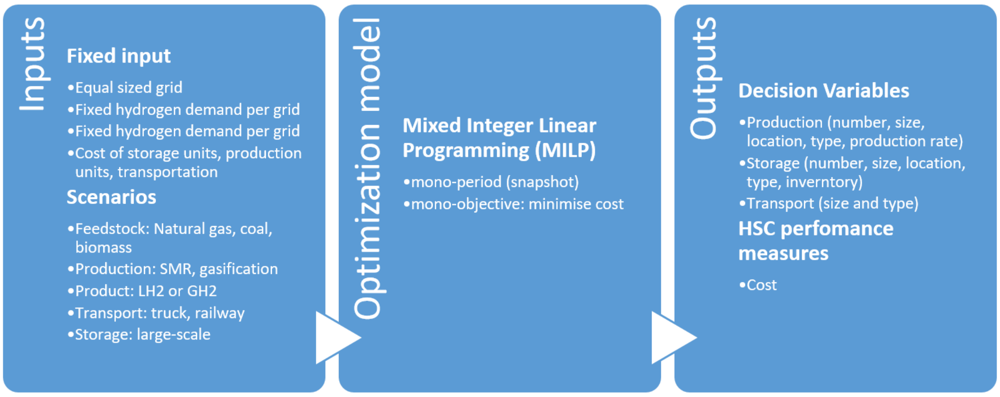


Figure 2.2: Schematic overview of the landmark research of Almansoori & Shah [19]

The result is an elegant, simple model that can be used as a basis for many models looking to expand this model. This is why this research of Almansoori and Shah [19] is regarded as the seminal literature of the HSCND field, and why so many researchers have based their work on this research. Other researchers have tried to improve the model of Almansoori and Shah [19] with several additions to or expansions of the model. A trend can be seen where authors start out with one model and then gradually expand it over time with subsequent papers. Examples of such authors are:

- De-Leon Almaraz (from a mono-period model [31] to a multi-period model [33] [32], to evaluation of the model on different geographical scales [34])
- Han (from a mono-objective model [43] to a multi-objective model [44])
- Kim & Moon (from a mono-objective model introducing demand uncertainty [50] to a multi-objective model including demand uncertainty [51])
- Almansoori & Shah (from their seminal paper as discussed [19], to a multi-period model including feedstock availability into the SC [20], to including hydrogen demand uncertainty and including refueling stations into the supply chain [21])

From this it can be concluded that it is best to first create a working, simplified MILP with several base assumptions, and then gradually expand this model as other researchers have done. A trade-off needs to be made constantly between accuracy of the model on the one hand and computation time on the other hand. In the next chapter (chapter 3) model properties will be discussed along with their (dis)advantages. In paragraph 3.6 the model properties selected in this thesis for the modelling of an alternative fuel supply chain in a port environment will be discussed.

3

Theoretical Framework: Models

In this chapter the model properties for hydrogen supply chain models will be subdivided into categories. These categories have been chosen on the basis of the literature review by Li et al. [57] as discussed in chapter 2. The strengths and weaknesses of the different model properties will be explored and examples of concrete research models will be given. This way a deliberate decision can be made on what model properties to use in this thesis. Only research papers including a full mathematical description of their model will be discussed in this literature review.

3.1. Overview of MILP model properties

Within MILP models there are various properties to consider. Figure 3.1 gives an overview of a HSC model and the types of modelling properties considered in this literature review. Setting the properties of a MILP model will have an effect on the accuracy of the output. Thus, selection of certain properties depends on the scope of the research and the accuracy required in the model. The types of properties considered are the modelling scale (paragraph 3.2), the objective function (paragraph 3.3), the time-frame (paragraph 3.4) and the input uncertainty (paragraph 3.5).

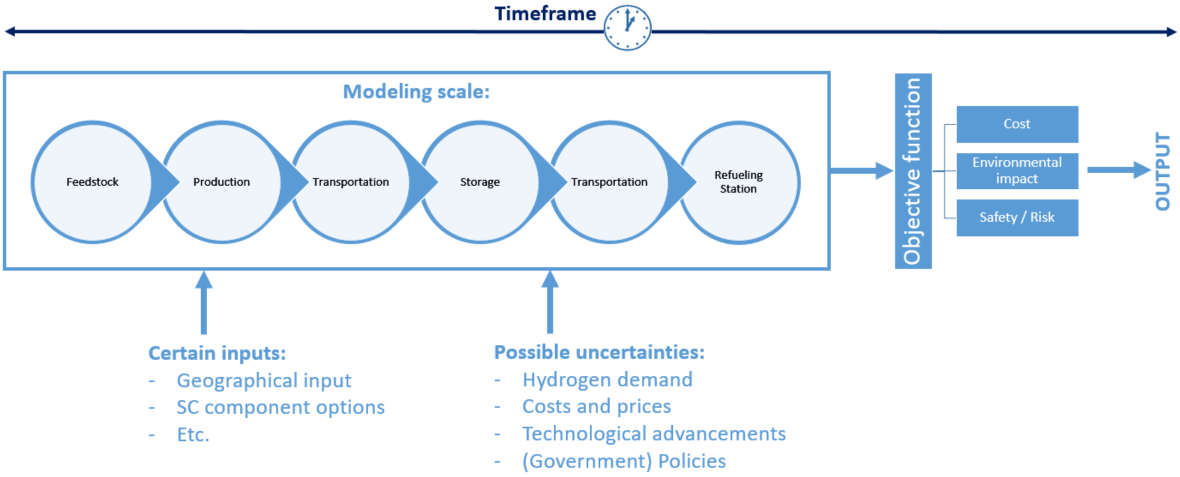


Figure 3.1: A schematic overview of a HSC model and its various model design choices

When designing a model there will always be a trade-off in model complexity and computing time: Adding more details to a model leads to substantially more decision variables to be evaluated. The computing time of the model will thus increase. To be able to process the information from the model more efficiently one could choose to simplify the model such that computing time is decreased. This however leads to a less accurate model; to a model that is only optimising part of the HSC; or to optimising only specific chosen options of a HSC instead of including all real-world possibilities.

3.2. modelling scale

When treating the modelling scale of a HSCND model this entails both the different echelons of a hydrogen supply chain as well as the spatial scale of the supply chain. The supply chain consists of multiple echelons (such as production, storage, transportation, etc.), of which models can either incorporate all components or model only part of the supply chain. Additionally, the researcher can choose the spatial scale in which he/she will model the supply chain: International, national, regional or local. Agnolucci and McDowall [15] identify three model categories based on the scale and the echelons of the HSC being incorporated in the model:

- **Energy system optimisation models:** Hydrogen demand and supply are both endogenously optimised. The model is usually focused on a national scale energy system, but could be applicable to smaller scales. The MARKAL model [8] and its successor model TIMES [62] [63], both created by the International Energy Agency represents this type of optimisation model and is the most frequently used in research papers of this sort. This model type goes through several iterations, firstly determining the hydrogen price corresponding to a certain infrastructure meeting a certain hydrogen demand. Secondly, in reaction to this hydrogen price and infrastructure configuration the changing demand is modelled.

- **Geographically explicit optimisation models:** This model type takes into account the complete supply chain, usually focused on a regional scale energy system, but in contrast to energy system optimisation models, hydrogen demand is an input of the model instead of being endogenously optimised. Landmark studies in this category are the models of Almansoori and Shah [19][20][21].

- **Refueling station-locating models:** This type of model focuses on the problem of optimally locating the refueling stations on a local level such that maximum hydrogen uptake by users is facilitated. The refueling station-locating models focus mostly on user patterns, traffic flows and refueling behavior of vehicles. For automotive users this problem is more relevant compared to maritime users in a port environment due to different refuelling behaviour of these users (as has been discussed in chapter 1.1.2).

This categorisation of models gives a good insight into model scales, which are highly dependent on the scope of the research. The port model will not include endogenous optimisation of hydrogen demand as is done in energy system optimisation models, as this is difficult to model accurately and leads to several weaknesses [15]. These are, among others, a weak representation of market structures, behavioral dynamics and of risk-aversion to new technologies. The port model will be a geographically explicit optimisation model as it can represent a spatially optimised HSC rather accurately for a certain demand. It will however be focused on a local level (the port environment), such that the model will also incorporate parts of the locally oriented refueling station-locating models.

As the HSCND will be done on a local level, the geographical input for the model can be done manually: The location(s) of the production and storage facility, as well as possible locations for refuelling stations can be chosen by evaluating the current lay-out of the port. Distances between supply chain components and users can then easily be determined by simply calculating these distances for the different transportation scenarios. Through this approach the decision variables regarding the locating of SC components is limited, thus keeping the model itself simple. Additionally, the model will only select locations that are feasible within the existing port lay-out instead of selecting an 'optimal' location of a storage facility which for example might require other existing infrastructure or buildings to be removed.

The model scope is not only relevant for selecting which supply chain echelons to incorporate into the model, but also for selecting the components of different echelons evaluated in the optimisation model. It is clear from Agnolucci and McDowall's [15] categorisation of models that the modelling scale and thus the HSC components considered differ per model depending on the problem definition. These SC components are decision variables of the model: variables which the optimisation algorithm can freely vary in order to find the optimal solution. The optimal solution is discovered by finding the best combination of decision variables within the boundaries of the model. Decision variables can either be integer or continuous. Li et al. [57] created an overview of decision variables used in previous HSCND models, which is shown schematically in figure 3.2. As can be seen not all possible decision variables

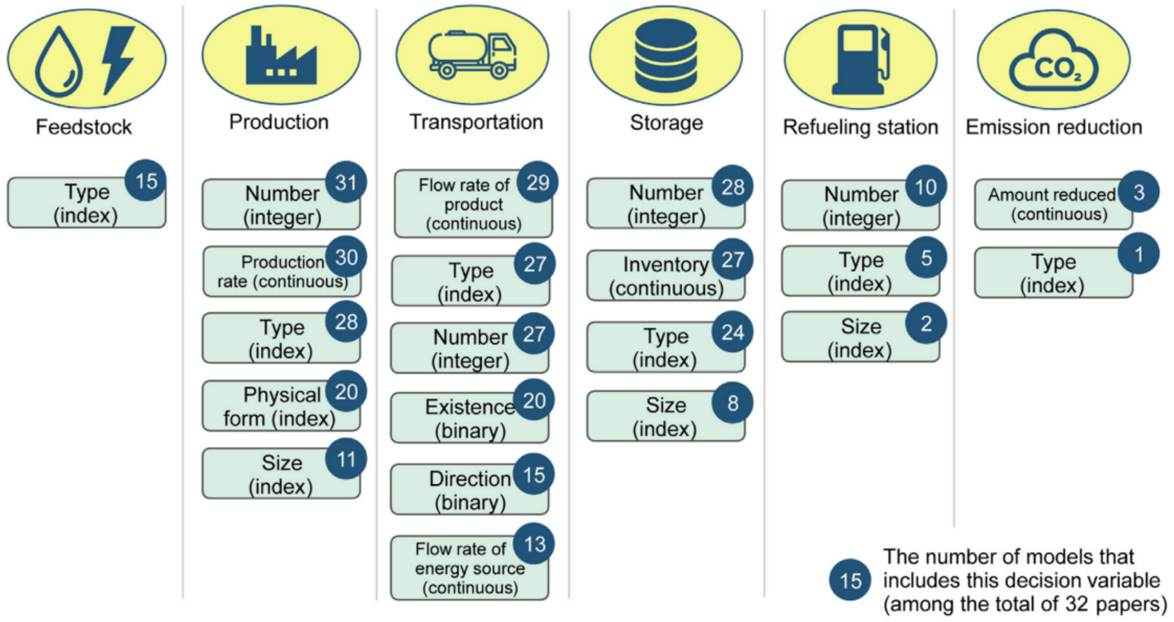


Figure 3.2: Model decision variables in HSCND models as defined by Li [57]

are all implemented in every model: Only the variables which are most relevant to the SC problem at hand will be selected. Decision variables for transportation are options for the transportation/distribution section such as (a combination of) the use of pipelines [44] [22], trucks [54], railway [82] or tanker ships [43] [81]. Similarly, different production, storage or refueling station types and sizes could be selected as decision variables, depending on the supply chain characteristics.

3.3. Objective Function

The objective function of an optimisation model is the function in which it is specified what variable output of the model should be maximised or minimised. Choosing an objective function for the model is to choose the performance measure against which the model outputs are tested. Three main objective functions can be identified in current models:

1. Minimise cost
2. Minimise risk (or: maximise the safety of the system)
3. Minimise total environmental impact (or: minimise GHGs)

All models evaluated by Li et al. [57] minimise cost. However, in contrast to models optimising their model for only one objective (mono-objective models), some model use multiple objective functions (so called multi-objective models, such as [50] [81] [76] [82] [42]), . Dagdougui [29] rightly states that optimising a mono-objective model could lead to solutions which might be beneficial with respect to costs, but compromises the environmental impact or safety of the hydrogen infrastructure. Nevertheless, using a multi-objective model is not the only solution to correctly modelling the trade-offs between cost, risk and environmental impact in the system. Environmental impact and safety could be included into a mono-objective cost-minimising model by representing these impacts as costs [57]. Increasing risk or increasing environmental impact then lead to higher costs. For example, Almansoori and Betancourt-Torcat [18] created a model where either a CO2 tax is included or where CO2 emissions are constrained. Han et al. [44] created a multi-objective model, where environmental impact is included as a cost but risk is separately optimised.

Per model one should evaluate whether a mono-objective model is sufficiently capable of representing the system or whether a more complex multi-objective model should be used. The most notable advantage of a multi-objective model is that a Pareto frontier can be plotted (a set of optimal solutions within certain boundaries), from which decision makers and stakeholders can make their own trade-off decisions between cost, risk and environmental impact.

Solution methods for multi-objective HSC models are either *a priori* or *a posteriori* approaches. An a priori solution method will endogenously select the best trade-off between different objectives, where the rules that need to be followed by the model are programmed beforehand. The most common a priori method is the weighted sum approach [44]. The concept of the weighted sum approach is to combine each objective function with a coefficient (the weight) and to minimise the weighted sum of the combined objectives. Hence, the multi-objective optimisation problem is converted into a string of single-objective optimisation problems [36]. The weights are based on the (subjective) perception of the importance of each single objective [44].

An a posteriori solution method evaluates the trade-off between different objectives only after the optimisation of the SC is complete. The ϵ-constraint method is the most used a posteriori approach to evaluating multi-objective models [44]. This approach, like the weighted sum approach, transforms the multi-objective problem into a set of single-objective optimisation problems. In the ϵ-constraint method one of the single-objectives is chosen to be minimised, whilst all other single-objectives are converted to inequality constraints bounded by some lower and upper allowable levels [36]. These bounds are obtained from the optimisation of each single objective separately [82]. The results from solving all the separate single objective problems lead to the Pareto curve [76] (a curve which shows the efficient points separating the feasible and infeasible design space of the problem). As mentioned before, preference is given to using the ϵ-constraint method for solving the specific HSC multi-objective model, as the corresponding Pareto curve is very useful for all stakeholders concerned because it gives a good insight in trade-offs of the model output.

3.4. Timeframe

Optimisation models can optimise a HSC either for a specific moment in time (the model is then called a mono-period or snapshot model), or it can optimise the HSC for a specified period of time which is usually for approximately 50 years (called a multi-period model). Mono- and multi-period models will most likely yield different solutions for the same problem, as hydrogen demands, cost of hydrogen and other model inputs are expected to change over time, thus requiring a SC to be able to accommodate those future changes. A mono-period model will only design a supply chain which will be sufficient for that specific moment in time, whilst a multi-period model will return a supply chain which will grow and transform simultaneously with the changing hydrogen demand and cost [32].

The length of the timeframe varies for multi-period models, ranging from 12 months (mainly used when modelling renewable energy sources as a main feedstock, due to seasonal fluctuations) to decades. Some models (such as Ref. [67], [81] and [17]) apply cost-discounting to the cost objective function, using a discount rate to equalise SC expenditures in different time-periods. Alternatively, some models optimise hydrogen supply chain infrastructures for discrete levels of demand (5%, 10%, etc.) with no explicit time dimension [15]. The nature of the supply chain should be considered when choosing the time-frame used in the model.

The port model in this thesis will be designed as a multi-period model over a timeframe of 40 years. This type of modelling is more adept to model a real world supply chain and is able to answer questions regarding the timing of supply chain investments which are likely to be raised by stakeholders. As the network evolves over time, new HSC components will need to be obtained to meet the increasing demand, such that the ability of a SC to evolve over time is crucial. The timeframe will range from 2020 to 2060, with timesteps of 10 years.

For a more realistic multi-period model, capacity expansion of facilities should also be incorporated in the model. As has been mentioned by Li et al. [57] in their recommendations, discrete facility capacity increments are recommended to be modelled (as in model Ref. [82]) instead of continuous increments (as has been done in Ref. [70]). Expansion of certain components in the supply chain can then expand in discrete steps as hydrogen demand grows over time. This will lower the initial investment cost of hydrogen facilities, as they are able to evolve with the changing hydrogen demand, such that the initial hydrogen infrastructure does not need to be overdimensioned to be able to accommodate future hydrogen demand.

3.5. Model uncertainties

HSCND models generally aim to model an infrastructure which covers a large time span. Additionally they attempt to predict unknown future hydrogen demands and costs (including unknown technological advancements). This leads to many uncertainties in such models. How to deal with these uncertainties is an important aspect of the model design, as this has a great effect on the reliability of the model outcome. However, modelling uncertainties also leads to a larger and more complex model, such that a trade-off needs to be made between model reliability and complexity. Nonetheless modelling of uncertainty has become increasingly popular in HSCND: in 2012, when Agnolucci and McDowall [15] wrote their literature review, only one paper (Kim et al. [51]) included stochasticity into the model design. In the literature review of Li et al. [57] published in 2019 the number of papers including uncertainty have grown substantially: Already half of the 32 models evaluated took uncertainty into account.

Models taking uncertainties into account attempt to avoid the over- or underdimensioning of supply chain facilities. The most notable sources of uncertainty in HSCND are:

- Hydrogen demand
- Cost of hydrogen, energy, or supply chain components
- Technological advancements of supply chain components and efficiencies
- Government policies regarding hydrogen as a fuel

Models with uncertain or incomplete data are not uncommon in linear programming models. The uncertainties in models are usually dealt with either *reactively*, by applying a sensitivity analysis to the output of the model, or *proactively*, by using (stochastic) programming formulations to incorporate uncertainty into the model [69]. In the port model only reactive methods will be used to evaluate uncertainty, to limit the complexity of the model. The reactive operation will be a sensitivity analysis applied to the output to conclude on the robustness of the model outcome. Possibilities for proactive ways to model uncertainty in HSCND as identified by Li et al. [57] are divided into three groups which are; (1) scenario analysis, stochastic programming and SAA, (2) fuzzy programming and (3) robust optimisation. These approaches will not be used in this thesis model set-up but will be discussed in the following paragraphs to provide an overview of model expansion possibilities.

The first group of uncertainty modelling approaches treat all outcomes of uncertainty in the model as different scenarios with corresponding probabilities. In **Scenario Analysis (SA)** these scenarios are used in HSCND for the hydrogen demand and are either optimistic, neutral or pessimistic scenarios. This type of modelling is used in research papers such as [32], [43], [50], [70]. **Two-stage stochastic programming (SP)** splits up the decisions in two stages: decisions that need to be made at this instant (such as the build of storage or production facilities) and decisions that can be made later when there is less uncertainty (such as the number of transportation units needed). This type of modelling is used by models such as the 2012 research paper by Almansoori and Shah [21], and other papers such as [30], [51], [74], [82]. The objective of the model is to minimise the cost of the first stage of the supply chain (which is in the nearby future thus can be predicted with more certainty), combined with minimising the expected cost of the following stages. The expected cost of both Scenario Analysis and Stochastic Programming can be found by calculating the cost per scenario and multiplying this by the probability of occurrence of that specific scenario, and then summing these costs. Li et al. [57] logically bring up the fact that this will lead to a greater model size as all possible scenarios will need to be calculated by the model. Another way to deal with scenario uncertainty is **Sample Average Approximation (SAA)**. Where the two earlier discussed uncertainty modelling approaches for SC design under uncertainty are suited for only a very small number of scenarios due to limitations in model size corresponding with longer computational times, SAA is more adept to incorporate a huge number of scenarios in supply chain design [83]. SAA selects a randomly chosen sample from all possible scenarios and solves the model for this selection of scenarios to compute the expectation of the output of the optimisation model. The result from the SAA analysis converges exponentially towards the true optimal solution of the total scenario set, such that a sufficiently good solution can be found by solving the moderately sized SAA problem [83]. This type of modelling would reduce computing time substantially with respect to SA and SP approaches, but is only necessary when the number of scenario possibilities is high.

The second group of uncertainty models uses **fuzzy programming (FP)** to deal with uncertainty of inputs. This type of programming quantifies linguistic rules, set up by experts in a specific field. This type of programming was used in the airport ecosystem paper [75], where the hydrogen demand has been modelled using fuzzy inequalities. This means that violation of certain constraints can be accepted up to some extent. Lower and upper values of hydrogen demand are defined which gives the maximum deviation of the average demand. The deviation is then varied, and for each deviation an optimal solution is found. This means that the solution thus is also eventually fuzzy [38]. The advantage of FP is that the model better fits the information available of the HSC. However, the common simplex algorithms for computing a problem solution can no longer be used [80], complicating the programming process of the model.

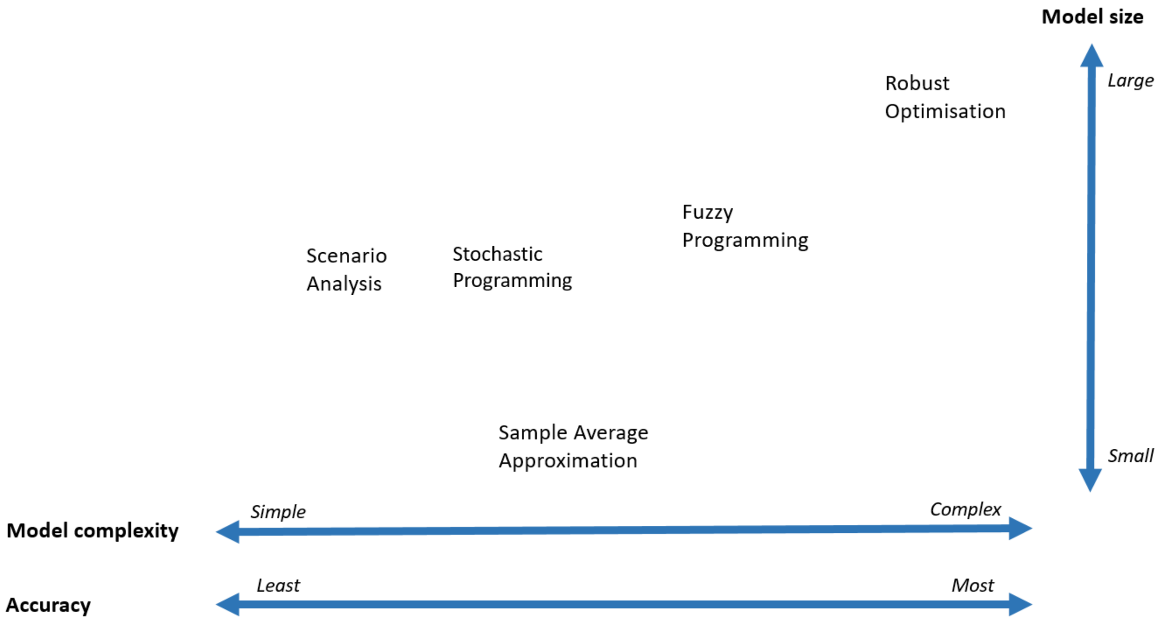


Figure 3.3: An overview of uncertainty modelling approaches

The last type of uncertainty modelling discussed in this review is **Robust Optimisation (RO)**. RO combines characteristics of both multi-objective programming and stochastic programming [69]. The biggest advantage of this type of uncertainty modelling is that the output of the model is generally less sensitive to different scenario inputs. It is more robust in the face of uncertainty. However, a RO approach is generally very complex and requires a lot of computational power. Additionally, a RO model will try to design a HSC solution which will need little adaptation throughout time to handle changing input (such as demand) [69]. This will lead to generally higher cost of the solution. When treating risk aversion the stochastic approaches to uncertainty are generally more reliable than robust optimisation models which focus more on the average performance of a HSC [49]. RO is thus an approach which will lead to a robust output of the model on the one hand, but a more complex, bigger and less risk oriented model on the other hand.

An overview of the most important characteristics of the five uncertainty modelling approaches is shown in figure 3.3. In this thesis model uncertainty will not yet be incorporated, as a more basic model approach is adopted to focus on the innovative parts of the port model: alternative fuel (including solids (NaBH4)) transport and storage, and maritime users in a port environment. A later model version should incorporate the uncertainty evaluation of input parameters by implementing a more complex uncertainty model.

