# Design of a waterborne construction logistics system for quay wall renovations in Amsterdam

C.P.G. van der Storm


TU Delft

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by

C.P.G. van der Storm

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| Student number: | 4260821 | |
| Thesis committee: | Prof. dr. ir. L. A. Tavasszy, | TU Delft, supervisor |
| | Dr. B. Atasoy, | TU Delft |
| | Ir. M. W. Ludema, | TU Delft |



TU Delft Delft University of Technology

Gemeente Amsterdam

# Preface

Living on the Herengracht in Amsterdam, I am daily confronted with renovation of Amsterdam's quay walls. I have seen up close how complicated this process is and how stressful it can be for the city. In the next few years, 200 kilometers of quay walls must be renewed in Amsterdam while with the current method, 500 - 2000 meters of quay walls are renovated per year. It came to my thought that a study of this subject might be an interesting subject of my thesis. Particularly, because with this subject my two study backgrounds, Bachelor Civil Engineering and Master Transport, Infrastructure & Logistics would perfectly come together.

In consultation with the Municipality of Amsterdam, the topic of my thesis "the design of a waterborne construction logistics system for quay wall renovations in Amsterdam" was chosen. Municipality of Amsterdam granted me access to all data relevant to this topic and put me in contact with different parties involved with the topic. I held interviews with stakeholders and gathered valuable information from them. Hereby, I would like to thank all stakeholders who took the time and effort to speak to me and explain their way of working. It was also important to attend, on a weekly basis, the "studentenuurtje" of the Municipality of Amsterdam. The feedback and input from supervisors and fellow students, more specifically from Jerry Gerges Tadrous, has been very helpful. I would like to express my gratitude to the Municipality of Amsterdam for giving me the opportunity to do my graduation research there.

Halfway through my thesis, I received an offer to join Coolblue as a logistics process engineer. Although I realized even then that this might not be wise until I had completed my thesis, this company and this position suited me so well that I took the step. Having a full-time job did cause a delay in completing my thesis. The fact that I eventually managed to complete the thesis is also thanks to Coolblue and my manager Rocío Cornelissen who gave me the opportunity and time to complete this project. Thank you for that. Additionally, I would like to thank my Coolblue colleague, Dirk van Overbeek, for the fresh perspective he had on the model.

But my greatest and special thanks and gratitude goes out to the graduation committee. As said, it was a long process, but the members of the committee remained involved and willing to help me and provide feedback. Their support and trust has been of indescribable value.

First of all, I would like to thank from this committee Marcel Ludema for the intensive and personal guidance throughout my thesis and for pointing me in the right direction during our several meetings. Marcel's expertise of construction logistics has brought my thesis to a higher level. Second, I would like to thank Lori Tavasszy, as chairman of the committee. His critical view on logistics systems in general gave me different insights each time. Lastly, I would like to thank Bilge Atasoy for the constructive feedback on my work which helped me deepen my thesis. This would not have been possible without the insight, guidance and patience of the graduation committee throughout the entire process.

My last thanks goes to my family and friends for their interest and support and confidence during this thesis phase. A special thanks to my friends who kept on motivating me, and my parents and Bas, my boyfriend, for the support during the last mile.

I hope you enjoy reading this thesis and hope that its contents will contribute to a more efficient and faster renovation of quay walls in Amsterdam that is less burdensome to the city and its inhabitants.

*Geraldine van der Storm*
*Amsterdam, July 2023*

# Executive summary


Urban areas cope with a growing demand for construction and renovation works. Approximately 30% of all urban freight transport is caused by construction related movements, having large impact on the cities in terms of nuisance, emissions, landscape degradation and safety for instance. Therefore the logistics of these construction projects, referred to as construction logistics, for transporting material, equipment and personnel is becoming increasingly important. The city of Amsterdam is an example of a city that needs to cope with this nuisance caused by construction logistics.