3.6. Conclusion: Modelling decisions

Resulting from the literature review the following structure will be used in the mathematical optimisation model:

- **Scale:** A local level modelling scale, taking into account the following echelons: production and storage facilities, fuel transportation (barges/trucks) and refueling stations. Feedstock availability for the production of the alternative fuels is out of scope.
- **Objective:** A single-objective model minimising cost.
- **Time-frame:** A 40 year time-frame in a multi-period model set-up, with a decade per time-step.
- **Uncertainty:** Not proactively incorporated in the model. Only a reactive approach to uncertainty will be incorporated by applying a sensitivity analysis to the model output.

As many innovations are implemented into the model with regard to the hydrogen carrier (LH2, GH2, or NaBH4) and the application (a maritime environment), a trade-off is must be made between the size and complexity of the model on the one hand and the model accuracy on the other hand.This trade-off has led to the model structure as describe above. Later models can expand their structure and thus incorporate more aspects of the complete supply chain. The design of the mathematical HSCND model, taking into account the model adaptations required for implementing NaBH4 as fuel and for implementing the model in a port environment as discussed in the previous chapters, is shown schematically in figure 3.4.

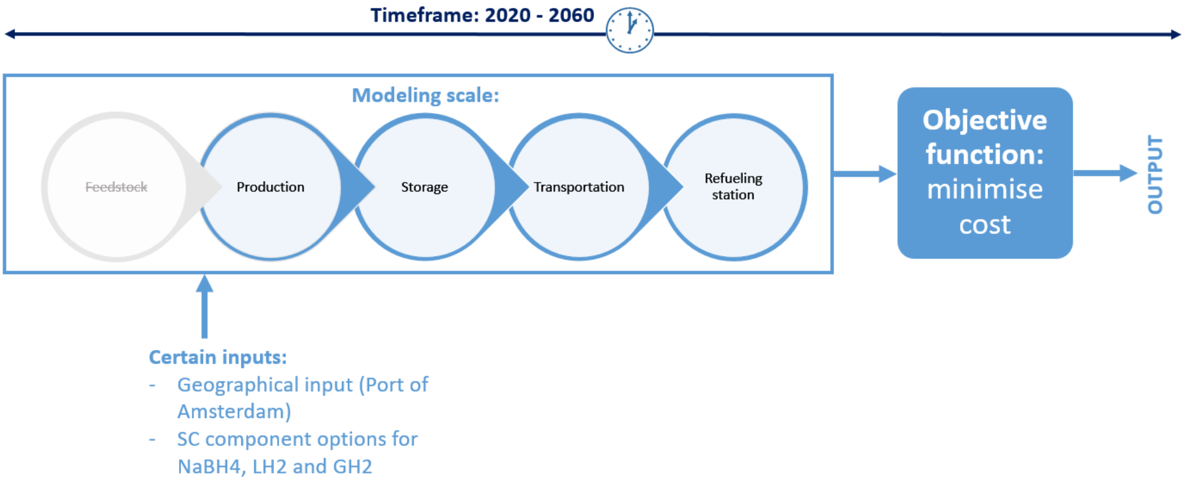


Figure 3.4: Overview of the port HSC model

II

The Model

4

Mathematical Model

In this chapter the mathematical model used to design the alternative fuel infrastructure will be formally introduced. The overarching modelling decisions (based on the literature review) have been described in chapter 3.6. In this chapter the model will be formulated starting from the demand side (paragraph 4.1), followed by the placement of refueling stations (paragraph 4.2), the transportation of the fuel (paragraph 4.3), the sizing of a general storage facility and a production facility (paragraph 4.4). The objective function (the overarching function which defines the objective of the model, namely minimising the overall cost of the infrastructure) is described in section 4.5. An overview of the notation used in this mathematical model is provided in section 4.7. All components under the header "parameters" are values that are required as input of the model. This input is discussed in chapter 5. As can be seen throughout this chapter, the model has been designed in a modular way such that it can easily be used for modelling the fuel supply chain for a wide variety of fuels and for a wide variety of ports as well, solely by changing the input of the model. This makes the model widely applicable.

4.1. Fuel demand

An important boundary condition of the supply chain design produced by the model is the ability of the supply chain to be able to always satisfy the fuel demand. The fuel demand d_{is}^t will depend on the time period t considered, the location i of the demand point and the vessel type corresponding with a delivery category s. Introducing this set of delivery categories s is part of the first model innovation as mentioned in chapter 1.2, where the specific maritime refueling convention is modelled. These different delivery categories s are displayed in figure 4.1. To account for the evolution of the demand for the alternative fuel over time a penetration factor PF_s^t is introduced. This factor represents the ratio of demand for alternative fuel with respect to the total fuel mix, for delivery category s and time period t. The penetration factor is multiplied by d_{is}, the total energy demand for each demand location i and delivery category s. This total energy demand is derived from the current fuel supply chain in the port of Amsterdam. Note that d_{is} represents demand of energy, whereas the complete supply chain model further focuses on fuel weights to be transported, stored and produced. For this reason the Weight-to-Energy ratio (WER) is introduced. This factor converts the energy demand to a specific fuel weight demand. The Weight-to-Energy ratio WER, mathematically indicated with $\mathcal{W}$, is dependent on the fuel used in the model, supporting the modular build-up of the model. Let I denote the set with all possible demand locations. Let S denote the set of fuel delivery categories. Let T denote the set of timeframes considered. The fuel (weight) demand formula is then given in equations (4.1).

$$d_{is}^t = PF_s^t d_{is} \mathcal{W} \qquad \forall i \in I, \quad \forall s \in S, \quad \forall t \in T \tag{4.1}$$

In this formula the two major model innovations of this thesis become apparent. The formula was based on the seminal work of Almansoori and Shah [20]. However the formula has been modified by firstly adding the dependency on the fuel delivery category s (thus incorporating a maritime refueling convention into the model), and secondly introducing $\mathcal{W}$ (such that a variety of fuels can be modelled).

4.2. Refueling stations

The placement and development of refueling stations within the port perimeter makes use of location theory, which is a type of mathematical optimisation problem. In location theory the placement of a facility is considered, taking into account both the investment costs of each potential location and the transportation costs for moving the product from the chosen location to the users.

To determine which refueling stations should be opened or expanded, to be able to offer the alternative fuel, demand points should be linked to refueling stations. The set of potential refueling stations (either by expansion of existing refueling station or by new build) is given by set J. From set J a subset must be selected by the model such that all demand locations are covered sufficiently. We introduce

$$Y_{ij}^{t} = \begin{cases} 1, & \text{if } i \in I \text{ is served by } j \in J \text{ at time } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.2}$$

Each demand location should be assigned to only one refueling station, as described in constraints (4.3). The assignment of demand points to refueling stations can change over time and is not fixed once chosen in certain time period. The refueling stations can supply fuel to only general bunkering station users $s = 3$ (also shown in figure 4.1).

$$\sum_{j \in J} Y_{ij}^{t} = 1 \qquad \forall i \in I, \quad \forall t \in T \tag{4.3}$$

Next, we introduce

$$X_{j}^{t} = \begin{cases} 1, & \text{if } j \in J \text{ is selected in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.4}$$

X_j^t can either represent the commissioning of a completely new refueling station, or the modification of an already existing refueling station to also supply alternative fuels from this station apart from current fuels. Constraints (4.5) state that demand points can only be assigned to refueling stations which are selected by the model.

$$Y_{ij}^{t} \leq X_{j}^{t} \qquad \forall i \in I, \quad \forall j \in J, \quad \forall t \in T \tag{4.5}$$

There is no set maximum number of refueling stations that can be opened: The objective of the model is to minimise the costs. Taking into account the storage building and operating cost will lead to the model automatically selecting the optimal number of refueling facilities.

The demand for each demand location $i \in I$ and time period $t \in T$ is given by d_{is}^{t}. Furthermore the refueling stations have a maximum storage capacity for fuel, $RCAP_j$, which models either a capacity expansion of an existing refueling station, or the build of a completely new refueling station. Constraints (4.6) state that the total daily demand of category $s = 3$ from all locations i linked to refueling station j must not exceed the daily storage capacity of the refueling station j. The factor β_R indicates the storage period factor for refueling stations, taking into account a margin of fuel needed to cover for daily uncertainties in both supply and demand as well as possible production plant / renewable energy interruptions.

$$\sum_{i \in I} d_{is}^{t} Y_{ij}^{t} \beta_R \leq RCAP_j X_j^{t} \qquad \forall j \in J, \quad s = 3, \quad \forall t \in T \tag{4.6}$$

Next, we introduce

$$IX_{j}^{t} = \begin{cases} 1, & \text{if a purchase/expansion of } j \in J \text{ takes place in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.7}$$

The assumption is made in this model that refueling stations, once built, will not disappear; they will neither be demolished nor removed. This leads to constraints (4.8) describing the evolution of refueling

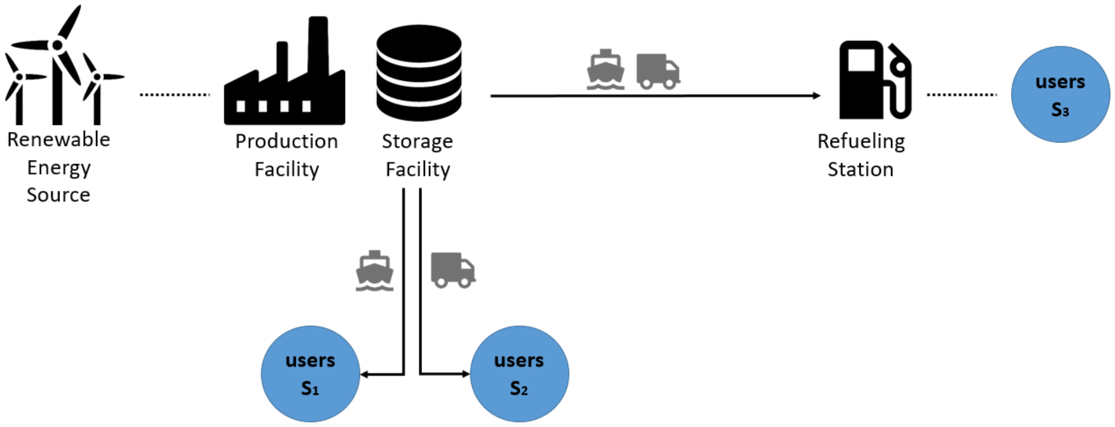


Figure 4.1: The different delivery categories incorporated in this model: s_1 represents the Ship-to-Ship (STS) fuel delivery; s_2 represents the Truck-to-Ship (TTS) fuel delivery; s_3 represents users navigating to the refueling station. Refueling stations can be restocked by both barges and trucks.

stations over time. Before $t = 1$ no alternative fuel refueling stations have been built yet, as defined in equations (4.9).

$$X_j^{(t-1)} + IX_j^t = X_j^t \qquad \forall j \in J, \quad \forall t \in T \tag{4.8}$$

$$X_j^0 = 0 \qquad \forall j \in J \tag{4.9}$$

4.3. Transportation

Transportation of an alternative fuel is an important factor in the total supply chain in the port. Using NaBH4 as a fuel adds complexity to the transportation problem as both the upstream NaBH4 and the downstream NaBO2 spent fuel stream should be modeled. H2, in both liquefied or compressed form, will only require upstream transportation as it does not produce solid rest products. Apart from a possible spent fuel back-flow, another challenge in modelling the transportation is the refueling convention in a maritime environment, which differs significantly from an automotive environment (for which many MILP models have already been designed). Fuel needs to be transported not only from the storage facility to refueling stations, but also from the storage facility directly to part of the users. This is an important aspect in the maritime refueling infrastructure, setting it apart from the automotive refueling infrastructure. In the work of Almansoori and Shah [19][20][21] an estimation of the average fuel delivery distance is used to calculate the transportation operating cost. Additionally the purchase of vehicles is not incorporated into the model. In this thesis however the fuel delivery distance is taken into account more precisely as the modelling scale is on a more local level. In modelling the transportation problem several elements are inspired by ambulance planning [90] and vehicle routing problems [78], however simplifications were made to ensure feasibility of the model.

For the transportation problem a set U, with subsets U_s, is introduced where U is the set of transportation units, distributed over two categories s: bunkering ships (s_1) and tanker trucks (s_2) which deliver the fuel. Ship types are connected to these two categories by its delivery preference: ship-to-ship (s_1), truck-to-ship (s_2) or refueling station (no delivery preference). In this transport problem a distinction is made between the first two categories (paragraph 4.3.1), where delivery of the fuel directly to the ship is the norm, and the third category (paragraph 4.3.2), where refueling stations need to be restocked by either trucks or barges (s_1 or s_2). At refueling stations users will visit the refueling stations themselves to refuel. The total purchase of all vehicles is discussed in paragraph 4.3.3.

4.3.1. STS and TTS delivery

For ship-to-ship and truck-to-ship delivery the fuel will be loaded at the combined production and storage facility by a transportation unit u_s (either a barge ($s = 1$) or a truck ($s = 2$)). The transportation unit will then navigate to the demand locations i where users are requesting refueling and refuel these vessels.

To model this the variable Z_{ius}^t is introduced;

$$Z_{ius}^t = \begin{cases} 1, & \text{if } \forall s \in \{1,2\}, \text{ vehicle } u \in U_s \text{ is assigned to } i \in I \text{ in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.10}$$

Due to not allowing split deliveries of fuel as stated earlier, Z_{ius}^t is a binary variable. Allocation of vehicles to demand points can change over time such that this variable is also dependent on t.

A vehicle of category s should only be sent to demand location i if there is demand for alternative fuel with delivery category s at that demand location. If there is no demand then point i should not be visited by that vehicle type. This is constrained in equations (4.11). In these equations $\mathcal{M}$ represents a large number.

$$\sum_{u \in U_s} Z_{ius}^t \leq \mathcal{M} \cdot d_{is}^t \qquad \forall i \in I, \quad \forall t \in T, \quad \forall s \in \{1,2\} \tag{4.11}$$

Using only these constraints for Z_{ius}^t would lead to the model always minimising these values to zero such that the transportation costs are lowest. To counteract this effect constraints (4.12) are introduced, which enforce the model to assign a vehicle to demand point i if there is a demand there.

$$\mathcal{M} \sum_{u \in U_s} Z_{ius}^t \geq d_{is}^t \qquad \forall i \in I, \quad \forall t \in T, \quad \forall s \in \{1,2\} \tag{4.12}$$

Now in this model the assumption is made that the capacity of a bunker ship or truck is for one full day. This means that a transportation unit, when used, is only able to deliver its goods until it is empty, and then finishes its work for the day: the barge/truck will not be restocked during a day to do a second delivery run. Using this assumption evades having to determine the time one delivery round takes and having to model the planning of these transportation units with respect to the time available in one day. Daily planning of vehicles requires that the transportation routes and refueling duration must be known, which complicates the model enormously. So, using the assumption that the barge / truck capacity is for a total day (no restocking of the barge or truck during the day), then one uses constraints (4.13) to ensure that the total demand at all demand points assigned to one vehicle is not bigger than the capacity b_{us} of that vehicle:

$$\sum_{i \in I} (Z_{ius}^t d_{is}^t) \leq b_{us} \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.13}$$

Next, binary decision variable Q_{us}^t is introduced:

$$Q_{us}^t = \begin{cases} 1, & \text{if } \forall s \in \{1,2\}, \text{ vehicle } u \in U_s \text{ is used in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.14}$$

Constraints (4.15) ensure that if the alternative fuel is transported to demand point i by vehicle $u \in U_s$ of supply category $s \in S$, in time period $t \in T$, then vehicle u_s is selected:

$$\sum_{i \in I} Z_{ius}^t \leq \mathcal{M} \cdot Q_{us}^t \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.15}$$

In these equations the big number $\mathcal{M}$ is again used, as $\sum_{i \in I} Z_{ius}^t$ can assume a value greater than 1, such that the right-hand constraints should fall away completely when $Q_{us}^t = 1$. The purchase of vehicles related to variable Q_{us}^t will be further discussed in paragraph 4.3.3.

4.3.2. Refueling station restocking

For category s_3 the transportation unit chosen can be either a barge or a truck, which will be used to restock the refueling station by transporting fuel from the production and storage facility to the refueling stations (see also figure 4.1). Users will then visit these refueling stations to pick up fuel (and possibly discharge spent fuel, should they sail on NaBH4). The modelling of this type of transportation within the port is similar to the STS and TTS refueling problem discussed in paragraph 4.3.1, with the difference that the transportation units navigate to refueling stations j instead of demand locations i, and the difference that transportation unit categories s are not fixed such that the model can choose both trucks and barges to restock the refueling stations. We introduce

$$R_{jus}^{t} = \begin{cases} 1, & \text{if } \forall s \in \{1,2\}, \text{ vehicle } u \in U_s \text{ is assigned to } j \in J \text{ in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.16}$$

Constraints (4.17) state that a vehicle should only be assigned to a refueling station j when that station is opened in that time period ($X_j^t = 1$). The big number $\mathcal{M}$ is used on the right hand side of the equations as the left hand side can become greater than 1 if multiple vehicles or vehicle types are assigned to the refueling station.

$$\sum_{s\in\{1,2\}} \sum_{u\in U_s} R_{jus}^{t} \leq \mathcal{M} \cdot X_j^t \qquad \forall j \in J, \quad \forall t \in T \tag{4.17}$$

Next, constraints (4.18) ensure that at least one vehicle u_s will be assigned to refueling station j if users with a fuel demand greater than zero are assigned to that refueling station in time period t. Simultaneously in constraints (4.18) it is stated that the capacity b_{us} of all vehicles delivering fuel to refueling station j should be greater than the total daily demand of all users visiting refueling station j:

$$\sum_{s\in\{1,2\}} \sum_{u\in U_s} R_{jus}^{t} b_{us} \geq \sum_{i\in I} d_{i3}^{t} Y_{ij}^{t} \qquad \forall j \in J, \quad \forall t \in T \tag{4.18}$$

To avoid the over-counting of the capacity of one vehicle multiple times in equations (4.18), the number of refueling stations visited by a transportation unit is limited in constraints (4.19). Note that this will lead to a possible overestimation of the transportation units required in the supply chain.

$$\sum_{j\in J} R_{jus}^{t} = 1 \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.19}$$

Next, we introduce

$$G_{us}^{t} = \begin{cases} 1, & \text{if } \forall s \in \{1,2\}, \text{ vehicle } u \in U_s \text{ is used in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.20}$$

Constraints (4.21) state that a transportation unit is used ($G_{us}^t = 1$) when that transportation unit is assigned to any of the refueling stations j in that time period. The purchase of vehicles related to variable G_{us}^t is further discussed in paragraph 4.3.3.

$$\sum_{j\in J} R_{jus}^{t} \leq \mathcal{M} \cdot G_{us}^{t} \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.21}$$

4.3.3. Vehicle purchase and time constraints

Both Q_{us}^t and G_{us}^t have been introduced to model the selection of a vehicle to deliver fuel to either ships directly or to refueling stations. The total number of transportation units of type u_s needed in time period t are captured in the newly introduced integer variables TU_{us}^t, defined in equations (4.22). In these equations the back-haul factor (BHF), represented mathematically by α, is a factor which depends on the fuel used in the supply chain. This factor is part of one of the model innovations of this thesis, enabling the model to design infrastructures for a wide variety of alternative fuels. For a supply chain using hydrogen as a fuel (either liquefied or compressed) there is no spent fuel to be transported back to the storage/production facility, so $\alpha = 1$. For NaBH4 however the reaction leading to the release of hydrogen in the reactor of a vessel produces spent fuel NaBO2 (as described in chapter 1.1.1). This spent fuel needs to be transported back to the production facility for it to be regenerated back into NaBH4. This leads to extra transport units needed: $\alpha > 1$. The exact value of the BHF for NaBH4 will

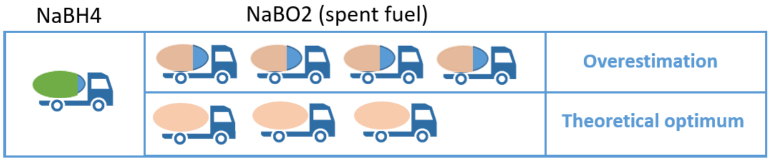


Figure 4.2: Graphical representation of possible overestimation of transportation units due to filling grade of back-haul units.

be calculated in chapter 5. Note that this use of the back-haul factor as done in equations (4.22) might lead to an overestimation of the total number of transportation units needed in some situations. This is because the filling grade of the transportation units is not taken into account for spent fuel in this model set-up. A graphical representation of this possible overestimation is shown in figure 4.2. In chapter 8 this overestimation and its effects will be further discussed.

$$TU_{us}^{t} \geq \alpha\left(Q_{us}^{t} + G_{us}^{t}\right) \qquad \forall t \in T, \quad \forall u \in U_s, \quad \forall s \in \{1,2\} \tag{4.22}$$

The purchase and sale of transportation units in time period t is captured in constraints (4.23). In these equations IT_{us}^{t} is an integer variable, which represents the number of vehicles purchased if its value is greater than zero. ST_{us}^{t} is an integer variable which represents the number of vehicles sold if its value is greater than zero. Both IT_{us}^{t} and ST_{us}^{t} have non-negativity constraints such that they are always greater than or equal to zero, given in constraints (4.24). Before $t = 1$ no transportation units are present yet in the alternative fuel supply chain, as defined in equations (4.25).

$$TU_{us}^{t} = TU_{us}^{(t-1)} + IT_{us}^{t} - ST_{us}^{t} \qquad \forall t \in T, \quad \forall u \in U_s, \quad \forall s \in \{1,2\} \tag{4.23}$$

$$TU_{us}^{t}, IT_{us}^{t}, ST_{us}^{t} \geq 0 \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.24}$$

$$TU_{us}^{0} = 0 \qquad \forall u \in U_s, \quad \forall s \in \{1,2\} \tag{4.25}$$

4.4. Production and Storage

In this conceptual model of the port infrastructure the location of the production and storage facility is fixed. The model will only have to determine the size of the production plant and the size of the storage facility. Let M denote the set of all possible production facility sizes and let N denote the set of all possible storage facility sizes. Next, two binary variables P_m^t and B_n^t are introduced:

$$P_m^t = \begin{cases} 1, & \text{if production facility of size } m \in M \text{ is used in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.26}$$

$$B_n^t = \begin{cases} 1, & \text{if storage facility of size } n \in N \text{ is used in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.27}$$

Constraints (4.28) state that only one production facility size can be chosen in one time period. Now the model needs ensure that the available capacity of the production facility ($PCAP_m$) is enough to meet the total demand of alternative fuel in the port. This is captured in constraints (4.29).

$$\sum_{m \in M} P_m^t = 1 \qquad \forall t \in T \tag{4.28}$$

$$\sum_{m \in M} \left[PCAP_m \cdot P_m^t\right] \geq \sum_{s \in S} \sum_{i \in I} d_{is}^t \qquad \forall t \in T \tag{4.29}$$

Next, we introduce

$$IP_m^t = \begin{cases} 1, & \text{if production facility of size } m \in M \text{ is commissioned in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.30}$$

$$SP_m^t = \begin{cases} 1, & \text{if production facility of size } m \in M \text{ is decommissioned in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.31}$$

The building/expansion of a production facility in time period t is captured in constraints (4.32). Before $t = 1$ no production facilities are present yet in the alternative fuel supply chain, as defined in equations (4.33).

$$P_m^{(t-1)} + IP_m^t - SP_m^t = P_m^t \qquad \forall m \in M, \quad \forall t \in T \tag{4.32}$$

$$P_m^0 = 0 \qquad \forall m \in M \tag{4.33}$$

This collection of equations (4.28 - 4.33) indirectly models capacity expansions, by decommissioning a smaller facility and replacing it by a larger facility. The capacity expansions are inspired by the model of Ogumerem [76].

Similarly, we introduce

$$IS_n^t = \begin{cases} 1, & \text{if storage facility of size } n \in N \text{ is commissioned in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.34}$$

$$SS_n^t = \begin{cases} 1, & \text{if storage facility of size } n \in N \text{ is decommissioned in time period } t \in T \\ 0, & \text{otherwise} \end{cases} \tag{4.35}$$

The model design for the capacity of the storage facility follows the same reasoning as the production facility. The selection of the storage facility is constrained in constraints (4.36 - 4.38). In these equations $SCAP_n$ represents the maximum storage capacity of a storage facility of size n. Note that in equations (4.37) the total demand is multiplied by storage factor β_{sto}, which is a factor used in order to design the facility for both supply and demand fluctuations, as well as plant interruptions and other unforeseen circumstances. Again, before $t = 1$ no storage facilities are present yet in the alternative fuel supply chain, as defined in equations (4.39).

$$\sum_{n \in N} B_n^t = 1 \qquad \forall t \in T \tag{4.36}$$

$$\sum_{n \in N} \left[SCAP_n \cdot B_n^t \right] \geq \sum_{s \in S} \sum_{i \in I} d_{is}^t \beta_{sto} \qquad \forall t \in T \tag{4.37}$$

$$B_n^{(t-1)} + IS_n^t - SS_n^t = B_n^t \qquad \forall n \in N, \quad \forall t \in T \tag{4.38}$$

$$B_n^0 = 0 \qquad \forall n \in N \tag{4.39}$$

4.5. Objective function

The total cost of the alternative fuel supply chain in a port environment consists of the following components:

- Facility Capital Cost (paragraph 4.5.1)
- Facility Operating Cost (paragraph 4.5.2)
- Transportation Capital Cost (paragraph 4.5.3)
- Transportation Operating Cost (paragraph 4.5.4)

These components are combined in the Total Cost Function as described in paragraph 4.5.5. The Facility Capital and Operating Cost functions are inspired by the work of Almansoori and Shah [20] and adapted to fit the maritime model (addition of refueling stations). The Transportation Capital and Operating Cost functions have been created separately for this specific model in the maritime environment.

4.5.1. Facility Capital Cost

The capital cost (FCC^t) for all the facilities combined (production, storage and refueling station) for each time period t is expressed in constraints (4.40). In these equations RCC_j, PCC_m and SCC_n are the capital costs related to the development of respectively a refueling station at location j, production facility of size m and storage facility of size m. PSC_m and SSC_n represent the selling cost of the production and storage facility of size m or n.

$$FCC^t = \sum_{j\in J}\left[RCC_j IX_j^t\right] + \sum_{m\in M}\left[PCC_m IP_m^t - PSC_m SP_m^t\right] + \sum_{n\in N}\left[SCC_n IS_n^t - SSC_n SS_n^t\right] \qquad \forall t \in T \tag{4.40}$$

4.5.2. Facility Operating Cost

The operating cost, FOC^t, of the facilities (production, storage and refueling station) are expressed in constraints (4.41). In these equations URC, UPC_m and USC_n are the unit production/storage costs related to the production, storage and maintenance and miscellaneous OPEX of respectively a refueling station, production facility of size m and storage facility of size n. URC is assumed to be independent of refueling station location j and thus independent of refueling station expansion or new build. The reason for this is that both station configurations have an overall comparable size. The total daily operating costs are multiplied by 365 such that FOC^t represents the yearly operating costs. The fuel demand is multiplied by 10^3 to account for URC, UPC_m and USC_n being given with respect to kilograms instead of tons.

$$FOC^t = 365 \cdot \left[\sum_{m\in M} P_m^t UPC_m + \sum_{n\in N} B_n^t USC_n \beta_{sto} + \sum_{j\in J}\sum_{i\in I} X_j^t \cdot URC \cdot Y_{ij}^t \beta_R\right] \cdot 10^3 \cdot \sum_{s\in S}\sum_{i\in I} d_{is}^t \qquad \forall t \in T \tag{4.41}$$

Note that equations (4.41) are actually non-linear as decisions variables X_j^t and Y_{ij}^t are multiplied with each other. However, the linear programming solver (which will be highlighted in paragraph 4.6) is able to solve this multiplication such that no adaptations of the model are necessary.

4.5.3. Transportation Capital Cost

The capital cost of the transportation units, TCC^t, is expressed in constraints (4.42). In these equations IV_{us} and SV_{us} are the fixed transportation capital costs connected to respectively purchasing or selling a vehicle of type u and delivery category s.

$$TCC^t = \sum_{s\in\{1,2\}}\sum_{u\in U_s}\left(IV_{us} \cdot IT_{us}^t - SV_{us} \cdot ST_{us}^t\right) \qquad \forall t \in T \tag{4.42}$$

4.5.4. Transportation Operating Cost

The transportation operating cost depends on the one hand on the delivery distance covered by the vehicle, and on the other hand on the number of transportation units needed. For the distance dependent part first the average distance travelled per vehicle must be calculated. For this the distance is approximated by assuming a travel pattern as displayed in figure 4.3.

The primary approach in this thesis work was to use the centroid of the destination points as location O, such that its location depends on the demand points to which the transportation unit has been assigned. Determining the x and y coordinates of the centroids (CX_{us}^t and CY_{us}^t) is shown in equations (4.43) and (4.44) respectively. Note that the centroids are found for both vehicles that deliver fuel to users directly as well as for vehicles that deliver fuel to refueling stations. In these equations x_i, y_i, x_j and y_j represent the x- and y-coordinates of the demand location i and refueling stations j respectively. Parameters PX and PY represent the x- and y-coordinate of the production/storage location. The total approximated distance travelled by a transportation unit doing one delivery round, defined as DTU_{us}^t, is given in equations (4.45). The distances are assumed to be Euclidean distances.

$$CX_{us}^t = \frac{\sum_{i\in I}\left(Z_{ius}^t x_i\right)}{\sum_{i\in I} Z_{ius}^t} + \frac{\sum_{j\in J}\left(R_{jus}^t x_j\right)}{\sum_{j\in J} R_{jus}^t} \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.43}$$

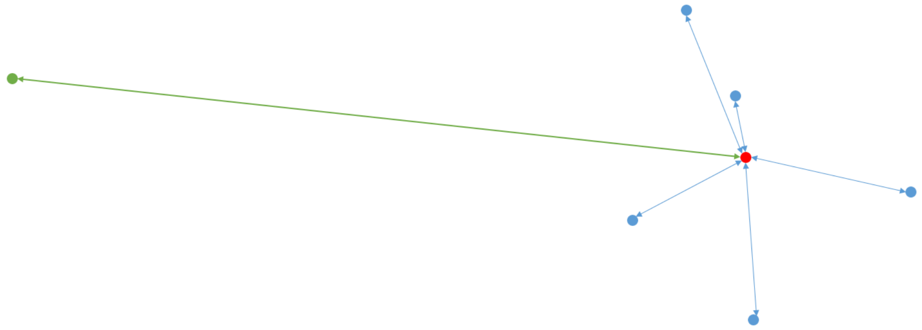


Figure 4.3: The assumed travel pattern of a transportation unit, to approximate its distance travelled. The vehicle travels from the production/storage facility (green dot) to the center point for transportation (red dot). From the centroid the vehicle shuttles to all its destinations (blue dots). Then the vehicle returns to the production/storage facility.

$$CY_{us}^{t} = \frac{\sum_{i\in I}\left(Z_{ius}^{t} y_i\right)}{\sum_{i\in I} Z_{ius}^{t}} + \frac{\sum_{j\in J}\left(R_{jus}^{t} y_j\right)}{\sum_{j\in J} R_{jus}^{t}} \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.44}$$

$$DTU_{us}^{t} = 2\sqrt{(PX - CX_{us}^{t})^2 + (PY - CY_{us}^{t})^2} + 2\sum_{i\in I} Z_{ius}^{t}\sqrt{(CX_{us}^{t} - x_i)^2 + (CY_{us}^{t} - y_i)^2} \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.45}$$

However, this primary approach to determine the distance travelled by each transportation unit cannot be solved by the linear programming solver, as there are multiple non-linearities in equations (4.43, 4.44, 4.45) (both division and squaring of decision variables). For this reason in the final approach a fixed center point is chosen in the port for all transportation units (with coordinates OX and OY). All distances from this center point to storage facility (d_{po}), demand locations i ($d_{o,i}$) and refueling stations j ($d_{o,j}$) are calculated in equations (4.46, 4.47, 4.48). The total approximated distance travelled by a transportation unit doing one delivery round, DTU_{us}^{t}, is then calculated in equations (4.49). Note that these travel distances represent an upper bound to the distance travelled by each transportation unit in reality. This will be further discussed in chapter 8.

$$d_{po} = \sqrt{(PX - OX)^2 + (PY - OY)^2} \tag{4.46}$$

$$d_{o,i} = \sqrt{(OX - x_i)^2 + (OY - y_i)^2} \qquad \forall i \in I \tag{4.47}$$

$$d_{o,j} = \sqrt{(OX - x_j)^2 + (OY - y_j)^2} \qquad \forall j \in J \tag{4.48}$$

$$DTU_{us}^{t} = 2 \cdot \left(d_{po} + \sum_{i\in I}\left(d_{o,i} Z_{ius}^{t}\right) + \sum_{j\in J}\left(d_{o,j} R_{jus}^{t}\right) \right) \qquad \forall u \in U_s, \quad \forall s \in \{1,2\}, \quad \forall t \in T \tag{4.49}$$

Now the distance dependent part of the transportation operating cost is given in equations (4.50). The distance dependent components of the TOC are linked to fuel costs (expressed in the fuel economy

FE_{us} of vehicle u_s and the fuel price FP_s), and the maintenance component (given by maintenance expenses ME_{us} per kilometer). These daily costs are multiplied by 365 to account for the number of days in a year, such that TOC_1^t represents a yearly transportation operating cost dependent on distance. Additionally the distance covered by a vehicle is multiplied by a tortuosity factor TF_s. This is a factor which accounts for the maneuvering of a transportation unit (of delivery category s), as in reality it will not be able to travel in a straight line to its destination.

$$TOC_1^t = 365 \sum_{u \in U_s} \sum_{s \in \{1,2\}} \left(TF_s \cdot \left(DTU_{us}^t \cdot 10^{-3} \right) \left(\frac{FP_s}{FE_{us}} + ME_{us} \right) \right) \qquad \forall t \in T \tag{4.50}$$

The transportation unit dependent part of the transportation operating cost, TOC_2^t, is given in equations (4.51). It is based on the costs for personnel, consisting of the driver wage (DW_s) and the driver operational hours (DO).

$$TOC_2^t = 365 \sum_{u \in U_s} \sum_{s \in \{1,2\}} \left(TU_{us}^t \cdot DW_s \cdot DO \right) \qquad \forall t \in T \tag{4.51}$$

The distance dependent part and the transportation unit dependent part together lead to the total yearly transportation operating cost, TOC^t, for each time period t, given in equations (4.52):

$$TOC^t = TOC_1^t + TOC_2^t \qquad \forall t \in T \tag{4.52}$$

4.5.5. Total Cost Function

The total cost function combines all previously discussed cost components, and applies a discount rate (dr) to account for expenses in different time periods. Using such a discount rate calculates the present value of future expenses. The application of a discount rate for capital costs is different from its application to operating costs, as capital costs are assumed to be financed at the beginning of the time period of the investment, whereas operating costs are added on an annual basis at the end of each of the years of which the time period consists. Operating costs are thus treated as an annuity. This annuity represents a time-period of 10 years in which the operating costs are incorporated on a yearly basis. Separate discount factors for capital costs (dfc^t) and operating costs (dfo^t) are calculated in equations (4.53) and (4.54) respectively. The distinction between dfc^t and dfo^t is inspired by Moreno-Benito's [67] approach to multi-period models. However equations (4.54) are improved in this model by using the formula for annuities as discussed by Berk and DeMarzo [26].

$$dfc^t = \frac{1}{(1+dr)^{10(t-1)}} \qquad \forall t \in T \tag{4.53}$$

$$dfo^t = \frac{1}{dr} \left(1 - \frac{1}{(1+dr)^{10}} \right) dfc^t \qquad \forall t \in T \tag{4.54}$$

Now the total cost (TC), which represents all expenditures combined and transformed to present value, is given in equation (4.55).

$$TC = 10^{-6} \cdot \sum_{t \in T} \left[dfc^t \left(10^6 \cdot FCC^t + TCC^t \right) + dfo^t \left(FOC^t + TOC^t \right) \right] \tag{4.55}$$

The objective of the model is to minimise the total cost of the infrastructure, as defined in equation (4.56).

$$\min TC \tag{4.56}$$

4.6. Software

The software used to program the mathematical model as discussed in this chapter is Python (version 2.7.18). Additionally the optimisation solver used is Gurobi (version 8.0.1). Python is chosen as a programming language as it is a fast and functional open source language. Because of these reasons Python is also the most widely used programming language. Gurobi is used as it is one of the most powerful and fast optimisation solvers available for this project. Gurobi uses a branch-and-bound algorithm to solve the model.

The optimality gap of a Mixed Integer Programming model is the difference between the best lower and upper bounds. The algorithm will end its search for the optimal value when the solution objective is within a specified gap from the optimal value. As a default Gurobi uses an optimality gap of $1e-4$. In this model an optimality gap op $2.5e-4$ is used to decrease the required modelling time. This value was found to be acceptable for the current model as the used input values already are prone to uncertainty. An overall optimal solution is thus not an option if the strong uncertainty in input values remain.

4.7. Overview of notation

	Sets
I	set of demand locations
J	set of current and potential refueling station locations
M	set of production facility sizes
N	set of storage facility sizes
S	set of fuel delivery categories to ship (ship-to-ship; truck-to-ship; bunkering station)
T	set of timeframes considered
U	set of transportation units, with subsets U_s for delivery category $s \in S$, where $s = \{1, 2\}$

	Binary Variables
B_n^t	1 if storage facility of size n is used in time period t 0 otherwise
G_{us}^t	1 if vehicle u_s is used in time period t for transport towards refueling stations 0 otherwise
IP_m^t	1 if production facility of size m is commissioned in time period t 0 otherwise
IS_n^t	1 if storage facility of size n is commissioned in time period t 0 otherwise
IX_j^t	1 if refueling station at location j is constructed/expanded in time period t 0 otherwise
P_m^t	1 if production plant of size m is used in time period t 0 otherwise
Q_{us}^t	1 if vehicle u_s is used in time period t for transport towards users 0 otherwise
R_{jus}^t	1 if refueling station j is visited by vehicle u_s in time period t 0 otherwise
SP_m^t	1 if production facility of size m is decommissioned in time period t 0 otherwise
SS_n^t	1 if storage facility of size n is decommissioned in time period t 0 otherwise
X_j^t	1 when refueling station location $j \in J$ is selected 0 otherwise
Y_{ij}^t	1 if demand location i is served by base location j 0 otherwise
Z_{ius}^t	1 if demand location i is visited by vehicle u_s in time period t 0 otherwise

	Integer Variables
IT_{us}^t	number of vehicles of type u_s purchased in time period t
ST_{us}^t	number of vehicles of type u_s sold in time period t
TU_{us}^t	number of transportation units of type u_s in time period t

	Continuous variables	
d_{po}	distance between production / storage facilities and center point for transportation	m
$d_{o,i}$	distance between center point for transportation and demand location i	m
$d_{o,j}$	distance between center point for transportation and refueling station j	m
d_{is}^t	fuel demand for each demand location i with delivery category s in time period t	ton/day
dfc^t	discount factor for capital costs in time period t	-
dfo^t	discount factor for yearly operating costs in time period t	-
DTU_{us}^t	approximated distance travelled by u_s in time period t	m
FCC^t	total facility capital cost in time period t	M€
FOC^t	total yearly facility operating cost in time period t	€/year
TC	total cost of the alternative fuel infrastructure in the port	M€
TCC^t	total transportation capital cost in time period t	€

TOC^t	total transportation operating cost	€/year
TOC_1^t	transportation operating cost (distance dependent part)	€/year
TOC_2^t	transportation operating cost (transportation unit dependent part)	€/year

	Parameters	
α	back-haul factor (BHF)	-
β_R	storage factor regarding refueling stations	-
β_{sto}	storage factor regarding storage facility	-
b_{us}	capacity of transportation unit u_s	ton
d_{is}	total energy demand for each demand location i with delivery category s	MWh/day
DO	driver operational hours	hrs/day
dr	discount rate	-
DW_s	driver wage	€/hr
FE_{us}	fuel economy of vehicle type u_s	km/L
FP_s	fuel price per delivery category	€/L
IV_{us}	fixed transportation capital costs connected to purchasing a vehicle of type u_s	€
$\mathcal{M}$	a large number	-
ME_{us}	maintenance expenses for transportation unit u_s	€/km
OX	x-coordinate of the center point for transportation	m
OY	y-coordinate of the center point for transportation	m
$PCAP_m$	maximum production capacity of production facility of size m	ton/day
PCC_m	capital cost related to the development of a production facility of size m	M€
PF_s^t	penetration factor of alternative fuel users during time period t	-
PSC_m	capital cost related to the sale of a production facility of size m	M€
PX	x-coordinate of production/storage location	m
PY	y-coordinate of production/storage location	m
$RCAP_j$	capacity limit of refueling station location j	ton
RCC_j	capital cost related to the development of a refueling station (expansion) at location j	M€
$SCAP_n$	maximum storage capacity of storage facility of size n	ton
SCC_n	capital cost related to the development of a storage facility of size n	M€
SSC_n	capital cost related to the sale of a storage facility of size n	M€
SV_{us}	fixed transportation capital costs connected to selling a vehicle of type u_s	€
TF_s	tortuosity factor	-
UPC_m	unit production cost of a production facility of size m	€/kg
URC	unit storage cost of a refueling station	€/kg/day
USC_n	unit storage cost of a storage facility of size n	€/kg/day
$\mathcal{W}$	weight-to-energy ratio (WER)	ton/MWh
x_i	x-coordinate of demand location i	m
x_j	x-coordinate of refueling station j	m
y_i	y-coordinate of demand location i	m
y_j	y-coordinate of refueling station j	m

5

Input of the model

In this chapter the base input will be discussed. This base input is the initial input used in the model and the base from which parameters can be varied to research its effect on the infrastructure. Input parameters related to LH2 and GH2 are gathered from relevant works including Almansoori and Shah [20] (on which most other literature has based their input, such as [70]). Values in dollars are converted using the ratio 1 dollar = 0,84 euro. The price of renewable energy is assumed to be fixed at 50 €/MWh. The strength of the model created in this thesis is its versatility, meaning that by using different input the model can be used for many different ports, fuels and scenarios. The input used here is thus one of these scenarios, specifically for Port of Amsterdam and the use of LH2, GH2 and NaBH4. An overview of all tables in this chapter discussing the input of the mathematical model can also be found in Appendix A.

5.1. Demand

5.1.1. Weight-Energy-Ratio (WER)

In the mathematical model the Weight-Energy-Ratio (WER) was introduced (chapter 4.1). This is a ratio used to translate the ships energy demand to the corresponding weight demand of a specific fuel. These ratio's of fuels vary due to different Lower Heating Values (LHVs) and different overall efficiencies with respect to on board energy conversion. The efficiencies incorporated in the calculations for LH2, GH2, NaBH4 and MDO/MGO are displayed in figure 5.1. The drive train is evaluated from tank to shaft. Propeller efficiency is not relevant for the WER as these are characteristics of the ship hull and are assumed to not change when using a different fuel type. Of course the use of a different fuel type might lead to a different overall sailing profile and thus other hull and propeller efficiencies. This will be further discussed in paragraph 8.3 of the discussion.

For **liquid and gaseous hydrogen** the drive train efficiencies are related to: the fuel cell which converts chemical energy into electrical energy, and the electrical motor converting electrical energy into mechanical energy. Using an electrical motor eliminates the need for a gearbox at the shaft. For the fuel cell an efficiency of 50% is assumed, using a PEM Fuel Cell which is particularly suitable for use on board of vehicles [55]. The efficiency of the electrical motor is assumed to be 95% [52].

For **NaBH4** the same efficiencies are used for the PEM fuel cell and the electrical motor. The difference with LH2 and GH2 fuels is the need for a reactor to release the hydrogen from the NaBH4. The efficiency of the reactor is assumed to be 98% [56]. Furthermore the LHV of the hydrogen released by NaBH4 is calculated using the weight percentage of the 4 hydrogen-atoms in NaBH4 and the 4 atoms released from H20 during the same reaction.

A WER is also calculated for **MDO/MGO**, such that the current fuel weight demand in Port of Amsterdam can be transformed into a current mechanical energy demand. The WER for an alternative fuel can then be used to estimate the alternative fuel weight demand in the port. The current prevailing drive train on board of ships is to have the energy source (MDO/MGO) converted into mechanical energy by

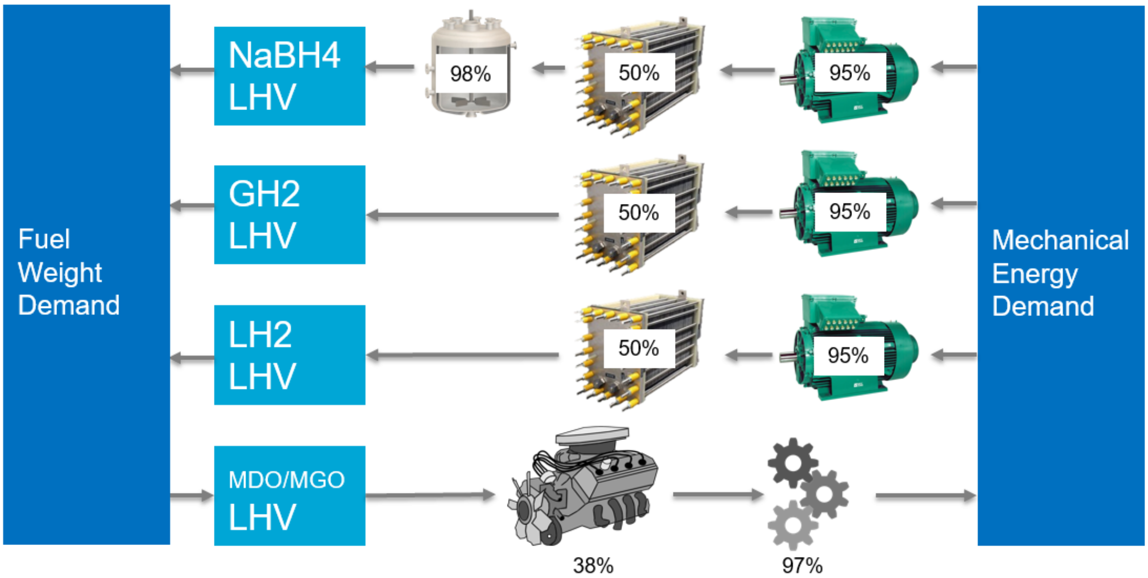


Figure 5.1: Drive train efficiencies taken into account for LH2, GH2, NaBH4 and MDO/MGO

	LH2	GH2	NaBH4*	MDO/MGO**
LHV [kWh/kg] [3]	33,3	33,3	7,10	11,85
Reactor η [-]	-	-	0,98	-
Fuel cell η [-]	0,5	0,5	0,5	-
Electrical motor η [-]	0,95	0,95	0,95	-
Diesel engine η [-]	-	-	-	0,38
Gearbox η [-]	-	-	-	0,97
WER [kg/kWh]	0,063	0,063	0,303	0,229

Table 5.1: Weight-Energy-Ratio's and drive train efficiencies of several fuels. * The LHV of the hydrogen released by NaBH4 is calculated using the weight percentage of the 4 hydrogen-atoms in NaBH4 and the 4 atoms released from H20 during the same reaction. ** The LHV of the combination of MDO/MGO is calculated using the proportion of MDO and MGO in the fuel mix as reported by Port of Rotterdam [14].

an engine. In this calculation the efficiency of a diesel engine is assumed to be 38% and, additionally, the use of a gearbox will lead to 97% efficiency at the propeller [52]. The WER-calculation is shown in equation 5.1. The values used for calculation of the WER of LH2, GH2 and NaBH4 and the results can be found in table 5.1.

$$WER = \frac{1}{\eta_{total} \cdot LHV} \tag{5.1}$$

5.1.2. Energy Demand in Port of Amsterdam

To determine the input regarding the fuel demand at several locations in the Port of Amsterdam, the total yearly demand for MDO and MGO is converted to a daily energy demand at the basins using the WER and the estimated number of berths per basin. This daily energy demand (d_{is}) is then an input for the mathematical model, which then uses the WERs of alternative fuels to convert this daily energy demand into a daily fuel weight demand per basin.

The total demand for MDO and MGO in the port of Amsterdam is calculated using the bunker sales data of port of Rotterdam of 2019 and the bunker data of Rotterdam and Amsterdam combined. The total bunker sale in Rotterdam in 2019 is 8,949,794 m^3 [14], and the total bunker sale of Rotterdam and Amsterdam combined is 1,4917,187 m^3 [2]. This leads to an estimated total of 5,967,393 m^3 bunker sales in Port of Amsterdam. This value is used in table 5.2 to calculate the daily energy demand for MDO and MGO in Port of Amsterdam, resulting in 11.54 GWh.