An additional problem that arises for the Municipality of Amsterdam is the fact that around 200 kilometres of quays need to be renewed in the upcoming years. Since these are large infrastructural projects, an enormous extra amount of movements through the city for the supply of material and discharge of waste can be expected in addition to the earlier mentioned 30% of construction related movements. This calls for a different approach in the form of executing construction logistics via water instead of road. Quays are already located on the water front and due to lack of space most construction sites need to be on the canals as well. Waterborne construction logistics might be a logical solution, but both the Municipality of Amsterdam as other users of this new system have no insight into what it entails and what the consequences are compared to road transport and to configuration changes in the waterborne system.

The main objective of this thesis project is to provide a solution to the problem mentioned above as follows: *To design a waterborne construction logistics system for quay wall renovations in the inner city of Amsterdam and to provide insight into the consequences of this system.*

For this thesis project an adapted version of the basic design cycle of Roozenburg and Eekels (2002) was used as a basis for designing the waterborne construction logistics system. From the design several waterborne construction logistics alternatives have been deducted and for these alternatives the expected consequences are stated. In order to give the users of the system more direction in their decisions, also a decision support tool is designed in this thesis project which will quantify the consequences of using a waterborne construction logistics system. This additional design cycle is therefore integrated in the design cycle of this thesis project.

Firstly a background study has been performed to gather sufficient information and knowledge to start designing. For the background study, desk and literature research is executed and interviews are being held with experts in the field. First of all, it is important to consider that seven material types can be distinguished for an average quay wall renovation project, which are dry bulk material, palletised material, prefab elements, long materials, machinery and equipment, liquid bulk material and miscellaneous. These categories have such different specifications with respect to transportation needs that they all follow a different logistics flow and is therefore leading in determining the used waterborne construction logistics alternative. It is important to state that for the supply streams more than 40% consists of dry bulk material and for the discharge streams, which is of comparable size to the supply streams, more than 98% consists of dry bulk material. This is therefore the most important material type to focus on, and therefore chosen as baseline in this thesis project.

From desk research and expert interviews the performance indicators of interest for the different stakeholders and the potential drivers and barriers of using a waterborne construction logistics system have been derived. The most important drivers are improved conditions in the city, such as less movements, load on cultural heritage, vehicle kilometers driven, emissions and other nuisance. Also the construction project efficiency can improve through better accessibility of the construction site and less time pressure on the construction site. The most important barriers are mostly related to the impact on the canals like the effects on water traffic, such as one-way water traffic, fairway profiles and the unknown impact on other water users. Other barriers are a lack of clear policy on this new way of transportation, limited fleet possibilities and most importantly the expected increase in logistics cost. From the drivers, barriers and named indicators by stakeholders, the indicators of interest for stakeholders are reshaped into logistics parameters, which are

the key performance indicators (KPIs) of this thesis project, which are the total logistics cost, consisting of transport, handling and storage cost, the amount of vessel movements, the amount of vessel kilometres and the amount of tonnes kilometres.

In the final part of the background study the present infrastructure and logistics elements that influence the design of the waterborne construction logistics system have been analysed and will serve as building blocks. These building blocks are separated into two pillars; transport elements and handling and storage elements. Elements that need to be considered for the transport elements are fairway and capacity profiles on the canals restricted by laws and regulations of the Municipality of Amsterdam. Also, a wide variety of transport types and fuel types are listed that are available or might become available in the near future. Examples are using hopper and deck barges with a tugboat, but also making use of self-propelled barges with mounted cranes are considered as transport options. For the handling and storage elements it is stated that nine hub locations are available in the Western port area of Amsterdam where transshipment activities can take place. Also, handling equipment is listed that corresponds to the earlier mentioned material types and load carriers that are available.

While keeping the building blocks in mind, the design of the waterborne construction logistics system have been made. For this, functional and non-functional requirements were generated based on an extensive background analysis that form a base for the design. Important requirements are for example that the system must be able to transport and handle all mentioned material types and that it must comply with water traffic regulations. The design architecture is eventually created by setting up the functions of the waterborne construction logistics system. These are the separate steps of the transport chain in which the material follows a path from supplier to the end location. These functions are then placed in a morphological chart and with brainstorming for every function possible means are added. The functions that are chosen are listed below.