Total bunker amount (m^3)	5,967,393
Percentage MDO + MGO	0.19
MDO + MGO bunker amount (m^3)	1,133,805
MDO + MGO combined density (ton/m^3)	0.851
MDO + MGO bunker amount (kton)	964
MDO + MGO WER (ton/MWh)	0.229
Yearly energy demand MDO + MGO (GWh)	4212
Daily energy demand MDO + MGO (GWh)	11.54

Table 5.2: Energy demand calculations for Port of Amsterdam.

i	**Harbor Basins**	**Berth Estimation (#)**	d_{is} **[MWh/day]**			x_i	y_i
			s = 1	**s = 2**	**s = 3**		
1	Afrikahaven	26	742	0	318	111543	492641
2	Amerikahaven	17	485	0	208	113182	492482
3	Australiehaven	22	628	0	269	113887	491577
4	Aziehaven	14	400	0	171	113456	490736
5	ADM/Westhaven, Capriweg	17	485	16	192	115771	492482
6	Sont- en Bosporushaven	19	542	0	232	116421	490842
7	Suezhaven	22	628	0	269	116464	490063
8	Usselincxhaven	18	514	0	220	117618	491841
9	Jan van Riebeeckhaven	11	314	0	135	118062	491556
10	Petroleumhaven	9	257	0	110	118818	491612
11	Coenhaven	11	314	0	135	119529	491313
12	Nieuwe Houthaven	20	571	0	245	120355	490801
13	Minervahaven	9	257	0	110	120004	490590
14	Mercuriushaven	37	1056	0	453	119349	490217
15	Houthaven	8	228	0	98	120832	489855
16	Het IJ Midden	7	200	0	86	122054	488208
17	Het IJ Oost	10	285	0	122	123739	488222
18	Noordzeekanaal	6	171	0	73	111589	493751

Table 5.3: Demand characteristics of Port of Amsterdam. For a graphical representation of the harbor basins see Appendix B

The daily energy demand is divided over different basins in the port by estimating the number of berths in that basin (using the map of PoA [10]) and using this ratio for the local daily energy demand. The division of basins in the Port of Amsterdam as used in this thesis is shown in Appendix B. The locations of these basins are defined by using ”Rijksdriehoek”-coordinates (RD-coordinates), a coordinate system which defines all locations in the Netherlands using x- and y-coordinates. A central point is chosen in every basin which is used as a definition of that basins’ location (x_i and y_i in the mathematical model). The local daily energy demand is then divided into different delivery category preferences (s in the mathematical model, see also figure 4.1): Ship-to-ship-, Truck-to-ship- or Refueling Station Bunkering. According to Port of Amsterdam the division between STS-bunkering and refueling station bunkering in Amsterdam is 70% and 30% respectively and only one truck per week delivers fuel for TTS-demand (delivering fuel for the port authority vessels at location Capriweg). The resulting d_{is} as input for the mathematical model (the total energy demand for each demand location i with delivery category s) is given in table 5.3.

5.1.3. Penetration Factor (PF)

The Penetration Factor (PF_s^t in the mathematical model) is a factor used in the model to describe the amount in which the alternative fuel has occupied the maritime market. This factor is used to describe how alternative fuel demand is expected to evolve over time. To be able to compare the different fuel type infrastructures with one another the same penetration factor must be used for all fuel types (LH2/GH2/NaBH4). The PF chosen depends on the future outlook on adoption of a new fuel, and is

t	PF_1^t	PF_2^t	PF_3^t
1	0	0,5	0
2	0	1	0,025
3	0,025	1	0,05
4	0,05	1	0,1
5	0,1	1	0,25

Table 5.4: Penetration factors PF_s^t over time chosen for different user types

dependent on many external factors, such as policy, fossil fuel prices, etc. A description of factors influencing the adoption rate of the alternative fuel by maritime users was given in chapter 1.1.2. For the base input the PF-values assumed for all alternative fuels are shown in table 5.4. Note the different adoption rates for different fuel delivery categories s. In this case it is assumed that the visitors of refueling stations ($s = 3$) are generally smaller inland vessels with 4-stroke engines, which are expected to more easily retrofitted. Additionally these inland vessels differ from short-sea ships ($s = 1$) with respect to their sailing profile and travelling range, such that in table 5.4 the PF for category $s = 1$ lags behind the PF for category $s = 3$. As the mathematical model is set-up on a conceptual level the user can experiment with different adoption curves for alternative fuels to evaluate the effect on the corresponding infrastructure.

The adoption rate of an alternative fuel depends on its characteristics and its correspondence to the following criteria for ships: (1) A beneficial volumetric density. (2) Safe storage and handling of the fuel on board and on the quay. (3) Transportability of the fuel (Can it be made available also at more remote ports? And is the fuel pumpable/transportable on board of the ship?). (4) Minimal to zero CO2-emissions.

Lastly the evolution of alternative fuel usage over time is also in its turn dependent on the development of maritime users themselves and their environment: (1) Technological advancements lead to lower costs of components needed for new fuels. (2) Alternative fuels will gain more popularity once the engineering behind it has been proven by demonstrators and early adopters. (3) More stringent emission targets in the future will stimulate ship owners even more to consider alternative fuels.

In this determination of the PF the following needs to be noted:

- As stated by Agnolucci and McDowall [15] the uptake of hydrogen fuels is expected to follow an **S-shaped curve**. Most new technologies follow this curve and actually many energy technologies, including new fuels for vehicles, follow this characteristic growth process. An overview of the S-curves used by other optimisation models for the automotive industry and the PF used in this thesis for different scenarios is given in figure 5.3. Note that a rather conservative adoption rate is assumed in the base input case.

- The **total ultimate market share** of the alternative fuels described in this thesis is not expected to be 100%: In the current energy market fuels coexist in the total fuel mix for maritime transport (examples are HFO, MDO, MGO and LNG coexisting). In the future it is expected that also alternative renewable fuels will coexist: Apart from LH2, GH2 or NaBH4 as energy carriers, alternative fuels might be LNG, biodiesel, ammonia, methanol, or other fuels. DNV-GL expects future ships to first use LNG as a transitioning fuel until alternative, fully renewable fuels are available on a large scale [37] (see figure 5.2), which is another reason for the conservative adoption rate used for alternative fuels in this thesis.

- The fastest adoption of the alternative fuel is expected by users which require their **fuel delivered by truck** (TTS, $s = 2$). This is because in the Port of Amsterdam these users are port authority vessels, which are highly dependent on the chosen policy of PoA. As PoA is already working on a demonstrator sailing on NaBH4 it is expected that they are likely to quickly implement a new fuel type onto all their vessels.

- Next follows the adoption of alternative fuels by **inland vessels** visiting refueling stations ($s = 3$). Smaller inland vessels are expected to adopt the alternative fuels as discussed in this thesis

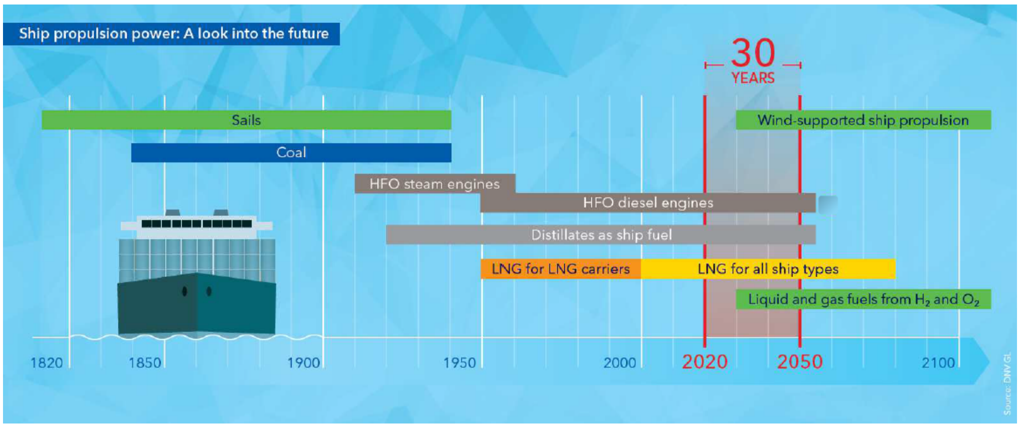


Figure 5.2: A look into future ship propulsion power according to DNV-GL [37]

β_R (-)	9	
β_{sto} (-)	90	
DO (hrs/day)	12	
dr (-)	0,035	
PX (m)	99972	
PY (m)	498454	
OX (m)	115975	
OY (m)	492697	
	barge ($s = 1$)	truck ($s = 2$)
TF_s (-)	1,4	1,4
FP_s (€/L)	0,445	0,97
DW_s (€/hr)	80	20

Table 5.5: Port specific input data

quicker than larger short-sea vessels, as these inland vessels usually have 4-stroke engines which are more easily retrofitted. Additionally their sailing profile and travelling range lend themselves more to adoption of alternative fuels. From this it follows that short-sea ships and larger inland ships ($s = 1$) are expected to have slowest adoption rate of new fuels.

5.2. Port Specifics

The port specific input is input related to the port lay-out and port characteristics/services. An overview of all input used regarding port specifics is given in table 5.5.

The storage factors for both refueling stations (β_R) and storage facility (β_{sto}) need to be determined. These factors are used to take into account both supply and demand fluctuations, plant interruptions and other unforeseen circumstances. Port of Rotterdam maintains a storage factor of 314 for its storage facilities. This value is derived from its total bunker storage capacity [12]. Using the average capacities of refueling stations [1] in Port of Amsterdam a storage factor of 9 is found for refueling stations. This storage factor for refueling stations β_R will also be used in this model. However the β_{sto} storage factor will be chosen a lot lower than the storage of such large volumes of liquid or gaseous hydrogen fuel would create a high safety risk in the port area which should be avoided. Additionally storage facilities of such proportions are not technically feasible yet. For NaBH4 these restrictions are not applicable, however for the base input the same storage factor will be used for all alternative fuels to correctly compare the infrastructures. The chosen β_{sto} is 90, meaning that a fuel buffer of about three months is available in the port. In chapter 7.1.2 the repercussions of using a larger β_{sto} of 314 on the LH2, GH2 and NaBH4 infrastructures will be discussed. Note that the fuel supply will depend on an intermittent renewable energy source (wind energy), such that a significant reserve is needed to deal with these fluctuations. Solutions to this problem could be diversification of wind energy sites or the diversification

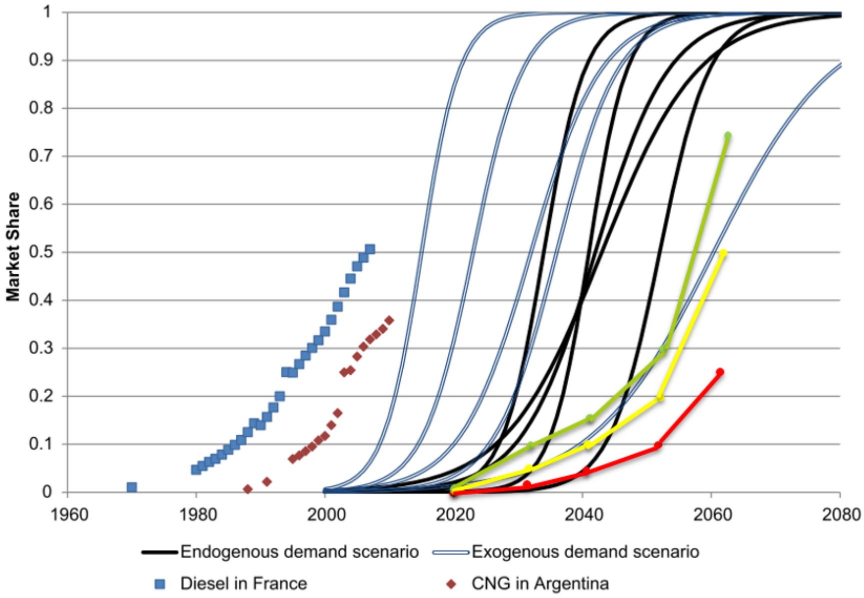


Figure 5.3: The penetration factors used in automotive hydrogen supply chain network design models [15] and the factors used in this thesis for fuel delivery category $s = 3$. The red line represents the base input used in the model. The yellow line and the green line represent an increase of 200% and 300% alternative fuel adoption respectively. These alternative inputs are discussed in chapter 7.1.2

of renewables used.

The driver operational hours (DO) are assumed at 12 hours a day in this model. Furthermore the discount rate (dr) used in this model is 3.5%. This is the value which is recommended for use when measuring the economic efficiency of long-term investment projects of public agencies [67]. The location coordinates for the production facility (PX and PY) are taken at the Averijhaven in Amsterdam, as this will become a hub for offshore wind energy, such that a production facility running on renewable electrical energy could be built there [9]. The central distribution point coordinates (OX and OY) in the port area, the point from which all transportation units will distribute their fuel, are defined at the Hemspoortunnel in Amsterdam, as this location is a central point with respect to all basins considered in the model.

The tortuosity factor (TF_s) is a factor which accounts for the maneuvering of a transportation unit and the added distance covered by this unit as a result. This value is set at a typical value of 1.4 for both barges ($s = 1$) and trucks ($s = 2$), based on Akgul [16] and Sultana [87]. The fuel price (FP_s) for barges is based on expected MGO prices [72] and the fuel price for trucks is taken from the model of Almansoori and Shah [20]. Lastly, the driver wage (DW_s) is determined using the truck driver wage from Almansoori and Shah [20] and Sabio [82]. For barges this value is multiplied by 4 to account for four estimated crew members on board of such a vessel. As stated before, an overview of all values mentioned in this section is given in table 5.5.

5.3. Refueling Stations

A feature of the model created in this thesis is to model the expansion or new build of refueling stations (described in chapter 4.2) to facilitate the transition towards alternative fuels. In the Port of Amsterdam there are currently six bunkering stations. For these refueling stations an expansion of 20% is assumed in their estimated fuel capacity. This can signify either an expansion of the refueling station or a renovation of the refueling station by exchanging part of its fossil fuel storage capacity for alternative fuel storage. Additionally, two extra locations for possible development of new refueling stations are identified. These refueling stations are assumed to have 100% of their capacity available for the alternative fuel researched in the model. The average bunker station capacity in the Port of Amster-

				LH2		GH2		NaBH4	
j	**Refueling Stations**	x_j	y_j	$RCAP_j$	RCC_j* **(M€)**	$RCAP_j$	RCC_j **(M€)**	$RCAP_j$	RCC_j **(M€)**
1	Trawlerkade	100824	497121	20	6,0	6,4	2,2	300	16,5
2	Amerikahaven Titan LNG	113228	492979	20	6,0	6,4	2,2	300	16,5
3	Zaanstad Zijkanaal G	117462	493226	20	6,0	6,4	2,2	300	16,5
4	Het IJ Reinplus	124905	488567	20	6,0	6,4	2,2	300	16,5
5	Slurink	125656	487431	20	6,0	6,4	2,2	300	16,5
6	Fiwado	125715	487122	20	6,0	6,4	2,2	300	16,5
7	C. Douwes-Kanaal West	120146	491429	100	19,3	32	6,3	1500	83,3
8	Nieuwe Zeehaven	116069	493104	100	19,3	32	6,3	1500	83,3

Table 5.6: Refueling station input parameters.

dam is assumed to be 1400 m^3 [1]. Translating this to refueling station capacities for different fuels in tons (taking into account the alternative fuel densities) leads to the values as shown in table 5.6. The capital costs related to these expansions or new builds are determined by extrapolating the storage facility capital costs of the alternative fuels to match the storage capacities of the bunkering stations. The storage facility capital costs will be discussed for each alternative fuel modelled in sections 5.4, 5.5 and 5.6. Additionally, the locations of all bunkering stations given in RD-coordinates (x_j, y_j), the bunkering station capacities ($RCAP_j$) and corresponding capital costs (RCC_j) can be found in table 5.6. Locations of new build refueling stations are chosen such that they are in the vicinity of common inland shipping sailing routes (close to river estuaries), to support adoption of alternative fuels.

5.4. Liquid Hydrogen Specific Input

The parameters used in the model for evaluating the liquid hydrogen infrastructure are summarised in table 5.7. The production parameters for small and medium sized production facilities are taken from Almansoori and Shah [20], as their research is considered as the most relevant work in the hydrogen supply chain field and many other scientific models have based their input on their research. In this respect the choice is made for hydrogen production by electrolysis. Other common hydrogen production technologies are steam methane reforming, coal gasification and biomass gasification. Electrolysis however is the only method where hydrogen can be produced as a completely renewable fuel. Only small ($m = 1$) and medium ($m = 2$) sized electrolysis based production facilities are treated by Almansoori and Shah [20]. To model larger facilities in the infrastructure (as they might be needed to be able to meet the daily LH2 demand in the port), the medium sized production facility is doubled/tripled with respect to capacities ($PCAP_m$) and capital costs (PCC_m and PSC_m). Virtually this means that when the model chooses a large production facility, two medium sized facilities will be built as larger facilities are not yet a reality. For this reason the unit production cost (UPC_m) of larger facilities is equal to the unit production cost of a medium sized facility. The selling cost of production facilities is assumed to be 40% of their original purchase cost. The unit production cost (UPC_m) for LH2 is based on the recent calculations by Cardona et al. [28]. In this respect the assumption is made that the electricity price will be driving force at higher production capacities. It is thus assumed that the same unit production cost value can be used for all larger facility sizes. Only the smallest size production facility ($m = 1$) has a higher unit production cost due to assumed economy of scale. The ratio used for this is taken from Almansoori and Shah [20].

In the input parameters for liquefied hydrogen production facilities the following process steps are taken into account [28]:

1. *Water purification*: The water needed for electrolysis is first pre-treated and then goes through a reverse osmosis process.

2. *Hydrogen production*: Hydrogen is produced from water by electrolysis, using a Polymer Electrolyte Membrane (PEM) electrolyser.

3. *Hydrogen liquefaction*: Liquefaction consists of mainly three steps. (1) Compression: Hydrogen is compressed in a three stage compressor. (2) Cooling: Temperature reduction by precooling and cryo-cooling. (3) Expansion: Hydrogen is liquefied by a reduction in pressure.

Production						
plant size, m	1	2	3	4	5	
$PCAP_m$	9,5	150	300	450	600	*ton/day*
PCC_m	51,3	557,4	1114,8	1672,2	2229,6	*M€*
PSC_m	20,5	223	445,92	668,88	891,84	*M€*
UPC_m	4,27	3,15	3,15	3,15	3,15	*€/kg*

Storage										
storage size, n	1	2	3	4	5	6	7	8	9	
$SCAP_n$	9,5	150	540	1080	2160	4320	8640	12960	17280	*ton*
SCC_n	4,2	28	103	206	412	824	1648	2472	3296	*M€*
SSC_n	1,7	11,1	41,2	82,4	165	330	659	989	1318	*M€*
USC_n	0,027	0,0084	0,0042	0,0042	0,0042	0,0042	0,0042	0,0042	0,0042	*€/kg/day*

Refueling Stations		
URC^*	0,0084	*€/kg/day*

Transport			
transport type, u_s	barge	LH2 tanker truck	
b_{us}	106	4	*ton*
IV_{us}	10.000.000	420.000	*€*
SV_{us}	4.000.000	168000	*€*
ME_{us}	0,082	0,082	*€/km*
FE_{us}	0,46	2,3	*km/L*
BHF	1		-

Table 5.7: Liquid hydrogen input parameters.

The capacities ($SCAP_n$), as well as the capital and operational costs of a liquid hydrogen storage facility are also taken from Almansoori and Shah [20]. Again the storage selling capital cost (SSC_n) is taken as 40% of the purchase cost (SCC_n). The biggest storage capacity from literature is 540 ton. Even bigger storage facilities are modelled by linearly expanding the large storage facility, just as has been done with the production facilities. Again the unit storage cost (USC_n) is kept constant. For liquid hydrogen refueling stations the unit storage cost (URC) is based on the unit storage cost of a medium storage facility ($n = 2$), as the refueling station storage capacities are in the range of medium sized storage facilities.

For the input regarding liquid hydrogen transport by truck again the work of Almansoori and Shah is used. For tanker trucks the values chosen for b_{us}, IV_{us}, ME_{us} and FE_{us} are all equal to the input used by Almansoori and Shah [20]. The capital cost for selling a vehicle is again taken as 40% of the original purchase cost. For barges the maintenance expenses (ME_{us}) are assumed to be equal to the maintenance expenses of a truck. The vehicle capacity (b_{us}) and the purchase cost of a barge (IV_{us}) are based on an existing LNG tanker in the Port of Amsterdam region. The capacity of the barge is found by taking the volume capacity of the LNG tanker [24] and translating this volume into a corresponding liquid hydrogen weight. The purchase cost is assumed equal to the cost of the LNG barge (10 million euros, [45]). Over time however up-following units are expected to be constructed more cheaply due to reduced engineering costs and the repeat order of components [45]. The fuel economy of the barge (FE_{us}) is found from the distance travelled per volume of fuel per ton of cargo displaced, which is given by a report for the National Waterways Foundation [47]. Lastly, the back-haul factor (BHF) for liquid hydrogen is equal to one, as there will be no spent fuel flow in a LH2-infrastructure.

5.5. Gaseous Hydrogen Specific Input

The parameters used in the model for evaluating the gaseous hydrogen infrastructure are summarised in table 5.8. The same discrete capacity sizes as LH2 are used for production and storage facilities for GH2. For the production costs (PCC_m, PSC_m, UPC_m) the ratios between the prices of LH2 and GH2 production facilities are used as derived from Cardona et al. [28]. The same ratios are used for the storage costs (SCC_n, SSC_n, USC_n). The unit storage cost (URC) is based on the unit storage cost of a medium storage facility (USC_2).

In the input parameters for compressed hydrogen production facilities the following process steps are taken into account [28]:

				Production						
plant size, m	1	2	3	4	5					
$PCAP_m$	9,5	150	300	450	600	*ton/day*				
PCC_m	39,9	433,2	866,5	1299,7	1339,6	*M€*				
PSC_m	15,9	173,3	346,6	519,9	535,8	*M€*				
UPC_m	3,68	2,72	2,72	2,72	2,72	*€/kg*				
				Storage						
storage size, n	1	2	3	4	5	6	7	8	9	
$SCAP_n$	9,5	150	540	1080	2160	4320	8640	12960	17280	*ton*
SCC_n	3,3	21,5	80,1	160,1	320,2	640,5	1280,9	1921,4	2561,9	*M€*
SSC_n	1,3	8,6	32,0	64,0	128,1	256,2	512,4	768,6	1024,7	*M€*
USC_n	0,0236	0,0073	0,0037	0,0037	0,0037	0,0037	0,0037	0,0037	0,0037	*€/kg/day*
				Refueling Stations						
URC^*		0,0073			*€/kg/day*					
				Transport						
transp. type, u_s	barge				LH2 tanker truck					
b_{us}	35				0,181	*ton*				
IV_{us}	7.770.000				326.000	*€*				
SV_{us}	3.108.000				130000	*€*				
ME_{us}	0,082				0,082	*€/km*				
FE_{us}	0,46				2,3	*km/L*				
BHF			1			-				

Table 5.8: Gaseous hydrogen input parameters.

1. *Water purification*: The water needed for electrolysis is first pre-treated and then goes through a reverse osmosis process.

2. *Hydrogen production*: Hydrogen is produced from water by electrolysis, using a Polymer Electrolyte Membrane (PEM) electrolyser.

3. *Compression*: Hydrogen is compressed from the pressure outlet of the water electrolysis using a three stage compressor.

For transportation of gaseous hydrogen (350 bar) the capacity (b_{us}) of a GH2-barge is again based on the volume capacity of the LNG tanker [24], whereby the volume capacity is translated to the corresponding weight capacity of GH2. The capacity of a tube trailer (a truck transporting gaseous hydrogen) is based on the input used by Sabio [82]. The capital costs (IV_{us} and SV_{us}) for both barge and truck are again determined by using the price ratios between LH2 and GH2, as this ratio is assumed similar for transport components. The maintenance expenses (ME_{us}) and fuel economy (FE_{us}) of GH2-specific barges and trucks are assumed the same as the values used for LH2 transportation units. The back-haul factor (BHF) for gaseous hydrogen is equal to one, as there will be no spent fuel flow in a GH2-infrastructure.

5.6. NaBH4 Specific Input

The parameters used in the model for evaluating the NaBH4 infrastructure are summarised in table 5.10. The same discrete capacity sizes as LH2 are used for production and storage facilities for NaBH4. Again the ratios based on Cardona et al. [28] are used for the production costs (PCC_m, PSC_m, UPC_m). The storage cost of NaBH4 is based on the work of Mele et al. [66], from which a storage cost (SCC_n) of 1.22 million euros is found for a small facility storing biomass. From this value the same economy of scale ratio is used as for LH2 and GH2 storage facilities to find values for the larger storage facilities. Furthermore, the unit storage cost (USC_n) of solid material is extremely low in comparison to LH2 and GH2. Mele et al. [66] value the unit storage cost at 0.365 \$/t/yr for all types of materials. In euros the daily cost per kilogram is then $8.40e-7$ €/kg/day. The unit storage cost for refueling stations (URC) is based on this same value.

In the input parameters for sodium borohydrate production facilities the following process steps are taken into account [28]:

	weight (kg/kg H2)	volume (L/kg H2)
NaBH4 (solid) [56]	4,69	4,38
NaBO2 (x = 0,20) [56]	18,12	12,83
BHF	4,86	3,93

Table 5.9: NaBH4 and spent fuel characteristics and BHF.

1. *Feed pre-treatment*: The spent fuel from the ships will be stored and thermally treated to remove water crystals from the sodium metaborate structure.
2. *Fuel (NaBH4) regeneration*: The treated spent fuel is mixed with MgH2 and fed to a ball mill reactor, where the reaction described in equation (1.2) takes place.
3. *Fuel purification*: The regenerated fuel is separated from other reaction products.
4. *Reductive agent (MgH2) regeneration*: The MgO produced in step 2 has to be regenerated to MgH2. This is performed through three reaction steps: (1) chlorination, (2) molten electrolysis and (3) hydrogenation

It must be taken into consideration that the NaBH4 production process is a process treating solids. This poses certain challenges regarding the technical feasibility of the plant and its maintenance costs. More research needs to be conducted to better evaluate these challenges.

The maintenance expenses (ME_{us}) and fuel economy (FE_{us}) of NaBH4-specific barges and trucks are again assumed the same as the values used for LH2 transportation units. The capacity (b_{us}) and capital cost (IV_{us}) of trucks transporting the solid NaBH4 is inspired by the values used by Mele et al. [66] in their research regarding transportation of sugar for biofuels. The scale-up of the transport capacity by using a barge is chosen by using a similar ratio between LH2 trucks and barges. The capital costs (IV_{us}) of the barge is based on the value used by Svanberg [88] for using bunker barges for methanol. The capital cost for methanol barges are assumed similar to NaBH4 barges as both fuels can be stored at ambient pressure and temperature. The selling cost of trucks and barges (SV_{us}) is, as goes for all selling costs, 40% of the purchase cost.

The back-haul factor (BHF) becomes important for transportation in a NaBH4-based infrastructure as a spent fuel stream will be present as well, where a solution of NaBO2 needs to be transported back to the production facility such that it can be regenerated. Based on the thesis work done by Dennis Lensing [56], this infrastructure design will incorporate a solid NaBH4 fuel flow - as the dry fuel variant is more stable (no stabiliser is needed and no decay of the fuel takes place over time) and easier to store than the liquid NaBH4 fuels - and a liquid spent fuel flow where a molar fraction of 0.20 NaBO2 is used. The assumption is made that a transportation unit cannot transport both NaBH4 and spent fuel in the same tank. This means that the spent fuel cannot be transported in the backhaul (the return trip of the truck/barge) of a transportation unit. Table 5.9 shows the weight and volume of both fuel and spent fuel with respect to 1 kg of H2. Additionally the weight- and volume-based back-haul factors are shown. The most restrictive BHF must be used in the model, which is the weight-based BHF of 4.86. In short this BHF means that for every truckload of delivering NaBH4 to users, 4 trucks need to be deployed to back-haul the spent fuel to the production facility.

Production

plant size, m	1	2	3	4	5	
$PCAP_m$	9,5	150	300	450	600	*ton/day*
PCC_m	57	614	1229	1843	2457	*M€*
PSC_m	23	246	491	737	983	*M€*
UPC_m	1,35	1,00	1,00	1,00	1,00	*€/kg*

Storage

storage size, n	1	2	3	4	5	6	7	8	9	10	11	
$SCAP_n$	9,5	150	540	1080	2160	4320	8640	17280	34560	51840	69120	*ton*
SCC_n	1,2	8,0	30	60	120	239	479	957	1915	2872	3830	*M€*
SSC_n	0,5	3,2	12,0	23,9	47,9	95,7	191,5	383,0	765,9	1149	1531,9	*M€*
USC_n	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	*€/kg/day*

Refueling Stations

URC^*	8,40e-7	*€/kg/day*

Transport

transp. type, u_s	barge	LH2 tanker truck	
b_{us}	650	25	*ton*
IV_{us}	1.500.000	25.200	*€*
SV_{us}	600.000	10.080	*€*
ME_{us}	0,082	0,082	*€/km*
FE_{us}	0,46	2,3	*km/L*
BHF	4,86		-

Table 5.10: Sodiumborohydrate (NaBH4) input parameters.

6

Verification of the model

After having programmed the model, the next step is to check whether this model actually reacts according to expectations. This verification is done by changing parameters of the model and checking whether the expected changes in the model output actually occur. With this verification one can test whether the implemented code is in accordance with the mathematical model, and whether the model behaves logically when changing certain parameters. The verification of the model is done by repeatedly following three steps:

1. Define a test-experiment
2. Define an hypothesis for the outcome of the experiment
3. Execute the experiment

Should the outcome of the experiment not match the hypothesis then (1) the supposition must be checked (are the assumptions made for the hypothesis correct?), (2) the mathematical model must be checked (are the formulas correct?) and (3) the implementation of the mathematical model in code must be checked (are there any errors in the code?). If any changes are made to the model then the complete verification run for all test-experiments must be started over. After a first preliminary check of the output parameters, the verification experiments are defined and executed. The complete verification experiments are described in table 6.1. The experiments are defined such that multiple characteristics of the model are tested. The model verification has been carried out with a reduced model size to decrease run times. Eventually all hypotheses have been confirmed and the model has thus passed all the verification tests.

Description	**Input value**	**Expected**	**Result**	**Pass/ Fail**
DEMAND				
Introduce a TTS fuel delivery demand at Suezhaven. This will increase the number of trucks assigned to this location. This might also increase the number of delivery trucks selected by the model. The total infrastructure cost will go up.	$d_{7,2} = 70$ MWh/day	$\sum_{u \in U_s} Z^t_{7,u,2} > 0 \forall t \in T$; $\sum_{u \in U_s} Q^t_{u,2} \geq 1 \forall t \in T$; $TC > 2453,53$ M€	$\sum_{u \in U_s} Z^t_{7,u,2} = 1 \forall t \in T$; $\sum_{u \in U_s} Q^t_{u,2} > 1 \forall t \in T$; $TC = 3015,74$ M€	PASS
Triple the demand for refueling station fuel at Australiëhaven. This will possibly (but not necessarily) increase the total capacity of refueling stations opened at $t = 5$. This will increase the number of vehicles restocking refueling stations at $t = 5$. The total cost will go up.	$d_{3,3} = 807$ MWh/day	$\sum_{j \in J} RCAP_j \cdot X^5_j \geq 1500$ ton; $\sum_{u \in U_s} \sum_{s \in S} G^5_{u,s} > 2$; $TC > 2453,53$ M€	$\sum_{j \in J} RCAP_j \cdot X^5_j = 2400$ ton; $\sum_{u \in U_s} \sum_{s \in S} G^5_{u,s} = 4$; $TC = 2743,95$ M€	PASS
Increase the coordinate x_i of Afrikahaven by 50 km. The total infrastructure cost will go up, due to an increased transportation operational cost.	$x_1 = 161543$ m	$TC > 2453,53$ M€	$TC = 2453,94$ M€	PASS
Decrease the penetration factor of STS refueling users in time period $t = 5$ to zero. This will lower the number of barges required for STS-refueling in time period $t = 5$, and consequently this will lead to the sale of barges at the end of time period $t = 4$. The total infrastructure cost will therefore decrease.	$PF^5_1 = 0$	$\sum_{u \in U_s} Q^5_{u,1} < 1$; $\sum_{u \in U_1} ST^5_{u,1} > 0$; $TC < 2453,53$ M€	$\sum_{u \in U_s} Q^5_{u,1} = 0$; $\sum_{u \in U_1} ST^5_{u,1} = 5$; $TC = 1810,06$ M€	PASS
REFUELING STATIONS				
Decrease the storage factor for refueling stations. It is expected that the total capacity of the refueling stations opened will be lower or equal to the original value. A lower storage factor will also lead to a decreased facility operating cost (FOC^t), and thus a decreased total cost.	$\beta_R = 1$	$\sum_{j \in J} RCAP_j \cdot X^5_j \leq 1500$ ton; $TC < 2453,53$ M€	$\sum_{j \in J} RCAP_j \cdot X^5_j = 300$ ton; $TC = 2440,09$ M€	PASS
Lowering the Weight-to-Energy ratio ($\mathcal{W}$) would lead to a lower weight demand in the port. Because of this it is expected that the total infrastructure cost will decrease due to an overall smaller fuel flow through the infrastructure. Amongst other things there will be less vehicles needed to transport the fuel and the production facility capacity will be lower.	$\mathcal{W} = 0,01$	$\sum_{u \in U_2} TU^5_{u,2} < 15$; $\sum_{m \in M} PCAP_m \cdot P^5_m < 450$ ton; $TC < 2453,53$ M€	$\sum_{u \in U_2} TU^5_{u,2} = 10$; $\sum_{m \in M} PCAP_m \cdot P^5_m = 150$ ton ; $TC = 331,51$ M€	PASS
Lower the capital cost (RCC_j) of the refueling station at Nieuwe Zeehaven ($j = 8$). It is expected that this refueling station will then be chosen by the model as it is cheaper than all other refueling stations. The total cost will then also decline.	$RCC_8 = 10$ M€	$X^t_8 = 1 \forall t \in T$; $TC < 2453,53$ M€	$X^t_8 = 1 \forall t \in T$; $TC = 2433,61$ M€	PASS
Increase the unit storage cost for refueling stations (URC). This is expected to increase the total infrastructure cost, due to an increased facility operational cost.	$URC = 0,30$ €/kg/day	$TC > 2453,53$ M€	$TC = 15549,85$ M€	PASS
Change the y-coordinates of all refueling stations by 50 km. It is expected that this will increase the total infrastructure cost as the travelling distances for transportation units will be increased, thus increasing the transportation operational costs.	$y_{j,new} = y_j - 50000$ m	$TC > 2453,53$ M€	$TC = 2454,59$ M€	PASS

Description	Input value	Expected	Result	Pass/ Fail
PRODUCTION FACILITY				
Lower the unit production cost (UPC_m) of all production facility sizes. This will decrease the facility operational costs, thus a decrease is expected for the total infrastructure cost.	$UPC_{m,new} = UPC_m - 0,50$ €/kg	$TC < 2453,53$ M€	$TC = 2184,06$ M€	PASS
Change the y-coordinate of the production facility (PY) by 100 km. The expectation is that the transportation operational costs will increase as the transportation units will need to cover more distance for fuel delivery, such that the total infrastructure cost will go up.	$PY = 598454$ m	$TC > 2453,53$ M€	$TC = 2567,40$ M€	PASS
Change the production capital cost of production facility size 5 (PCC_5) to 10 M€. In this case also change the selling cost for this production facility accordingly to $PSC_5 = 4$ M€. It is expected that the model will select this production facility size for all time periods as it has the largest capacity and the cheapest capital cost. Additionally the total infrastructure cost is expected to decrease do to the cheaper production facility.	$PCC_5 = 10$ M€ ; $PSC_5 = 4$ M€	$P_5^t = 1 \forall t \in T$; $TC < 2453,53$ M€	$P_5^t = 1 \forall t \in T$; $TC = 1584,20$ M€	PASS
STORAGE FACILITY				
Increase the unit storage cost (USC_n) of all storage facility sizes. This will increase the facility operational costs, thus an increase is expected for the total infrastructure cost.	$USC_n = 0,50$ €/kg	$TC > 2453,53$ M€	$TC = 26706,00$ M€	PASS
Decrease the storage factor for the storage facility (β_{sto}). This will decrease the total storage capacity needed in the infrastructure design, such that this capacity is expected to be lower or equal to the original value (thus also possibly decreasing the facility capital cost, FCC^t). Additionally this lower storage factor will lead to a decreased facility operating cost (FOC^t) such that the total infrastructure cost will decrease.	$\beta_{sto} = 30$	$\sum_{n \in N} SCAP_n \cdot B_n^5 \leq 34560$ ton; $TC < 2453,53$ M€	$\sum_{m \in M} SCAP_n \cdot B_n^5 = 17280$ ton; $TC = 1890,15$ M€	PASS
Change the storage capital cost of storage facility size 9 (SCC_9) to 10M€ and the selling cost to 4M€ to ensure the same relation between buying and selling. This will lead to the model selecting this storage facility size for all time periods as this storage facility will be the cheapest option with sufficient storage capacity. Additionally the total infrastructure cost is expected to decrease due to the decreased storage facility investment required.	$SCC_9 = 10$ M€ ; $SSC_9 = 4$ M€	$B_9^t = 1 \forall t \in T$; $TC < 2453,53$ M€	$B_9^t = 1 \forall t \in T$; $TC = 1526,27$ M€	PASS
TRANSPORTATION				
Increasing the driver operation hours (DO) will lead to an overall higher transportation operating cost due to increased total salary for workers, and thus a higher total infrastructure cost.	$DO = 24$ hrs/day	$TC > 2453,53$ M€	$TC = 2488,53$ M€	PASS

Description	**Input value**	**Expected**	**Result**	**Pass/ Fail**
Increasing the maintenance expenses of trucks ($ME_{u,2}$) significantly is expected to lead to a higher transportation operational cost for trucks, such that the total infrastructure cost will increase. This might also lead to less trucks being deployed and using barges instead for fuel transportation.	$ME_{u,2} = 1,00$ €/km	$\sum_{u \in U_2} TU^5_{u,2} \leq 15$; $\sum_{u \in U_1} TU^5_{u,1} \geq 5$; $TC > 2453,53$ M€	$TU^5_{u,2} = 15$; $TU^5_{u,1} = 5$; $TC = 2466,43$ M€	PASS
Decreasing the fuel economy ($FE_{u,1}$) of barges means that the barge would require more fuel for the same distance travelled, thus increasing the transportation operational cost. It is expected that the total infrastructure cost will increase. The number of barges selected for fuel transportation is expected to stay the same, as already the minimum number of barges is selected in the base model.	$FE_{u,1} = 0,1$ km/L	$\sum_{u \in U_1} TU^5_{u,1} = 5$; $TC > 2453,53$ M€	$TU^5_{u,1} = 5$; $TC = 2502,53$ M€	PASS
Increase fuel price of trucks (FP_2). This will lead to a higher transportation operational cost for trucks, such that the total infrastructure cost is expected to increase. This might also lead to less trucks being deployed and using barges instead for fuel transportation.	$FP_2 = 5,00$ €/L	$\sum_{u \in U_2} TU^5_{u,2} \leq 15$; $\sum_{u \in U_1} TU^5_{u,1} \geq 5$; $TC > 2453,53$ M€	$TU^5_{u,2} = 15$; $TU^5_{u,1} = 5$; $TC = 2478,15$ M€	PASS
Decrease the driver wage of barges DW_1. This will lead to a lower transportation operational cost for barges. The total infrastructure cost is thus expected to decrease. It is possible that due to this lower cost for barges more barges will be selected for fuel transportation, and the number of trucks deployed might decrease.	$DW_1 = 20$ €/hr	$\sum_{u \in U_1} TU^5_{u,1} \geq 5$; $\sum_{u \in U_2} TU^5_{u,2} \leq 15$; $TC < 2453,53$ M€	$TU^5_{u,1} = 10$; $TU^5_{u,2} = 5$; $TC = 2441,04$ M€	PASS
Change the x-coordinate of the central distribution point (OX) by 100 km. The expectation is that the transportation operational costs will increase as the transportation units will need to cover more distance for fuel delivery, such that the total infrastructure cost will go up.	$OX = 215975$ m	$TC > 2453,53$ M€	$TC = 2591,05$ M€	PASS
Lowering the tortuosity factor of trucks (TF_2) will lead to a decreased distance having to be covered by trucks in the port. This in turn will lead to a lower transportation operational cost and thus a lower total infrastructure cost. The lower tortuosity factor will not affect the number of trucks selected as the number of barges used is already at a minimum, such that it is not possible to trade barges for trucks to further lower operational costs.	$TF_2 = 1,0$	$\sum_{u \in U_2} TU^5_{u,2} = 15$; $TC < 2453,53$ M€	$TU^5_{u,2} = 15$; $TC = 2451,51$ M€	PASS
Increasing the carrying capacity of trucks ($b_{u,2}$) will lead to less trucks needed in the infrastructure. This in turn will lead to a decreased total infrastructure cost.	$b_{u,2} = 200$ ton	$\sum_{u \in U_2} TU^5_{u,2} \leq 15$; $TC < 2453,53$ M€	$TU^5_{u,2} = 10$; $TC = 2449,38$ M€	PASS

Description	Input value	Expected	Result	Pass/ Fail
Lower the purchase cost of barges ($IV_{u,1}$) to a value lower than the purchase cost of trucks. In this case also change the selling cost for barges accordingly. The model might select more barges and less trucks. The total infrastructure cost is expected to be lower.	$IV_{u,1} = 10000$ €; $SV_{u,1} = 4000$ €	$\sum_{u\in U_1} TU^5_{u,1} \geq 5$; $\sum_{u\in U_2} TU^5_{u,2} \leq 15$; $TC < 2453,53$ M€	$\sum_{u\in U_1} TU^5_{u,1} = 5$; $\sum_{u\in U_2} TU^5_{u,2} = 15$; $TC = 2449,79$ M€	PASS
OTHER				
By increasing the discount rate (dr) it is expected that the total cost will decrease as future expenses will be discounted more and thus contributing less to the total infrastructure cost.	$dr = 0,10$	$TC < 2453,53$ M€	$TC = 650,83$ M€	PASS
When the back-haul-factor (α) is increased, the expectation is that more transportation units will be deployed. This will also lead to a higher total infrastructure cost.	$\alpha = 8$	$\sum_{u\in U_1} TU^5_{u,1} \geq 5$; $\sum_{u\in U_2} TU^5_{u,2} \geq 15$; $TC > 2453,53$ M€	$TU^5_{u,1} = 8$; $TU^5_{u,2} = 24$; $TC = 2477,33$ M€	PASS

Table 6.1: Systematic verification of the model

7

Results

This chapter will evaluate the output generated by the model. The results of the model are discussed in Section 7.1. In this section the set-up of the infrastructures for LH2, GH2 and NaBH4 are compared to each other in their steady state as well as compared when varying important parameters. Next, the output of the model is assessed by applying a sensitivity analysis (Section 7.2) to two influential parameters of the model (discount rate and penetration factor). Note that using this model a comparison is made mostly with respect to cost of the infrastructures, whereas for example safety, public opinion and regulation of the different fuels are also important factors to take into account.

7.1. Main Results

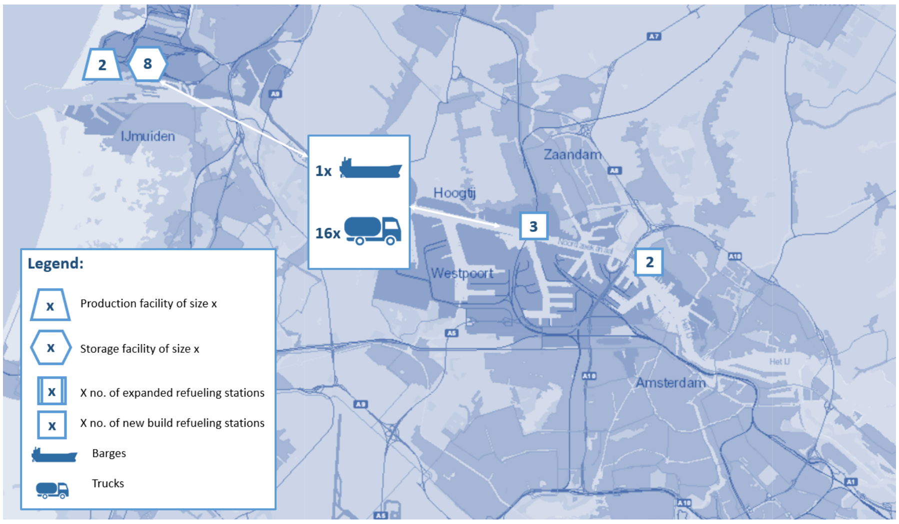
The main research question was: "How do the port refueling infrastructures of sodium borohydrate, liquid hydrogen and gaseous hydrogen compare to each other with respect to costs and supply chain set-up in terms of where, when, and at what sizes to build up the production, storage, distribution and refueling facilities?". For the main results the different infrastructures are compared in five ways:

1. How do the base infrastructures of LH2, GH2 and NaBH4 compare to each other with respect to cost and configuration? (paragraph 7.1.1)
2. How do these infrastructures compare to each other when using more extreme input of the penetration factor and storage factor? (paragraph 7.1.2)
3. How does varying the unit production cost of the NaBH4-infrastructure affect its total cost with respect to LH2 and GH2? (paragraph 7.1.3)
4. How does varying the storage capital cost of the NaBH4-infrastructure affect its total cost with respect to LH2 and GH2? (paragraph 7.1.4)
5. How does varying the production capital cost of the NaBH4-infrastructure affect its total cost with respect to LH2 and GH2? (paragraph 7.1.5)

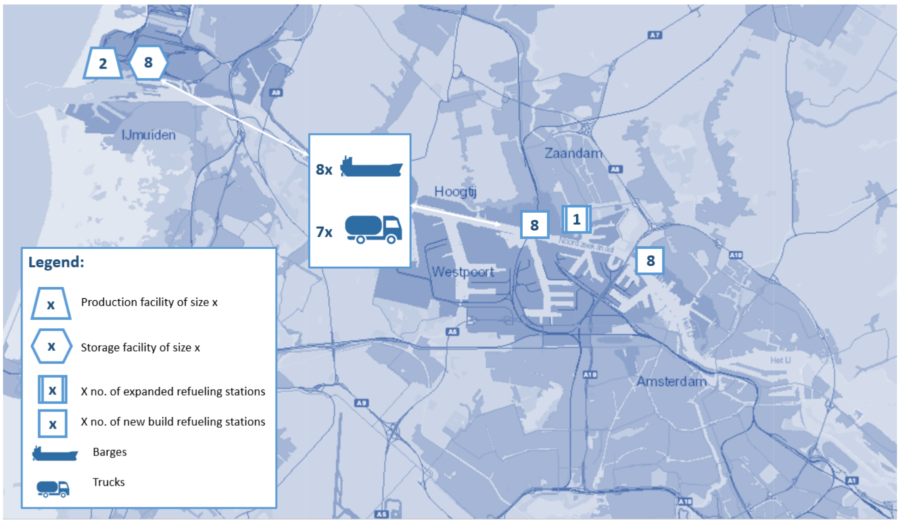
Next, in paragraph 7.1.6 the combinations of cost reductions of several expenses for the NaBH4-infrastructure are explored.

7.1.1. Infrastructure Comparison LH2, GH2 and NaBH4

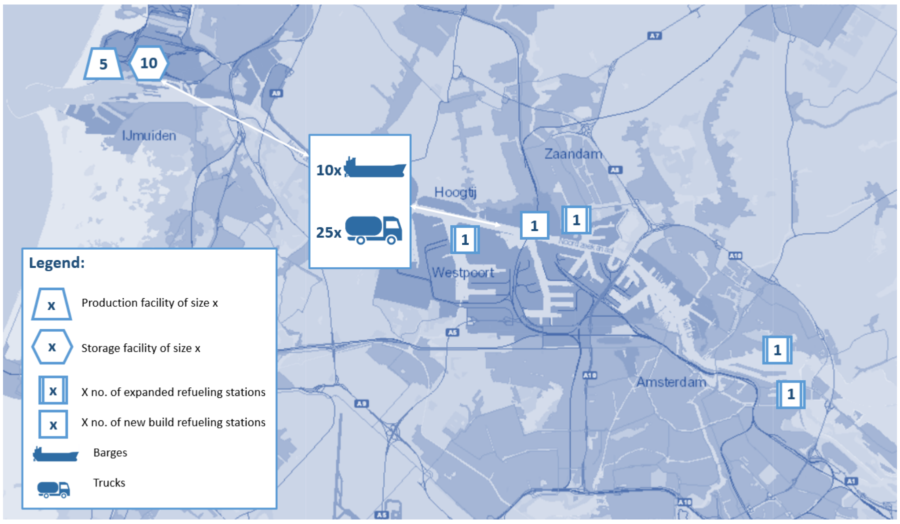
When running the model it designs a complete infrastructure for five time periods for a specific alternative fuel. Using the base input as determined in chapter 5 the infrastructure design is given as output of the model. The overall cost distribution and the selection of the important infrastructure components over time for all evaluated alternative fuels are shown in table 7.1. Additionally, this selection of components including the locating of refueling stations in time period $t = 5$ (the year 2060) is shown graphically for the different alternative fuels in figures 7.1a, 7.1b and 7.1c.



(a) LH2



(b) GH2



(c) NaBH4

Figure 7.1: Snapshot visual representation of hydrogen infrastructure designs in the year 2060

	LH2 INFRASTRUCTURE					GH2 INFRASTRUCTURE					NABH4 INFRASTRUCTURE					
TC	2634,51					2244,17					3810,35					[M.€]
FCC	1663,95					1299,88					2831,85					[M.€]
FOC	928,92					804,64					899,11					[M.€]
TCC	7,66					25,19					6,11					[M.€]
TOC	33,99					114,46					73,28					[M.€]
	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	
Demand	0,5	6,44	24,58	48,16	106,17	0,5	6,44	24,58	48,16	106,17	2,42	30,95	118,24	231,63	510,62	[ton/day]
Size P	1	1	2	2	2	1	1	2	2	2	1	2	2	5	5	[-]
Size S	2	4	6	8	8	2	4	6	8	8	3	6	8	10	10	[-]
Ref. Expanded	0	0	0	0	0	1	1	1	1	1	1	1	2	4	4	[#]
Ref. New build	1	1	1	2	5	0	3	3	6	16	0	0	0	0	1	[#]
Barges (STS)	0	0	1	1	1	0	0	1	1	2	0	0	5	5	5	[#]
Trucks (TTS)	1	1	1	1	1	7	7	7	7	7	5	5	5	5	5	[#]
Barges (ref.stat.)	0	0	0	0	0	0	1	1	2	6	0	0	0	0	5	[#]
Trucks (ref.stat.)	0	2	3	6	15	0	0	7	7	0	0	10	15	25	20	[#]

Table 7.1: Optimisation results for the hydrogen supply chain for LH2, GH2 and NaBH4

Snapshot comparison of infrastructures
The first infrastructure design discussed in this chapter is the **LH2 infrastructure**. Within this infrastructure we see that the model selects the production and storage facility such that it is able to provide for the demand in that time period (no selection of a much larger facility such that the extra cost for expansion is avoided. This is due to the discount rate chosen, as will be further discussed in section 7.2.1). A preference for trucks as transportation units can be seen as they are better to use in a situation with a gradual demand growth, due to the fact that the capacity of each truck is smaller than a barge. The capacity of a barge is of such proportions that it is not beneficial to use them for restocking of refueling stations using the modelled demand profile. A barge is only selected once to be used for STS-refueling. Moreover in table 7.1 it can be seen that the growing demand for liquid hydrogen over the time periods considered quickly asks for a big refueling station capacity such that the model expresses a preference for new build refueling stations. The total capacity of expandable refueling stations is simply not enough to meet the total demand for hydrogen at refueling stations.