- Material type
- Transport type
- Load carrier
- Handling equipment
- Vessel load
- Fuel type
- Storage type
- Material type return flow
- Load carrier return flow

For every element, or function, in this thesis project, multiple choices can be made, which are stated in the morphological chart. Bases on choices made from the means in morphological chart, keeping in mind that there are interdependencies between functions and means, physical design alternatives can be generated.

Finally, one baseline and three design alternatives are generated and presented as a physical design alternative with corresponding expected consequences. Dry bulk material is chosen as the material type of interest in the course of this thesis project. The baseline is chosen as the most plausible scenario of the waterborne construction logistics system. For this baseline it is chosen that a hopper barge is tugged by a tugboat. The hopper barge can carry 80 tonnes of material and has an average loading rate of 75%. Also, for this baseline scenario, it is assumed that all material will be stored on site for either up to one or up to three days.

The three design alternatives and their most important characteristics are:

- **Self-propelled electrical barge with mounted crane**: No tugboat needed for this alternative. Also, the handling equipment is attached to the vessel.
- **Just-in-time delivery**: To investigate the trade-off between transporting large amount of materials (60 tonnes) that need to be stored at site and transporting smaller loads (27 tonnes) that can be used right away.
- **Use skips as storage location**: Faster handling on site by using three large skips instead of dry bulk that needs to be handled per cubic meter. Drawback is the weight and size restriction, meaning a maximum of 36 tonnes can be transported per shipment.

These consequences will be calculated by a decision support tool. The model designed uses Excel as a tool to calculate the consequences of choosing different design alternatives compared to the baseline scenario and compared to the conventional way of transport, via road.

When we compare the calculated consequences derived from the decision support tool to the expected consequences of the design alternative, the following takeaways are of importance. For all alternatives the amount of vessel movements is larger than for the baseline scenario. This has significant impact on the total transport cost and thus for the total logistics cost it is always more advantageous to increase the volume a vessel can transport. What can also be seen is that the transport and handling cost for Just in Time deliveries do not outweigh the additional cost for storage on site. It is therefore recommended to use the transport type as temporary storage location as long as the fleet has sufficient capacity.

Also, the decision support tool provides the option for users to compare one of the waterborne construction logistics system alternatives to a road scenario. From this can be concluded that using waterborne construction logistics is always preferred over road transport with respect to the amount of movements (80% average decrease) and the amount of vehicle/vessel kilometres (79% average decrease). The amount of tonkilometres is the same for both modalities as long as the travelled distance to and from the construction site is the same. In this thesis project it is assumed that trucks always take the shortest route in terms of kilometres. When trucks during congestion take the shortest routes in terms of time, the amount of tonkilometres for road transport will increase significantly. When we look at the total logistics cost, which is a summation of the total transport cost, total handling cost and total storage cost, it can be concluded that when vessels structurally carry 81.9 tonnes on average per shipment, the total logistics cost for waterborne transport become lower than for road transport.

The total logistics cost of the waterborne construction logistics system is most sensitive to changes in vessel load and vessel speed. The larger the average load transported to and from the construction site, the fewer vessel kilometres are travelled, which has an enormous impact on the cost. Especially for lower average vessel speed (less than 8 kilometres per hour), the total logistics cost increase exponentially. It is not investigated in this thesis project how an increase in vessel load relates to the possible vessel speed. Therefore it is recommended for the Municipality of Amsterdam is to investigate the optimal trade-off value between the average vessel load and vessel speed. Another important finding is that since the weight of the transported material is normative over volume and the amount of tonnes has significant impact on the KPIs, the Municipality should try to stimulate constructors to use as less and light material as possible for the renovation works.

Based on assumptions and scoping decisions in this thesis project, the most important recommendations for further research are as follows. Firstly, this thesis project focused on the conventional construction methods for quay wall renovations whilst it might be interesting to investigate and integrate innovative construction methods in the designed waterborne construction logistics system. The inventory cost of holding construction material in the entire supply chain are not taken into account in this thesis project, since this is uncoordinated within construction logistics and mostly performed on an ad hoc basis. However, it could be interesting to calculate the trade-off between storing at the construction site versus on the hub. Finally, it is recommended to study how the fluctuating construction material demand over the project duration has impact on the output parameters.

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# 1
# Introduction

## 1.1. Problem background

Due to urban population growth worldwide, the demand for construction and renovation works has increased in cities (van Amstel, van Merriënboer, & Balm, 2015). The construction industry is an industry that is essential in creating infrastructures that contribute to more sustainable, attractive and economically viable urban areas that are needed to cope with the increasing amount of residents (van Amstel et al., 2015). But in the process of creating these areas in cities, construction also has its negative impact on the environment, since a lot of materials and equipment are utilised and huge amounts of waste are generated (Shakantu, Muya, Tookey, & Bowen, 2008). This results in large quantities of construction related transport movements, mostly performed by truck, in and around city centers, which cause in their turn congestion, road accidents, CO2 emissions and other air pollutants, noise nuisance and landscape degradation (Shakantu et al., 2008).

## 1.2. Current situation construction logistics

During this thesis project, the following definition for construction logistics, stated by van Amstel et al. (2015), is used: "the scope of construction logistics concerns all supply and disposal shipments of building materials, construction equipment and construction personnel to and from the construction site (van Amstel et al., 2015)". According to van Amstel et al. (2015), research showed that 18% of heavy weight trucks and 43% of light commercial vehicles in Amsterdam are construction related, which does not even include waste generated by construction activities. These vehicles cause several issues in the city center of Amsterdam and also for actors involved in construction projects.

Construction related trucks and vans are responsible for approximately 30% of all urban freight transport, resulting in a large amount of vehicle movements and vehicle kilometres travelled in the city center. This results in congestion in the city with its corresponding consequences, but it also induces queuing lines and late deliveries of material and equipment at construction sites, which has a negative impact on the efficiency of construction projects. This in its turn causes longer project duration and hence more construction related movements. Additionally, most trucks and other construction vehicles and equipment are powered by diesel or other fossil fuels, which cause negative effects on the environment. Due to the large amount of construction vehicles moving through the city and queuing near the construction site, increase in $CO_2$-, $NO_x$ and $PM_{10}$-emissions can be expected, next to noise hindrance for residents.

Construction projects require large amounts of materials and thus heavy vehicles. These heavy vehicles not only pose a threat to other road users and have their impact on safety, but they also place a heavy burden on the current infrastructure of the city center. As a consequence, this has led to a decrease in lifetime of quay walls, side structures and bridges of the Amsterdam canals. Together with deferred maintenance of bridges and quays throughout the past decades, these heavy loads cause sinkholes, settlements of parking spots, cracks and in worst case scenario even collapse of quay walls or bridges.

### 1.2.1. Quay wall and bridge renovation projects

As stated above, the quays and bridges of the city of Amsterdam are in need of replacement. At this moment, the municipality of Amsterdam has no specific planning for the coming five or ten years, but there are some quays and bridges that did receive a status already. In Figure 1.1 construction works that are scheduled (red), ongoing (blue) and finished (green) are visible on the map of Amsterdam. Bridges on this map are indicated with dots, whereas quays are indicated as lines.