The next infrastructure discussed is the **compressed hydrogen infrastructure (GH2)**. Again the model selects the production and storage facility with the lowest capacity possible in each time period, as to minimise the cost. The storage capacities are identical to the LH2-storage capacities in each time period, as these capacities are weight-based in this model and the weight-flow through both infrastructures is expected to be identical. It should be kept in mind however that compressed hydrogen storage facilities will be more voluminous than the LH2 storage facilities as the compressed hydrogen is stored much less densely in comparison to liquid hydrogen. The question is whether the port has enough space for such a large storage facility. Note that the advantage of liquefying hydrogen (or using NaBH4 as a fuel) is the option of more dense storage of the fuel. This same storage density problem is depicted in the number of refueling stations needed in the infrastructure. In 2060 a total of 18 new build refueling stations (with capacity of 35 tons of gaseous hydrogen) would be required to facilitate the refueling with gaseous hydrogen. Here the difference with a liquid hydrogen infrastructure, where only 6 new build stations are required in 2060, is evident. Recall that the refueling station capacities in this model have been derived from the volume available. Of course the 18 refueling stations of 35 tons could also be seen as 9 stations of 70 tons, etc. However this number does depict the disadvantage of using gaseous hydrogen in an infrastructure quite well, where a lot of volumetric capacity is needed for storing the fuel. This also has implications for the space available inside the port as well as the safety of storage. This same volume constraint is visible in the number of vehicles needed to transport the compressed hydrogen (as can also be seen in figure 7.1b). There is a higher preference for barges when compared to a liquefied hydrogen infrastructure as their individual capacity in tonnage is lower such that barges become economically more attractive with respect to trucks with an extremely low capacity.

Lastly the **NaBH4 infrastructure** will be discussed. Due to the much higher WER (as described in chapter 5.1.1) the weight-based demand for NaBH4 is also higher with respect to a liquefied or compressed hydrogen infrastructure: A lot more weight tons of fuel need to flow through the infrastructure to satisfy the energy demand of the users. This has its repercussions on both the production and storage facility size needed, which have both higher weight capacities when compared to LH2 and GH2 infrastructures (Note that in this model these facilities are gravimetrically constrained, whereas NaBH4 has a clear advantage in volume constraints. This will be discussed further in chapter 8). The number

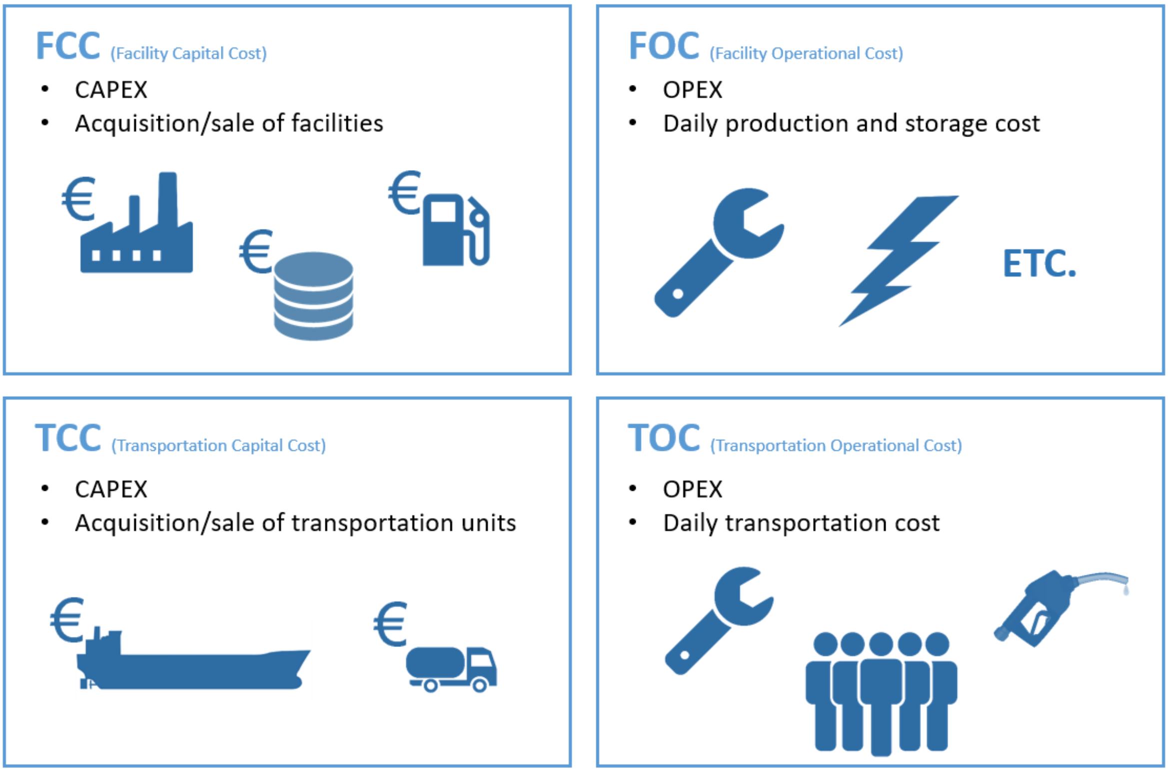


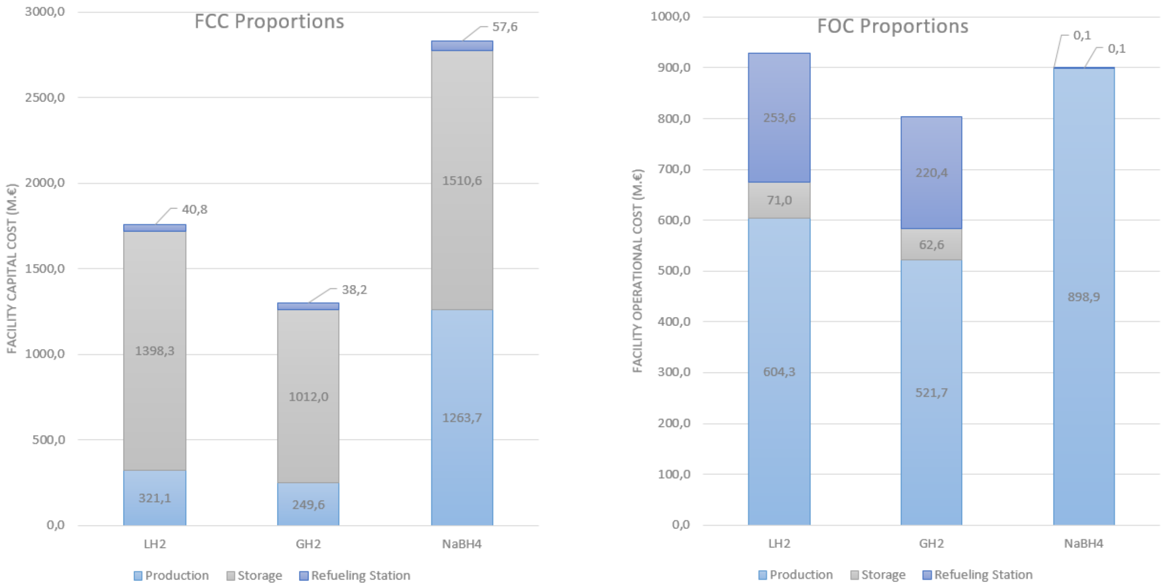
Figure 7.2: A graphical overview of the building blocks of the cost of the infrastructures.

of refueling stations required however is much lower. This can be explained due to the fact that the refueling stations are based on volume constraints and, as the density of NaBH4 is very high with respect to LH2 and GH2, thus the refueling stations can store a high weight of NaBH4. By expanding existing refueling stations already most of the storage capacity can be provided. In 2060 the first new build refueling station solely for NaBH4 will have to be developed to meet the growing demand for NaBH4. As regards transportation, the back-haul factor (BHF, as described in chapter 5.6) ensures that the transportation units selected are always a multiple of 5 such that enough transportation units are available to transport both the fuel and spent fuel. This leads to the number of trucks and barges required for transport in the NaBH4 infrastructure is even higher than needed in the compressed hydrogen infrastructure.

Cost comparison of infrastructures

Next the infrastructures as described above will be compared to each other with respect to costs. The costs are divided into four categories: the Facility Capital Cost (FCC), the Facility Operating Cost (FOC), the Transportation Capital Cost (TCC) and the Transportation Operating Cost (TOC). What is incorporated into each of these categories is amply described in chapter 4.5. A schematic overview of the costs considered is also shown in figure 7.2.

The Facility Capital Cost (FCC) of the different fuels are compared to each other in figure 7.3a. The first conclusion that can be drawn from these bar-charts is that the refueling stations are relatively low in capital costs with respect to the production and storage facility. This is logical and can be explained by the lower storage factor and thus capacity needed for refueling stations, as well as the fact that only part of the total alternative fuel demand in the port will flow through refueling stations. The storage capital cost however is much higher for all fuel infrastructures, especially for the LH2 and GH2 infrastructure this is the highest proportion of the facility capital cost. For NaBH4 the storage capital cost is the highest, which can be related to the much higher weight demand of the fuel and thus more weight storage capacity is needed to serve this demand (again, note the gravimetrically constrained storage facility capacities). Additionally the production capital cost is very high for NaBH4 with respect to LH2 and GH2. A notable conclusion from these bar-charts also is the fact that the compressed hydrogen



(a) Facility Capital Cost (FCC) comparison

(b) Facility Operating Cost (FOC) comparison

Figure 7.3: Comparison of hydrogen infrastructure expenses for different fuels

infrastructure has the lowest facility capital cost, which can be explained due to much less components needed to compress the gas with respect to liquefying hydrogen. The components taken into account for production of the alternative fuels have been described in paragraphs 5.4, 5.5 and 5.6. In conclusion this makes the FCC for GH2 the cheapest, followed by LH2 and finally NaBH4, for which FCCs are expected to be highest in this specific scenario.

The Facility Operating Cost (FOC) of the different fuels are compared to each other in figure 7.3b. From this chart it can be concluded that a compressed hydrogen infrastructure in comparison to a liquid hydrogen infrastructure has lower production, storage and refueling station operating cost as less complex components are required (again reference is made to paragraph 5.5). Another important conclusion from this chart is the visible advantage of using NaBH4 from an operational point of view: this infrastructure has extremely low storage and refueling station operating cost. As it is a solid powder-like substance the storage of it is very simple and low maintenance, especially compared to LH2 and GH2 where more components are needed to ensure safety of the storage system.

The transportation capital and operating costs are compared for each fuel in figure 7.4. Here we see a clear advantage for liquefying the hydrogen and thus being able to transport more fuel in one truck when compared to compressed hydrogen, where the trucks and barges have a much lower capacity. This leads to both a higher capital cost and a higher operational cost. For NaBH4 the transportation cost is much lower than GH2 as the capacity of the transportation units is higher and the purchase cost is lower as these trucks and barges need less complex components to ensure safe transportation of the fuel. The transportation cost for NaBH4 however is still higher than the transportation cost for LH2, despite the fact that the transportation units for liquefied hydrogen will cost more due to their complexity and safety related issues. The higher NaBH4 transport cost can be explained by the spent fuel flow which also has to be transported back to the production facility.

7.1.2. Infrastructure Comparison with alternative input

Another interesting insight to research is how the infrastructure cost for LH2, GH2 and NaBH4 will change when using alternative input. Three cases will be analysed: (1) How do the infrastructure costs change when the penetration factor is increased by 200% for STS-refueling and for users of refueling stations. (2) How do the infrastructure costs change when the penetration factor is increased by 300% for STS-refueling and for users of refueling stations (see figure 5.3). (3) How do the infrastructure costs change when the storage factor β_{sto} is set at 314 days (the current value used in Port of Rotterdam)

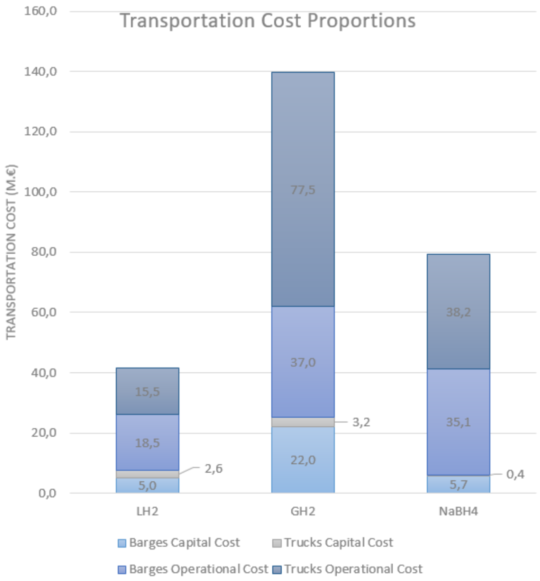


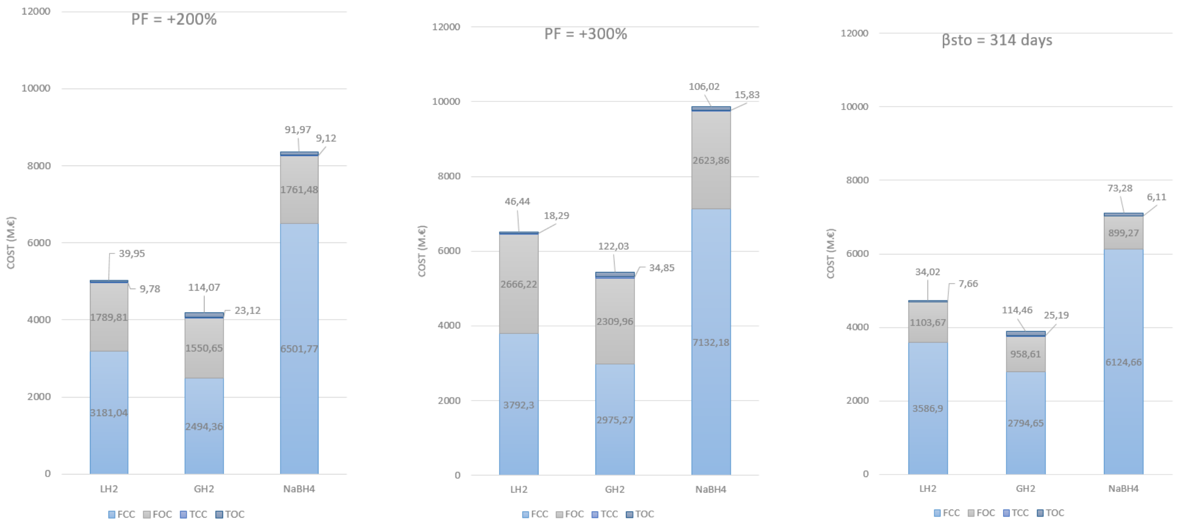
Figure 7.4: Transportation related infrastructure expenses for LH2, GH2 and NaBH4

instead of 90 days? Analysing these cases will give a better insight into possible other scenarios as this can still change easily over the long time-period considered. More importantly, it tests the representativeness of the model. The results of the above mentioned cases are displayed both in figure 7.5 as well as in table 7.2.

In figure 7.5a the infrastructure cost distribution is displayed for NaBH4, LH2 and GH2 for an increase of 200% of the penetration factor. In figure 7.5b the cost distribution of the different fuel infrastructures is displayed after modelling an increase of 300% of the penetration factor. This simulates a more optimistic adoption rate for an alternative fuel, but given the increasingly stringent measures to diminish climate change, can certainly become a possible scenario. Due to the increased fuel demand larger facility capacities are needed, leading to an increase in FCC for all fuels. The larger demand will also lead to more fuel production, and in proportion also more fuel storage in both the storage facility and the refueling stations, thus increasing the FOC as well. The transportation capital and operational costs increase but at a relatively lower pace, as the model selects more barges for all fuel types modelled due to an increasing demand in fuel to be transported. These barges will then become profitable to use. Note that different increases of the penetration factor do not influence the relationships between the different alternative fuel infrastructures.

In figure 7.5c the infrastructure cost distribution is displayed for NaBH4, LH2 and GH2, when the model is run with a storage factor of 314 days. This value is equal to the estimated storage factor currently used in the Port of Rotterdam for MDO and MGO storage. In the base input model a lower storage factor of 90 days was used to contain the storage capacities. Scaling this up to a higher factor leads to the cost distribution as seen in figure 7.5c. Most interesting to note in this figure is that the facility operating costs for the NaBH4-infrastructure in particular are low in relation to the other fuel infrastructures as the added daily storage cost of NaBH4 is very low. Apart from these lower costs NaBH4 also has the great advantage of increased safety of storage with respect to liquefied hydrogen. Transportation and production costs will not change due to a different storage factor as the daily demand is still identical. With respect to total infrastructure cost the compressed hydrogen infrastructure is still the cheapest option.

It can be concluded that NaBH4 as a fuel will become more beneficial from a financial perspective relating to the infrastructure costs when scaling up the storage capacity in the port (higher storage factor β_{sto}). This is mainly due to the extremely low operational costs for storage of the fuel with respect to liquid hydrogen, which have a big effect on infrastructures spanning a large time horizon. In all scenar-



(a) Infrastructure cost distribution at 200% increase of PF

(b) Infrastructure cost distribution at 300% increase of PF

(c) Infrastructure cost distribution at storage factor of 314 days

Figure 7.5: Comparison of hydrogen infrastructure expenses for alternative input

		Resulting change in TC (%)		
Parameter	**Change (%)**	**LH2**	**GH2**	**NaBH4**
PF_s^t	200	191	186	220
PF_s^t	300	248	243	259
β_{sto}	349	180	173	186

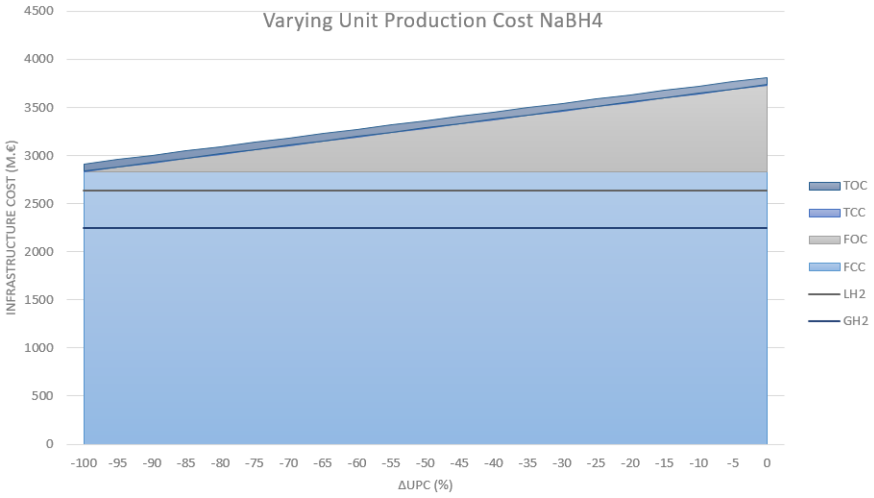
Table 7.2: Sensitivity analysis of changes in total cost as a result of big changes in input values

ios considered gaseous hydrogen will be the cheapest option and NaBH4 will be the most expensive. This will of course still have to be placed in a larger picture with other aspects of the fuel such as safety, public opinion, regulations and policy, and the fuel preference of ships.

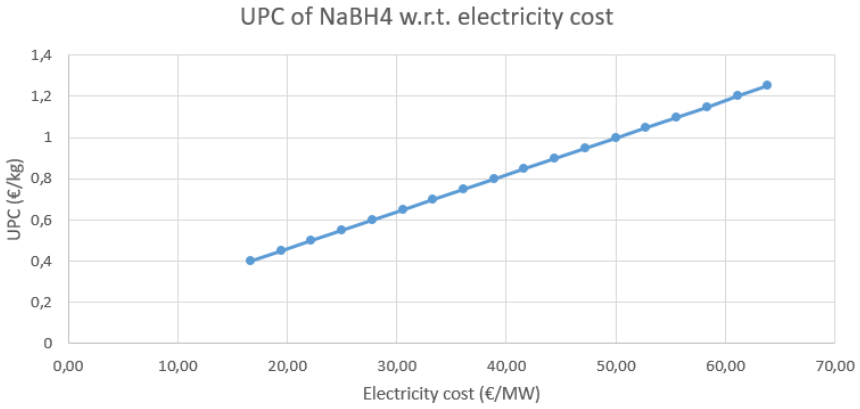
7.1.3. Varying UPC

In this paragraph the effect of varying the unit production cost (UPC) of the NaBH4-infrastructure on its total cost with respect to LH2 and GH2 is evaluated. The main reason to evaluate this cost item is because NaBH4-production on a large scale (as proposed in this model) is not yet in operation. This leads to uncertainty related to these production costs on a large scale. By using different scenarios for UPCs as an input for the optimisation model its effect on the total infrastructure cost for each separate infrastructure designed can be evaluated. The infrastructure expenses for NaBH4 are plotted against different UPC-reductions in figure 7.6a. Varying the UPC only affects the Facility Operating Cost (FOC) as can be seen in the figure. Additionally the total infrastructure costs for the LH2 and GH2 base case are displayed in the graph as lines. From this it can be concluded that the NaBH4 infrastructure will not become competitive with the LH2 infrastructure if only the UPC is reduced. More cost reductions are needed to achieve that, such as reduction of storage and production facility costs (as will be discussed in paragraphs 7.1.4 and 7.1.5). An additional conclusion is that changing the UPC does not influence the configurational choices of the model and it thus also does not influence other cost items (such as the facility capital costs or the transportation related costs).

The unit production cost of NaBH4 is highly dependent on the electricity cost. The link between the UPC of NaBH4 and the electricity cost is shown in figure 7.6b. Decreasing electricity cost leads to a decreased unit production cost for NaBH4. However, when comparing the total infrastructure cost for NaBH4 and LH2 / GH2 as is done in figure 7.6a, it should be kept in mind that decreasing the UPC for NaBH4 due to lower electricity cost would also lead to a lower UPC for LH2 as this value also depends on the electricity price. Thus, a decrease in the NaBH4 UPC should be achieved by optimising the



(a) Varying the UPC for NaBH4



(b) UPC of NaBH4 as a function of the electricity price

Figure 7.6: Evaluating the Unit Production Cost (UPC) of NaBH4

production process such that less electricity is needed for production. The regeneration of MgH2 (a component used in the regeneration process of NaBO2 to NaBH4) requires the most energy. Using an alternative Mg salt (such as MgBr2) could lead to a lower energy requirement [28]. By reducing the energy requirements for regenerating NaBO2 the UPC will decrease thus reducing the total cost for the NaBH4 infrastructure.

7.1.4. Varying CAPEX Storage NaBH4

The strength of the created model is the ability to vary input variables to research their effect on the output of the model. In this paragraph the effect of varying the storage capital cost of the NaBH4-infrastructure on its total cost with respect to LH2 and GH2 is evaluated. The Storage Capital Cost related to the purchase (SCC) and sale (SSC) of NaBH4 storage facilities will then be varied. There are two reasons for evaluating the variation of these cost items: (1) The CAPEX for the NaBH4 infrastructure are dominated by the storage and production facility related expenses. (2) Due to unfamiliarity related to the storage of NaBH4 on a large scale there is still a lot of uncertainty related to its capital costs.