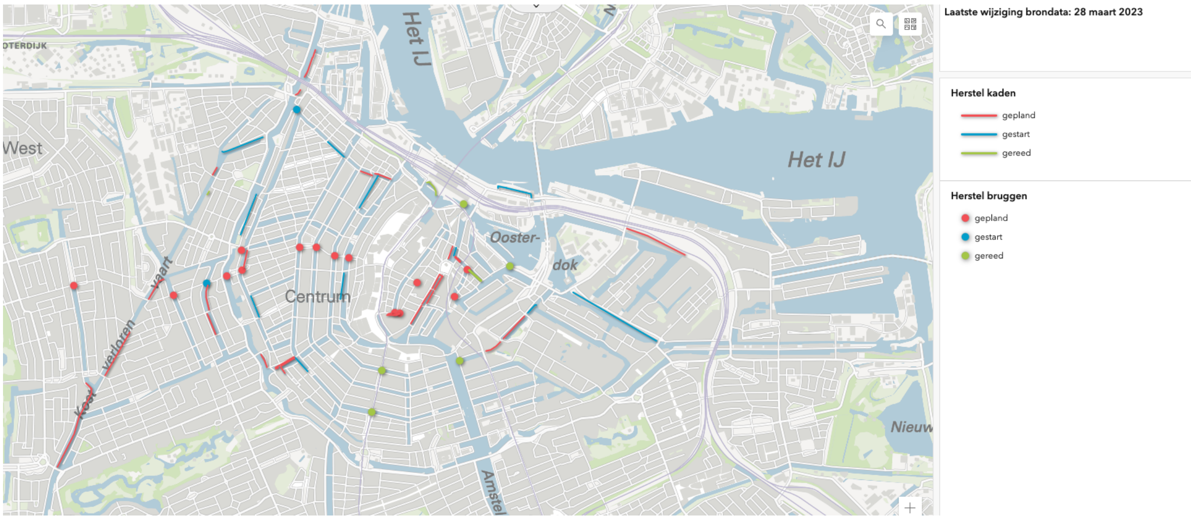



Figure 1.1: Planned, ongoing and executed quay wall renovations in Amsterdam (Gemeente Amsterdam, 2023a)

When we look at the quay walls in scope of this program (see Figure 1.2), the majority of the renovation projects are located in the city center of Amsterdam within the area inside the ring road S100, also known as the historical city center of Amsterdam. Since this is the oldest part of the city, it is a logical consequence most quays are in need for a reconstruction and therefore in this thesis project the attention goes to quay wall renovations in this specific area.

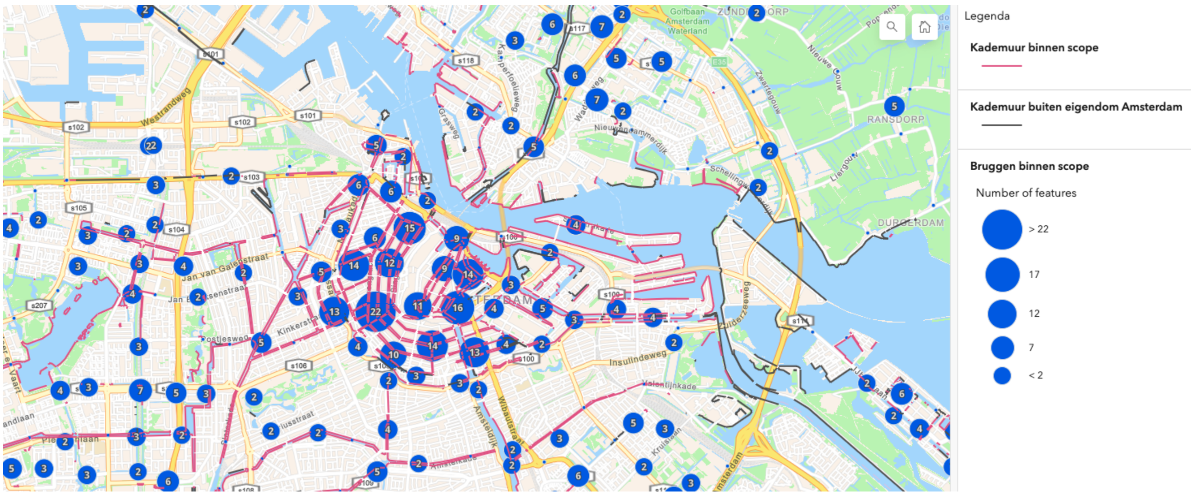



Figure 1.2: Quay walls in scope for renovations in Amsterdam (Gemeente Amsterdam, 2023a)

Amsterdam faces a major challenge to restore the bridges and quays in the city. Program Bridges and Quays of the municipality of Amsterdam (Gemeente Amsterdam, 2020c) focuses on 829 traffic bridges and approximately 200 kilometres of quay walls founded on deep soil layers, which are the structures that are important for the functioning of the city or whereby the risks of constructive defects are estimated to be high. Currently, the municipality of Amsterdam is renewing an average of 500 meters of quay walls and one bridge per year. The ambition is to achieve a renewal of two kilometers of quay wall and six to eight bridges per year from 2024 onwards. A large share of these constructions are located in the historic city center, which will place the Municipality of Amsterdam for a large and complex task to organize. It will take many years, a lot of stakeholders are involved and it causes more undesirable construction related movements towards the city center. But it also offers opportunities for the future, since it provides space for sustainability initiatives. These initiatives can be applied to urban planning, such as renewal and greening of quays and streets to provide more space for cyclists and pedestrians. Moreover, it is a window of opportunity for the encouragement of waterborne transport of freight in the city and for the use of the current infrastructure the way it was invented for, namely logistics purposes.

Especially for construction logistics related to these quay wall and bridge renovation projects, it is a logical step to encourage transport of materials and equipment via waterways instead of the road. A reason why this would be a convenient way of transport for this specific type of construction projects, is the fact that all construction sites are located on the water front. Therefore it is expected that no additional last mile shipments on the road need to be executed. Additionally, the storage areas of these renovation works are often limited and a possible solution could be the usage of push barges as storage platform during construction activities.

The large amount of construction material and equipment that need to be transported to the quays would previously always be transported by the conventional way of construction logistics, namely via road. Road transport currently is the most used modality for construction related transport movements in Amsterdam, which can be explained by inexpensiveness, maneuverability and fear of innovation.

With the addition of waterborne transport options to the system, the transport chain will change and a schematic overview is shown in Figure 1.3. In this new configuration, it is possible to ship directly to the construction site by smaller vessels. But it is also possible to use a hub or construction consolidation center that can transship material and equipment from road to water transport carriers, but also from large barges to smaller vessels.

A construction consolidation center or hub that is seen on the upper part of the transport chain, is primarily utilized for distribution, with material deliveries being aggregated and disseminated to a single construction site or a group of sites (Lundesjo, 2011). This is in contrast to the traditional method of delivering building materials, which involves suppliers and carriers delivering directly to the job site (de Bes et al., 2018). A hub is a proven convenient (Balm, Berden, Morel, & Ploos van Amstel, 2018) construction materials delivery facility on the outskirts of town, close or at a construction site. The objective of a hub is to receive, store, inspect, and transport construction materials in a well-organized manner for building sites (de Bes et al., 2018). Especially with the introduction of waterborne construction logistics, these hubs might become more popular when it can facilitate transshipment to all sorts of vessel types that can carry construction material to and from the sites.