Figure 7.7 shows the effect of varying the SCC with a certain percentage on the total infrastructure cost. Note that the selling cost of storage facilities were defined as 40% of the purchase cost of that facility, such that by varying SCC automatically SSC will need to be adjusted as well. From this graph

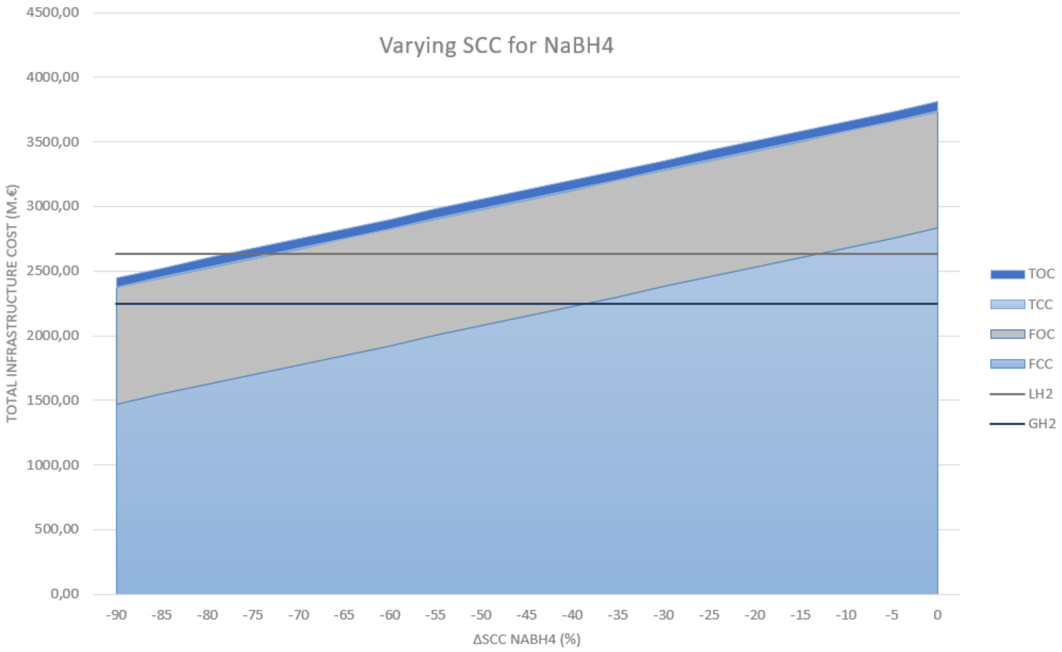


Figure 7.7: Varying the Storage Capital Cost for NaBH4

it can be concluded that decreasing the storage facility cost will lead to a linearly decreasing total infrastructure cost: Changing the SCC does not influence the configurational choices of the model and it thus also does not influence other cost items (such as the facility operational costs and the transportation related costs). A NaBH4 based infrastructure would become competitive with a LH2 infrastructure when the SCC is decreased by 78%. As the input for storage facility cost for NaBH4 is based on the storage of biomass, there could be quite a difference between the currently used facility cost and the eventual facility cost. This will be further discussed in chapter 8.4.

7.1.5. Varying CAPEX Production NaBH4

Another way of evaluating the effect of varying the capital cost of the NaBH4-infrastructure on its total cost with respect to LH2 and GH2 is by adjusting the Production Capital Cost. The Production Capital Cost related to the purchase (PCC) and sale (PSC) of NaBH4 production facilities will then be varied. There are two reasons for evaluating the variation of these cost items: (1) The CAPEX for the NaBH4 infrastructure are dominated by the storage and production facility related expenses. (2) Due to a low TRL and the unfamiliarity of developing NaBO2 regeneration facilities on a large production scale there is still a lot of uncertainty related to its capital costs.

Figure 7.8 shows the effect of varying the PCC with a certain percentage on the total infrastructure cost. Note that, just as with the storage capital cost, the selling cost of production facilities are defined as 40% of the purchase cost of that facility, such that by varying PCC automatically PSC will need to be adjusted as well. From figure 7.8 it can be concluded that a NaBH4 based infrastructure will become competitive with a LH2 infrastructure when the PCC is decreased by 93%. Additionally, changing the PCC does not influence the configurational choices of the model and it thus also does not influence other cost items (such as the facility operational costs and the transportation related costs). Regarding decreasing the capital cost of the production facility the best option is to focus on the reactor cost, as this is represents the highest cost percentage for the NaBH4 production facility [28]. Due to the slow kinetics of the system a large volume and amount of reactors are needed. Improving these kinetics (for example by optimizing the reactor conditions and using better catalyst) would lead to less reactors needed and thus a lower production capital cost. A cost decrease of 93% however is extremely unlikely to be accomplished. A cost reduction of the total infrastructure cost for NaBH4 should be achieved by reducing multiple cost components.

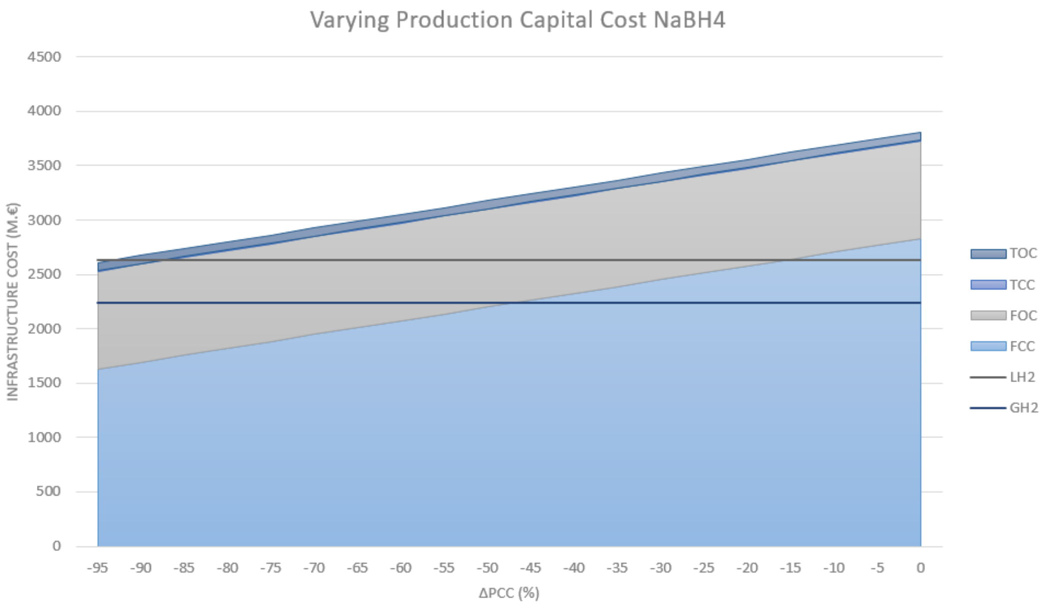


Figure 7.8: Varying the Production Capital Cost for NaBH4

7.1.6. Combining Cost Reductions

In determining the input it became clear that uncertainties in these values are unavoidable. This is mainly because the model treats new alternative fuels which have not been applied yet in current infrastructures. Additionally the model simulates a long time period of multiple decades. These influences on the uncertainties of parameters will be further discussed in chapter 8. The fundamental assumptions used when determining the input of course influence the results of the model.

These influences lead to uncertainties, such that it may occur that certain parameters will be different from the ones used in this research. In the previous paragraphs already some influential parameters have been evaluated with respect to the total infrastructure cost: The SCC (Storage Capital Cost), the PCC (Production Capital Cost) and the UPC (Unit Production Cost). A combination of cost reductions of these parameters would lead to different conclusions regarding the competitivity of NaBH4 with a LH2-infrastructure. In figure 7.9 the combinations of cost reductions required to make the NaBH4-infrastructure competitive with the LH2-infrastructure are shown as a light blue area. All reduction combinations which are located on the blue area in the plot are LH2-competitive NaBH4-infrastructures. All points above the blue area are infrastructures where using NaBH4 as an alternative fuel would be more cost effective than using LH2 according to this model. It can be seen that reducing only the UPC will never lead to a cost competitive NaBH4-infrastructure. It will only be effective when combining this reduction with reduction of the storage and/or production capital cost. Note that in figure 7.9 the values for the liquefied hydrogen infrastructure are assumed to be fixed, whereas there is of course also uncertainty related to the liquefied hydrogen infrastructure costs.

7.2. Sensitivity Analysis

A sensitivity analysis is an important postoptimality analysis to perform on the model as this will assess the sensitivity of certain input parameters. By evaluating changing model parameters the crucial values of these parameters will be determined which will affect the solution of the model. In the sensitivity analysis parameters are no longer assumed to be certain but treated as estimates. In a way varying the UPC, SCC and PCC as done in paragraphs 7.1.3, 7.1.4 and 7.1.5 is also a sensitivity analysis of these input variables. Varying these cost parameters had no influence on the configuration of the infrastructure and thus on the optimality of the solution. Additionally, large variations of the storage factor and the penetration factor have also already been evaluated in paragraph 7.1.2. In this sensitivity analysis two parameters will be evaluated: the discount rate (section 7.2.1) and the penetration factor

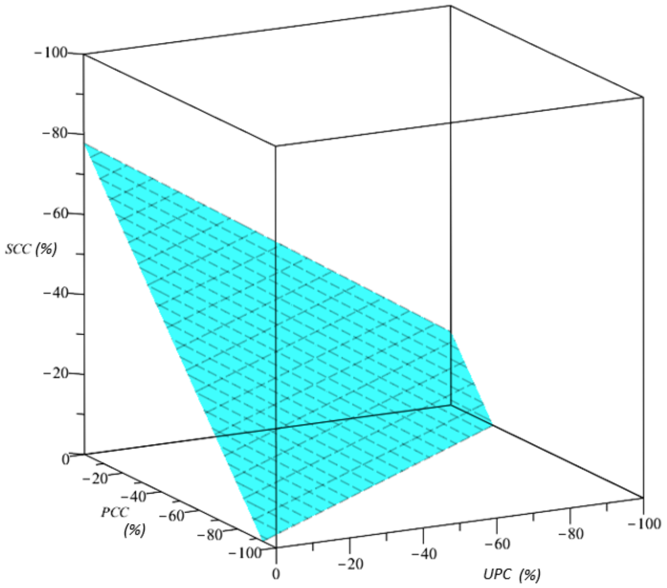


Figure 7.9: LH2 competitive combinations of different cost reductions for the NaBH4 infrastructure.

(section 7.2.2). The allowable range for these parameters is examined: How much can their value be changed without the overall solution changing?

7.2.1. Discount Rate

The discount rate represents the time value of money. As this model is a multi-period model spanning a large time period of 40 years, the discount rate will have a substantial effect on the total cost of an infrastructure. This can be clearly seen in figure 7.10. In this figure the total cost of NaBH4 infrastructure designs as an output from the model are evaluated with respect to the discount rate chosen. The range evaluated in this figure is from a 0% discount rate, where time value of money is thus not incorporated into the calculations, to a 10% discount rate, which is the common discount rate used when taking a shareholder point of view. The 3.5% discount rate used in the base input of the model is based on the economic efficiency of long-term investment projects of public agencies [67]. Between a discount rate of 3.0% and 4.5% the infrastructure set-up per time period is identical (depicted by the blue dots in figure 7.10). When using discount rates lower than 3.0% changes in the timing of purchases can be seen. The lower the discount rate the more the model will select larger facilities earlier in time. Logically, delaying large expenses has no benefit at lower discount rates. At discount rates chosen higher than 4.5% the model expresses a clear preference for delaying large expenses and thus choosing for capacity expansions of large facilities in every time period when the capacities of the previous time period no longer are sufficient.

7.2.2. Penetration Factor Curves

In determining the sensitivity to small changes in the penetration factor the shape of the original curve is kept consistent. The complete adoption curve for refueling station visiting vessels ($s = 3$) is multiplied by a factor to simulate these small changes. Part of the curves used are displayed in figure 7.11a. The adoption curve for STS-refueling vessels follows this same shape but lags behind one time period. In this sensitivity analysis the TTS-refueling vessels are assumed to maintain the same adoption rate as used in the original model. The effect of varying the penetration factor of the alternative fuel on the total cost of a NaBH4 infrastructure is displayed in figure 7.11b. It can be seen that when decreasing the demand the total cost of the infrastructure will decrease as unit production and storage costs fall and less transportation units are needed. The opposite statement holds for increasing the penetration factor. The cost variations as can be seen in the blue line are due to changes in the number of transportation units needed in the infrastructure. Transportation units are seen as fluid assets as they can easily

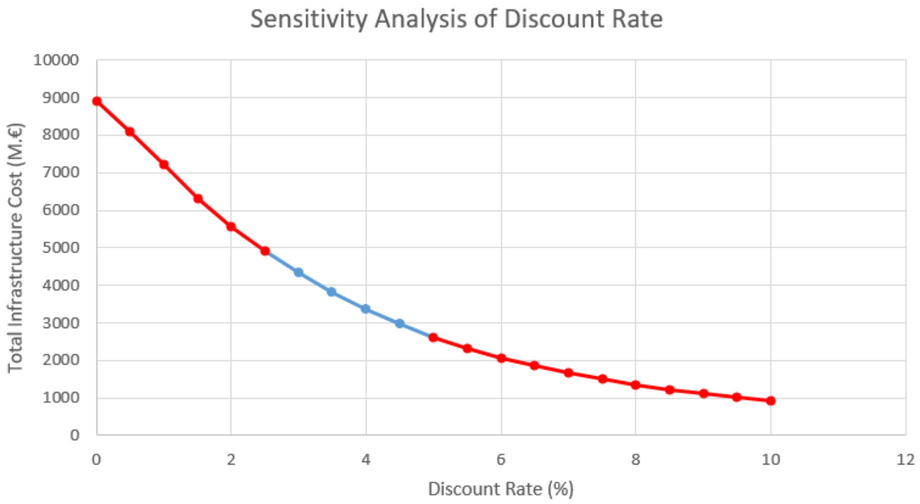
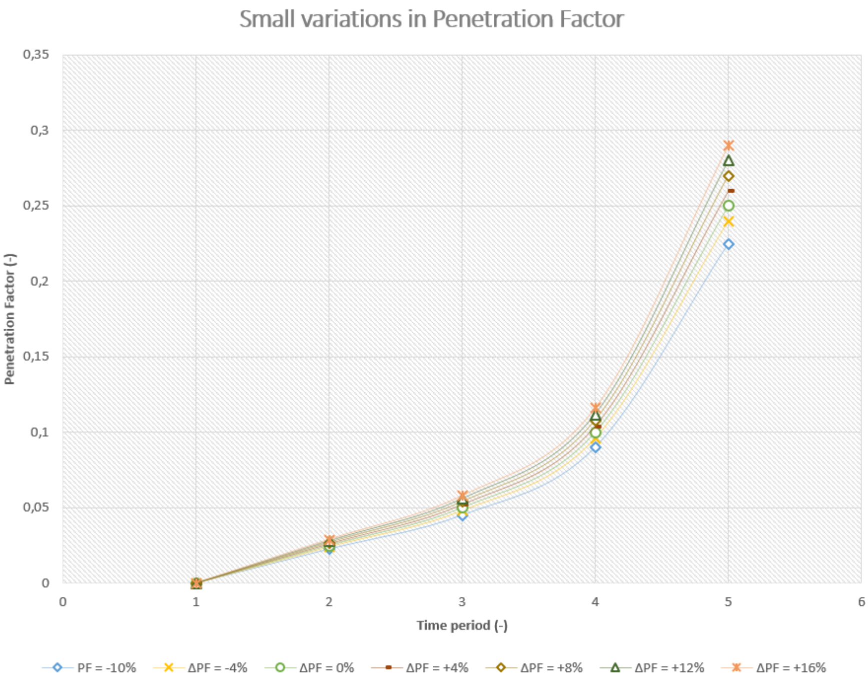
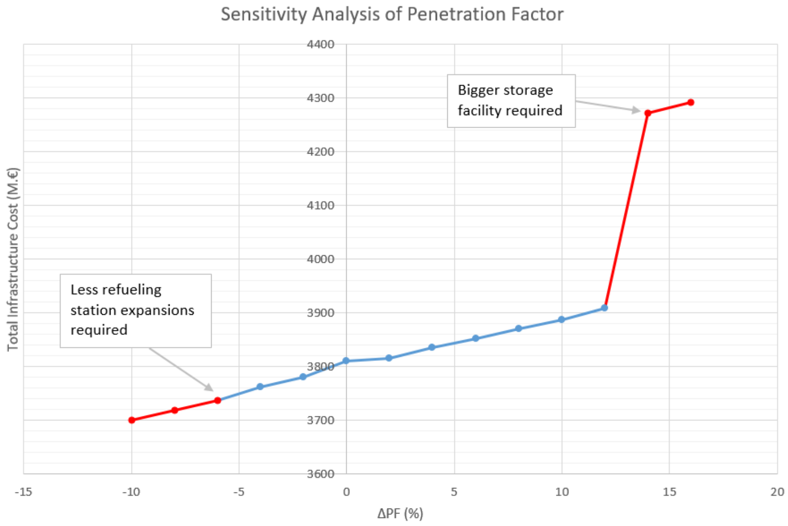


Figure 7.10: Discount Factor Sensitivity Analysis for a NaBH4-based infrastructure

be purchased and sold, such that a changing number of transportation units is not seen as a hard change in the optimality of the solution. The amount and timing of the building of refueling stations, storage facilities and production facilities are factors which are more fixed. When the infrastructure configuration in the solution changes with respect to these fixed assets, the points are displayed in red. What can be concluded is that the penetration factor can grow by 12% from the original model values without it changing the fixed infrastructure components. With higher penetration factors a higher storage capacity is required. A decrease of the penetration factor however influences the infrastructure components already at a lower percentage of 6%. At that value less refueling station expansions are required in time period $t = 4$ and $t = 5$, as less fuel storage at refueling stations is required.



(a) Examples of the PF-curves used in sensitivity analysis



(b) Sensitivity analysis of PF. Red indicates changing solution infrastructure configuration.

Figure 7.11: Penetration Factor (PF) Sensitivity Analysis

8

Discussion

The goal of this thesis was to create an infrastructure optimisation model capable of designing an infrastructure in a port environment, for several alternative fuels. The goal of this model was to provide an initial overview of the infrastructure design required for a certain fuel and a certain corresponding demand, and to evaluate how different fuels compare to each other with respect to their infrastructure costs. Even though this goal has been achieved by the current model, there are several aspects in which the model can be developed further to result in more specific output. In this chapter the model and its results will be discussed within the frame of the assumptions made in the model, and the influence of these assumptions will be assessed. What is important to note is that the model is intended as a preliminary design tool for an infrastructure, which can be used to understand the interaction between infrastructure components and the alternative fuel considered. The current model has achieved this objective. However, the model has a qualitative approach, and without validation the model can not be taken as an accurate view of reality in quantitative sense.

8.1. Decision Level of the Model

The mathematical model as described in chapter 4 is a model on a strategic and tactical decision level: the focus is on the overarching plan or set of goals for the infrastructure to be designed. In this model the focus was on the infrastructure design over a long period of time such that details of the design, such as specific vehicle routing and timing, are partly simplified. As the model is focused on the long-term horizon of HSC development the operational level is not as important. The model would become too complex to take daily fluctuations and transportation routes into account. For this reason this has been neglected. A model including operational decision levels would lead to a more accurate representation of reality.

An effect of neglecting the operational decision level into the model is the overestimation of the transportation units needed in the model. This assumption is especially apparent in the NaBH4 infrastructure, where the back-haul-factor (BHF) becomes of importance (equation 4.22). The model automatically selects a large amount of vehicles (which are needed to transport back the spent fuel), however this is not linked to the actual filling grade of the spent fuel transportation units selected (as shown in figure 4.2). This means that the units transporting spent fuel might not be completely filled, leading to an overestimation of the number of vehicles needed. For example, the capacity utilisation of trucks and barges restocking refueling stations is calculated in table 8.1 for the LH2, GH2 and NaBH4 base infrastructures at $t = 5$. It should be noted that, although the capacity utilisation is relatively low (especially for the GH2 and NaBH4 infrastructure), its effects on the total infrastructure cost are relatively small as transportation costs only amount of 1.14%, 5.18% and 1.64% of the LH2, GH2 and NaBH4 infrastructure respectively.

Additionally the time needed for the loading of fuel, the transportation of the fuel and the bunkering of the fuel is not incorporated into the model. Designing an operational model on a smaller time scale would be interesting, to incorporate the planning of fuel deliveries and what this would mean for the

	LH2	GH2	NaBH4
fuel weight transport need (ton/day)	31,9	31,9	744,5
transport weight capacity available (ton)	60	210	3750
capacity utilisation (%)	53,1	15,2	19,9

Table 8.1: The capacity utilisation of transportation units for different refueling infrastructures.

number of transportation units needed and its corresponding costs. The bunkering of fuel is a process which takes place in the port 24/7, such that one refueling truck or barge might be able to perform more refueling errands in one day than the current assumption of only one trip per day in the mathematical model. Additionally the routing of the transportation units is modelled as a shuttle model (as depicted in figure 4.3), which will lead to an overestimation of the distance having to be travelled by each transportation unit. It should be noted however that this modelling on an operational level, including routing to some extent, will highly complicate the model, whereas the gains are relatively small (due to low transportation costs).

8.2. Extra model features

Apart from approaching a more realistic model from a transport mapping point of view, other features could be added to create a more realistic interaction between components. Firstly, in the current model the lifetime of components is not yet incorporated and will affect the total cost of the infrastructure. This has already been suggested by Agnolucci and McDowall in their review of papers [15]. Moreno-Benito et al. [67] have already implemented the lifetime of storage facilities, refueling stations and transportation units in their model.

Secondly, the infrastructure design is focused on alternative fuels, which currently are not yet widely implemented in the transport sector. The new technologies linked to these fuels are currently expensive but are expected to decrease in price due to increasing knowledge of these processes and added experience. The current model assumes a constant price for infrastructure components regardless of the time period considered. Applying a learning rate to the cost of these technologies due to accumulated experience would approach reality better in this aspect. A learning rate is for example implemented in the work of Brey et al [27], De-León Almaraz et al [32] and Almansoori and Shah [21]. The effect of applying a learning rate depends of course on the value used per alternative fuel.

Lastly, in the current model there are no costs linked to the loading and unloading of the alternative fuel. For automotive models this is neglected as the average batch sizes are very low. In the maritime industry the amount of fuel per user is much higher. Due to the complexity of maintaining the correct environment for storing compressed or cryogenic hydrogen the loading and unloading of the fuel will take time and it will cost money to ensure the right circumstances for bunkering of the fuel (using for example coolers and compressors to bunker). The same statement is true for sodium borohydrate, where the transshipment of the fuel is complex as the fuel is in a solid state. In a way the bunkering technology must be incorporated in the model from a cost perspective, but more importantly from a time perspective when zooming in to a more operational modelling level as was discussed in section 8.1.

8.3. Input and Estimations

In this chapter the qualitative approach of this model has already been emphasised. The quantitative output of the model is highly dependent on the input used. Several variables have already been evaluated in chapter 7.2 in a sensitivity analysis. Throughout papers a wide variety of input can be identified, however many papers have based their input on the values used by Almansoori and Shah [19], which was also used as a base for input variables in this model. The strength of the optimisation model created in this thesis is the possibility of varying the input and evaluating the resulting output and drawing qualitative conclusions from this when comparing several infrastructures. This variation of input has been researched in this thesis with parameters such as the storage facility capital cost, the production facility capital cost, the discount rate, the penetration factor of an alternative fuel and the storage factor used for the general storage facility. To be able to really use the model for purchase-related decisions and the actual development of an alternative infrastructure the input data must be analysed very thoroughly for the specific situation and the corresponding outlook of the Port of Amsterdam.

In paragraph 7.1.6 the decrease in production capital cost, storage capital cost and unit production cost of NaBH4 needed to make that infrastructure cost competitive with a LH2-infrastructure has been discussed. These parameters are still very uncertain for NaBH4, due to a low TRL and the unfamiliarity with development of NaBH4 production and storage facilities on a large scale. For this reason also the applicability of economy of scale on larger facilities is still undetermined. The same statement applies to the transport costs and transport unit capacities for NaBH4. For all these values a reduction in cost would lead to the competitiveness of the NaBH4-infrastructure coming one step closer. Note that also the cost values used for the GH2- and LH2-infrastructure are subject to uncertainties. This means that the input used in the model should be further researched to reduce the corresponding uncertainties.

Additionally the back-haul factor (BHF) for NaBH4 was assumed to be 4.86 as the spent fuel stream was expected to contain a lot of water still. Should it be possible to treat the spent fuel such that it is a solid containing less H20, then the BHF would be much lower and this in turn would lead to lower transportation costs for the NaBH4-infrastructure as less transportation units will be needed. However, the energy required for dehydrating the spent fuel should be kept in mind in this calculation, as this could lead to an increasing fuel demand if vessels will require more energy to treat their spent fuel.

In the estimations for energy demand in the Port of Amsterdam, future projections of energy efficiency of ships and a possible increase in energy demand have not yet been taken into account. Additionally, the adoption of alternative fuels influences the energy management on board of ships. This could lead to different sailing profiles. Moreover, alternative fuel storage and possible heavier or lighter components for the propulsion system will influence the total vessel weight and thus will influence the energy demand of the ship. More research must be done in this area to further specify the future energy demand of vessels.

8.4. Gravimetric Constraints

As has been mentioned in chapter 7, the storage facilities in this mathematical model are gravimetrically constrained. This choice was made due to the following reasons:

- Other HSCND models in found literature all have gravimetrically constrained the production and storage capacities. This means that also most input found is based on weight.
- Solids will encounter stresses when compacted in storage due to stockpiling of the substance. Over time this could influence the structure and behavior of the solid, which is called time consolidation. NaBH4 has different structures depending on the pressure applied to it. For this reason the assumption is made that NaBH4 will have to be gravimetrically constrained with respect to storage as most likely many separate silos with a low filling degree are necessary to evade too much pressure build up at the bottom of the silo.
- The cost for laying foundations for storage facilities are generally substantial. The type of foundation is dependent on the weight of the storage of the alternative fuel. This is another reason to gravimetrically constrain storage facility capacities, as with a higher weight storage comes a higher foundation cost.

There is currently not enough knowledge about the upscaling of NaBH4 storage. To be able to correctly assess the cost for NaBH4 storage facilities more research must be done on the behavior of NaBH4 with respect to storage, the changing structure of NaBH4 when stored under pressure and what effect this has on the manageability of the substance.

Note that a volume constraint or a weight constraint would have the same modelling effect as they are linked to one another through the density of the substance (as shown in equation 8.1). However, it should be kept in mind which factor, either volume or weight, will be constraining for each alternative fuel, and this must then be translated to the corresponding weight constraint to use as an input for the gravimetrically constrained model. This must be done for production, storage and transport capacities. In this regard the current input used for NaBH4 should be examined further, as there is much uncertainty still associated with the storage and transport capacities. It was found striking that especially the storage cost for NaBH4 is as high as it is in the designed infrastructures. Especially for NaBH4 there is no knowledge to be found yet on the storage capacities (both in weight and volume) on a large scale. The provisional values used for NaBH4 storage and transport capacities and costs are currently based on storage and transport capacities of sugar and biomass. However, these values must be placed in a bigger framework including density, manageability and other properties of the solid being stored. This might very well lead to different storage and transport costs and thus should definitely be researched further. Most importantly, a decreased storage cost could make the use of NaBH4 as a maritime fuel a feasible concept.

$$\rho = m/V \tag{8.1}$$

8.5. Optimisation Objective

The current model focuses on optimising the infrastructure from a cost perspective. The financial aspect of an alternative fuel infrastructure is a very important one on a decision making level, however it needs to be balanced against a background of many other factors, such as safety, policy, public acceptance and the preference for certain fuels from the perspective of the maritime users. As has already been stated in chapter 3.3 of the literature review, optimising a mono-objective model could lead to solutions which might be beneficial with respect to costs, but compromises the environmental impact or safety of the hydrogen infrastructure [29]. Weighing the cost however is a very useful starting point for comparing different infrastructures in a single-objective model.

Expanding the model to a multi-objective optimisation tool would enable the users to weigh different factors against each other to make a well-considered and thought-out decision on what refueling infrastructures to develop. As has been mentioned in paragraph 3.3 of the literature review several researches have created multi-objective models, such as [76], [81] and [34]. For example, safety risks could be incorporated into the model separately, making the model a multi-objective model. As stated by Huétink et al. [46] the social acceptance of technologies influences the technological trajectory of hydrogen as a fuel in the transport sector and is a factor to be taken into account in developing an alternative refueling infrastructure. The approach for applying multi-objective optimisation to the mathematical model with the ϵ-constraint method has been amply described in chapter 3.3. In short, in the ϵ-constraint method one of the single-objectives is chosen to be minimised, whilst all other single-objectives are converted to inequality constraints bounded by some lower and upper allowable levels [36]. The results from solving all the separate single objective problems lead to the Pareto curve which shows the efficient points separating the feasible and infeasible design space of the problem). A graphical example of such a Pareto-curve is shown in figure 8.1.

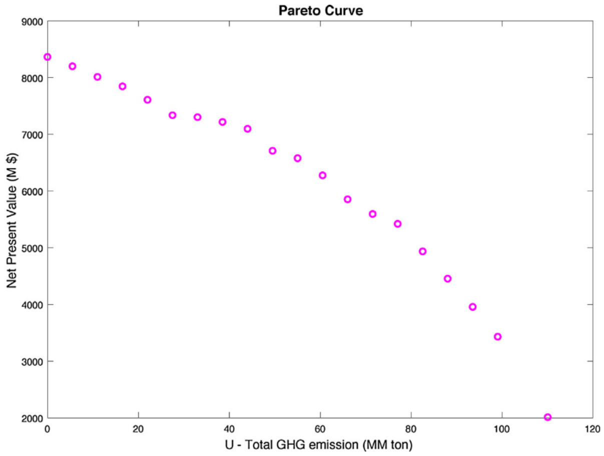


Figure 8.1: Example of a pareto-curve resulting from a multi-objective optimisation model by Ogumerem et al. [76]

9

Conclusion

This research aimed to shed a light on the cost and composition of hydrogen supply chain infrastructures in a port environment for several alternative fuels from the perspective of the maritime end-user. The goal was to provide a base for future research on the maritime infrastructure hydrogen supply chain design, and this has certainly been achieved. The model utility is apparent in not only being able to model the future development and corresponding costs of the refueling infrastructure, but also in its applicability in researching the interaction of maritime refueling infrastructure components with each other and with the demand and set-up choices of the port. In that respect this research offers a mathematical base for further research in hydrogen supply chain design in a port environment.

The main research question of this thesis was: *”How do the port refueling infrastructures of sodium borohydrate, liquid hydrogen and gaseous hydrogen compare to each other with respect to costs and supply chain set-up in terms of where, when, and at what sizes to build up the production, storage, distribution and refueling facilities?”*

The choice was made to create a mathematical optimisation model (Mixed Integer Programming), because this model type is able to evaluate many variables simultaneously to achieve a complete infrastructure design for the Port of Amsterdam. The model has been designed modularly in such a way that by applying different inputs also other fuel types and port locations can easily be evaluated. Based on a quantitative and qualitative analysis of the results (chapter 7) the following conclusions can be drawn:

Fuel infrastructure comparison
An overview of the main costs and infrastructure components for each alternative fuel supply chain considered (LH2, GH2 and NaBH4) per time-period is given in table 9.1. For the **production** cost it can be concluded that (1) the NaBH4-infrastructure is the most expensive. This can mainly be explained due to the reactors, which not only are expensive, but also many of them are necessary. Additionally the operational costs for production are high due to the high energy requirements of the production plant. (2) The liquefied hydrogen infrastructure has lower production costs than a NaBH4-infrastructure. (3) The gaseous hydrogen infrastructure has the cheapest production cost both in facility capital cost and operational cost. The difference in efficiencies regarding either compression or liquefaction of hydrogen explains the difference in cost between LH2- and GH2-production.

When looking at the **storage** cost, it can be seen that in this model (1) the LH2-infrastructure has the highest storage cost component. (2) Next follows the storage cost for NaBH4. It is cheaper than LH2, especially due to the extremely low operational cost for storing the solid hydrogen carrier. Storing NaBH4 is promoted to be easy and safe to store leading to low storage operational costs. (3) Lastly, the GH2-infrastructure is cheapest with regards to the storage cost. Mainly less energy is needed to maintain the right storage conditions when compared to liquefied hydrogen. Additionally the storage capital cost is the lowest of all fuels considered.

With respect to **transportation** cost however (1) the GH2-infrastructure is the most expensive. This can be attributed to the low capacity available per transportation unit to transport GH2, such that many trucks and barges are required to distribute all fuel in the harbor. (2) Next follows the total transportation cost for NaBH4. This costs can be explained due to the spent fuel flow back to the production facility, to this end requiring more transportation units. (3) The LH2-infrastructure has the lowest transportation cost as the transport capacity is highly increased for the vehicles with respect to gaseous hydrogen transport due to the higher density.

Overall a compressed hydrogen infrastructure is the cheapest option when taking all infrastructure components and daily operational costs into account. This can be attributed to the low fuel weight demand by users and the relatively low cost of components with respect to a (more complex) liquid hydrogen infrastructure. The sodium borohydrate based alternative infrastructure has the highest cost in this set-up, mainly due to a very high weight demand with respect to both compressed and cryogenic hydrogen and due to the currently high estimated costs for production and storage capital cost of the fuel. Important to note is that these infrastructure costs need to be placed in a greater perspective where apart from its cost (as evaluated in the current single-objective model) also the safety of the fuel, the corresponding public opinion, regulations and policy, the transportability and the user friendliness of the fuel are important fuel characteristics.

Parameter uncertainty
Due to unfamiliarity with the production and storage of NaBH4 on a large scale, several input parameters have been varied to evaluate their effect on the total infrastructure cost and to compare these varying infrastructure costs with the LH2- and GH2-infrastructure. The influential parameters evaluated were the Storage Capital Cost (SCC), the Production Capital Cost (PCC) and the Unit Production Cost (UPC). With the parameters used in this model the NaBH4-infrastructure would become cost-competitive with the LH2-infrastructure at a reduction of 78% for the SCC or a reduction of 93% for the PCC. A decrease in PCC could be achieved by improving the reaction kinetics to achieve lower total reactor costs. It can also be concluded that the NaBH4-infrastructure will never become competitive with the LH2-infrastructure if only the UPC is reduced. A decrease in unit production cost could be achieved by optimising the production process such that less electricity is needed for production. A combination of cost reductions of SCC, PCC and UPC would lead to different conclusions regarding the competitivity of NaBH4 with a LH2-infrastructure: In figure 7.9 the combinations of cost reductions required to make the NaBH4-infrastructure competitive with the LH2-infrastructure have been shown.

Gravimetric constraints
As has been discussed in chapter 8, one should take into consideration that the current model is gravimetrically constrained. This is very important to take into account when determining the input used for each alternative fuel. Especially for NaBH4 there is no knowledge to be found yet on the storage capacities (both in weight and volume) on a large scale. This makes the input used for the gravimetrically constrained model at this moment still very uncertain. The storage cost make up a large proportion of the NaBH4 total infrastructure cost, such that this uncertainty could have a large effect on the conclusions drawn at this point. Most importantly, a decreased storage cost could make the use of NaBH4 as a maritime fuel a feasible concept. Thus, more research into large scale NaBH4 storage is required.

	LH2 INFRASTRUCTURE					GH2 INFRASTRUCTURE					NABH4 INFRASTRUCTURE					
TC	2634,51					2244,17					3810,35					[M.€]
FCC	1663,95					1299,88					2831,85					[M.€]
FOC	928,92					804,64					899,11					[M.€]
TCC	7,66					25,19					6,11					[M.€]
TOC	33,99					114,46					73,28					[M.€]
	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	
Demand	0,5	6,44	24,58	48,16	106,17	0,5	6,44	24,58	48,16	106,17	2,42	30,95	118,24	231,63	510,62	[ton/day]
Size P	1	1	2	2	2	1	1	2	2	2	1	2	2	5	5	[-]
Size S	2	4	6	8	8	2	4	6	8	8	3	6	8	10	10	[-]
Ref. Expanded	0	0	0	0	0	1	1	1	1	1	1	1	2	4	4	[#]
Ref. New build	1	1	1	2	5	0	3	3	6	16	0	0	0	0	1	[#]
Barges (STS)	0	0	1	1	1	0	0	1	1	2	0	0	5	5	5	[#]
Trucks (TTS)	1	1	1	1	1	7	7	7	7	7	5	5	5	5	5	[#]
Barges (ref.stat.)	0	0	0	0	0	0	1	1	2	6	0	0	0	0	5	[#]
Trucks (ref.stat.)	0	2	3	6	15	0	0	7	7	0	0	10	15	25	20	[#]

Table 9.1: Optimisation results for the hydrogen supply chain for LH2, GH2 and NaBH4

10

Recommendations for future research

The goal of this thesis was to map the differences in future supply chains for alternative fuels in the port environment. For a preliminary approach this has been successful, but the conclusions per fuel infrastructure are dependent on the input used. A more robust model considering variations in input (such as demand and supply chain components cost) would be preferred. This can be achieved by extending the current model. Concluding from the assumptions and current limitations of the model the following recommendations can be made for these future research paths:

- **Demand scenarios from a user perspective:** It is recommended to include the user perspective better in the input of the infrastructure model. This can be done by including an analysis per ship type of sailing profiles, preferences for specific alternative fuels and for bunkering categories ("s" in the mathematical model, see also figure 4.1). Performing such an analysis will lead to a more elaborated and realistic demand input for the mathematical model. Additionally, multiple other fuel types could be included in the model, such as methanol and ammonia.
- **Solids storage and transport:** As has been stated in chapter 8.4, further research is required in the field of large scale storage of NaBH4 should this be further considered as a future maritime fuel. The physical implications of storing, handling and transporting this substance and the spent fuel (NaBO2) in combination with its costs are currently still uncertain. Note that this model is gravimetrically constrained, which is important to take into account in combination with the input used for (especially) NaBH4. As knowledge on the storage capacities (both in weight and volume) on a large scale is lacking, the input used for the current model is still very uncertain. This uncertainty could have a large effect on the drawn conclusions. Decreasing the storage cost for the NaBH4-infrastructure could make it competitive with a LH2-infrastructure from a cost perspective. For this reason it is recommended to better understand large scale storage of NaBH4 within this gravimetrically constrained model.
- **Mathematical additions to the model:** Two impactful additions can be made to the current mathematical model of the port environment. The first is the incorporation of **uncertainty modelling** with respect to either the alternative fuel demand or the supply chain component costs. An ample description of possibilities within the field of uncertainty modelling is provided in chapter 3.5. Incorporating uncertainty modelling into the mathematical model would make the output more robust in the face of uncertain input parameters. The second addition to the model would be the expansion to a **multi-objective model** (most importantly incorporating risk / safety into the model), to more clearly provide an overview of the trade-off between risk and cost of alternative fuels. A description of multi-objective models and the ϵ-constraint methods is given in chapter 3.3.

A

Appendix A: Base input tables

	LH2	GH2	NaBH4*	MDO/MGO**
LHV [kWh/kg] [3]	33,3	33,3	7,10	11,85
Reactor η [-]	-	-	0,98	-
Fuel cell η [-]	0,5	0,5	0,5	-
Electrical motor η [-]	0,95	0,95	0,95	-
Diesel engine η [-]	-	-	-	0,38
Gearbox η [-]	-	-	-	0,97
WER [kg/kWh]	0,063	0,063	0,303	0,229

Table A.1: Weight-Energy-Ratio's and drive train efficiencies of several fuels. * The LHV of the hydrogen released by NaBH4 is calculated using the weight percentage of the 4 hydrogen-atoms in NaBH4 and the 4 atoms released from H20 during the same reaction. ** The LHV of the combination of MDO/MGO is calculated using the proportion of MDO and MGO in the fuel mix as reported by Port of Rotterdam [14].

Total bunker amount (m^3)	5,967,393
Percentage MDO + MGO	0.19
MDO + MGO bunker amount (m^3)	1,133,805
MDO + MGO combined density (ton/m^3)	0.851
MDO + MGO bunker amount (kton)	964
MDO + MGO WER (ton/MWh)	0.229
Yearly energy demand MDO + MGO (GWh)	4212
Daily energy demand MDO + MGO (GWh)	11.54

Table A.2: Energy demand calculations for Port of Amsterdam.

i	**Harbor Basins**	**Berth Estimation (#)**	d_{is} **[MWh/day]**			x_i	y_i
			s = 1	**s = 2**	**s = 3**		
1	Afrikahaven	26	742	0	318	111543	492641
2	Amerikahaven	17	485	0	208	113182	492482
3	Australiehaven	22	628	0	269	113887	491577
4	Aziehaven	14	400	0	171	113456	490736
5	ADM/Westhaven, Capriweg	17	485	16	192	115771	492482
6	Sont- en Bosporushaven	19	542	0	232	116421	490842
7	Suezhaven	22	628	0	269	116464	490063
8	Usselincxhaven	18	514	0	220	117618	491841
9	Jan van Riebeeckhaven	11	314	0	135	118062	491556
10	Petroleumhaven	9	257	0	110	118818	491612
11	Coenhaven	11	314	0	135	119529	491313
12	Nieuwe Houthaven	20	571	0	245	120355	490801
13	Minervahaven	9	257	0	110	120004	490590
14	Mercuriushaven	37	1056	0	453	119349	490217
15	Houthaven	8	228	0	98	120832	489855
16	Het IJ Midden	7	200	0	86	122054	488208
17	Het IJ Oost	10	285	0	122	123739	488222
18	Noordzeekanaal	6	171	0	73	111589	493751

Table A.3: Demand characteristics of Port of Amsterdam

β_R (-)	9	
β_{sto} (-)	90	
DO (hrs/day)	12	
dr (-)	0,035	
PX (m)	99972	
PY (m)	498454	
OX (m)	115975	
OY (m)	492697	
	barge (s=1)	truck (s=2)
TF_s (-)	1,4	1,4
FP_s (€/L)	0,445	0,97
DW_s (€/hr)	80	20

Table A.4: Port specific input data

				LH2		GH2		NaBH4	
j	**Refueling Stations**	x_j	y_j	$RCAP_j$	RCC_j* **(M€)**	$RCAP_j$	RCC_j **(M€)**	$RCAP_j$	RCC_j **(M€)**
1	Trawlerkade	100824	497121	20	6,0	6,4	2,2	300	16,5
2	Amerikahaven Titan LNG	113228	492979	20	6,0	6,4	2,2	300	16,5
3	Zaanstad Zijkanaal G	117462	493226	20	6,0	6,4	2,2	300	16,5
4	Het IJ Reinplus	124905	488567	20	6,0	6,4	2,2	300	16,5
5	Slurink	125656	487431	20	6,0	6,4	2,2	300	16,5
6	Fiwado	125715	487122	20	6,0	6,4	2,2	300	16,5
7	C. Douwes-Kanaal West	120146	491429	100	19,3	32	6,3	1500	83,3
8	Nieuwe Zeehaven	116069	493104	100	19,3	32	6,3	1500	83,3

Table A.5: Refueling station input parameters.

					Production					
plant size, m	1	2	3	4	5					
$PCAP_m$	9,5	150	300	450	600	*ton/day*				
PCC_m	51,3	557,4	1114,8	1672,2	2229,6	*M€*				
PSC_m	20,5	223	445,92	668,88	891,84	*M€*				
UPC_m	4,27	3,15	3,15	3,15	3,15	*€/kg*				
					Storage					
storage size, n	1	2	3	4	5	6	7	8	9	
$SCAP_n$	9,5	150	540	1080	2160	4320	8640	12960	17280	*ton*
SCC_n	4,2	28	103	206	412	824	1648	2472	3296	*M€*
SSC_n	1,7	11,1	41,2	82,4	165	330	659	989	1318	*M€*
USC_n	0,027	0,0084	0,0042	0,0042	0,0042	0,0042	0,0042	0,0042	0,0042	*€/kg/day*
					Refueling Stations					
URC^*	0,0084	*€/kg/day*								
					Transport					
transport type, u_s	barge	LH2 tanker truck								
b_{us}	106	4	*ton*							
IV_{us}	10.000.000	420.000	*€*							
SV_{us}	4.000.000	168000	*€*							
ME_{us}	0,082	0,082	*€/km*							
FE_{us}	0,46	2,3	*km/L*							
BHF	1		-							

Table A.6: Liquid hydrogen input parameters.

					Production					
plant size, m	1	2	3	4	5					
$PCAP_m$	9,5	150	300	450	600	*ton/day*				
PCC_m	39,9	433,2	866,5	1299,7	1339,6	*M€*				
PSC_m	15,9	173,3	346,6	519,9	535,8	*M€*				
UPC_m	3,68	2,72	2,72	2,72	2,72	*€/kg*				
					Storage					
storage size, n	1	2	3	4	5	6	7	8	9	
$SCAP_n$	9,5	150	540	1080	2160	4320	8640	12960	17280	*ton*
SCC_n	3,3	21,5	80,1	160,1	320,2	640,5	1280,9	1921,4	2561,9	*M€*
SSC_n	1,3	8,6	32,0	64,0	128,1	256,2	512,4	768,6	1024,7	*M€*
USC_n	0,0236	0,0073	0,0037	0,0037	0,0037	0,0037	0,0037	0,0037	0,0037	*€/kg/day*
					Refueling Stations					
URC^*	0,0073	*€/kg/day*								
					Transport					
transp. type, u_s	barge	LH2 tanker truck								
b_{us}	35	0,181	*ton*							
IV_{us}	7.770.000	326.000	*€*							
SV_{us}	3.108.000	130000	*€*							
ME_{us}	0,082	0,082	*€/km*							
FE_{us}	0,46	2,3	*km/L*							
BHF	1		-							

Table A.7: Gaseous hydrogen input parameters.

Production

plant size, m	1	2	3	4	5	
$PCAP_m$	9,5	150	300	450	600	*ton/day*
PCC_m	57	614	1229	1843	2457	*M€*
PSC_m	23	246	491	737	983	*M€*
UPC_m	1,35	1,00	1,00	1,00	1,00	*€/kg*

Storage

storage size, n	1	2	3	4	5	6	7	8	9	10	11	
$SCAP_n$	9,5	150	540	1080	2160	4320	8640	17280	34560	51840	69120	*ton*
SCC_n	1,2	8,0	30	60	120	239	479	957	1915	2872	3830	*M€*
SSC_n	0,5	3,2	12,0	23,9	47,9	95,7	191,5	383,0	765,9	1149	1531,9	*M€*
USC_n	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	8,40e-7	*€/kg/day*

Refueling Stations

URC^*	8,40e-7	*€/kg/day*

Transport

transp. type, u_s	barge	LH2 tanker truck	
b_{us}	650	25	*ton*
IV_{us}	1.500.000	25.200	*€*
SV_{us}	600.000	10.080	*€*
ME_{us}	0,082	0,082	*€/km*
FE_{us}	0,46	2,3	*km/L*
BHF	4,86		-

Table A.8: Sodiumborohydrate (NaBH4) input parameters.

B

Appendix B: Port Basin Division

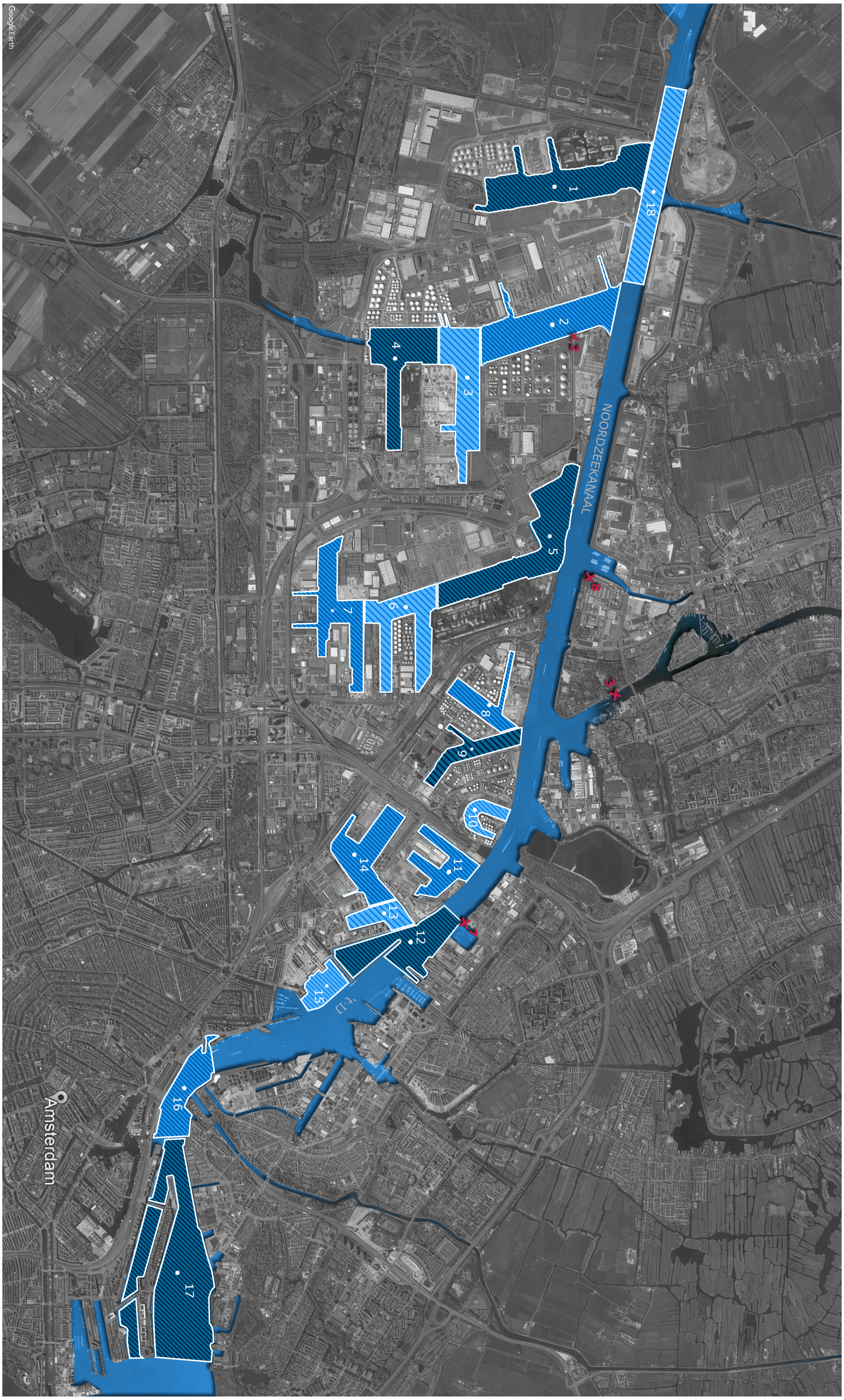


Figure B.1: Port of Amsterdam map with chosen basin division and refueling station locations.

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