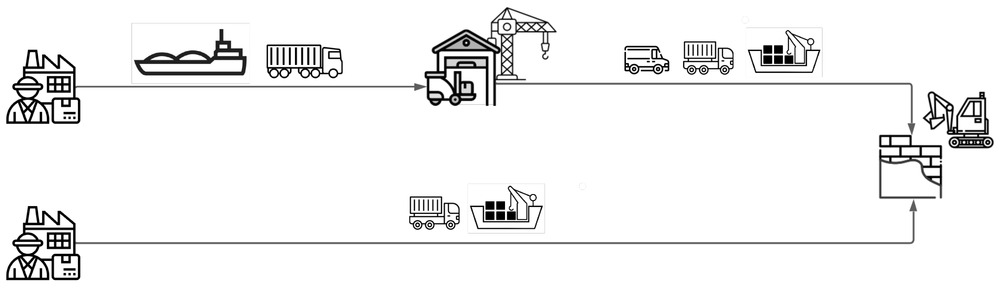


Figure 1.3: Quay wall renovation transport chain including waterborne options

## 1.3. Problem definition

Since very little literature is available regarding a waterborne construction logistics system and the consequences resulting from this initiative, a need for more insight into the consequences of using a waterborne construction logistics system arises for key stakeholders and other users of the system. Stakeholders are holding back from the concept of transport over water, which is mostly caused by expectations that are never proven to be right. Apart from the fact that they are not aware of the impact of transport over water on current situations, users of the system are often not aware of the metrics belonging to their current way of working as well. Stakeholders often do not have an overview of the performance of construction logistics based on the chosen transportation mode for supply and discharge of materials and equipment, which can be explained by the fact that within the construction industry, data are not always gathered and shared. This results in the fact that decision makers are not able to take well-considered decisions about the potential shift from road transport to waterborne transport. Therefore, also the need for a decision support tool arises that can quantify the consequences of using transport over water based on criteria of interest. Expectations are that the amount of movements will decrease significantly as will the corresponding effects on the city such as emissions, noise hindrance and accidents, which are part of a big social cost benefit analysis for the Municipality. An expected drawback of waterborne construction logistics is an increase in logistics cost due to higher operational and storage cost. This paper focuses on providing insight into the consequences of waterborne construction logistics on a project level, but it should be clear that the potential additional cost for transporting over water need to be balanced against the social benefits such as saved cost for traffic deaths, increased health of residents and accessibility of the city.

### 1.3.1. Experience from use cases

Amsterdam Vaart! is a project executed by a consortium consisting of the Port of Amsterdam, research institute TNO, water company Waternet and the Municipality of Amsterdam. The objective of this collaboration is to support and monitor construction projects in the city of Amsterdam in order to achieve a modal shift from road to waterway transport. During the chosen construction projects with construction logistics via waterways, two of which quay wall renovation projects, all transport flows are monitored and afterwards compared to the reference scenario where all construction logistics shipments are performed by road transport. On the basis of the first phase of this research (van Rijn, 2020) it can be concluded that in most cases vehicle movements and vehicle kilometers will decrease on total project duration. In addition, in certain cases it is also seen that there is a reduction in CO2 emissions when using waterborne transport. This study of van Rijn (2020) and underlying research investigates the consequences of using a waterborne construction logistics system, but also provides an overview for all sorts of construction projects, removing the focus from the very urgent problem of quay wall renovations in the upcoming years. This thesis project will focus on the definition of a waterborne construction logistics system specifically for quay wall renovation projects, since these projects have great potential for successful logistics over water. Amsterdam Vaart! provides insight into expected consequences of the waterborne system based on an expectation overview of all material movements of the project, whereas this thesis project will give a more high over view on the consequences before definition of the exact amount of expected vessel or truck movements.

## 1.4. Thesis project objective

Based on the problem definition described above and need from a stakeholder perspective, the main objective of this thesis project can be described as follows:

- *To design a waterborne construction logistics system for quay wall renovations in the inner city of Amsterdam and to provide insight into the consequences of this system*

The main objective can be divided into the following sub-objectives:

- To perform an analysis to define the consequences of using waterborne construction logistics specifically for quay wall renovation projects
- To define a system that incorporates waterborne transport for construction logistics in the city centre of Amsterdam

- To develop a model that can quantify and give insight into the consequences of using waterborne construction logistics specifically for quay wall renovation projects

In Section 2.1.1 the thesis project activities with both research questions as design objectives are mentioned that will contribute to reaching the main objective.

## 1.5. Scope and delimitation

The scope and delimitation of this thesis project will be summed up below:

- This thesis project will only focus on quay wall renovation projects, which means no bridge projects or other construction projects are taken into account. This can be explained by the fact that construction projects are often unique and therefore very complex to integrate in one system. In the case of quay wall renovation projects, the construction activities always take place on the water front, resulting in an opportunity to design a waterborne construction logistics system for these specific projects. Furthermore, for these projects the Municipality of Amsterdam is the principal of the project and can therefore influence decision making concerning a shift to waterborne construction logistics.
- Additionally, based on the planned quay wall projects for the coming years, only quay wall renovation projects within the historical center of Amsterdam are considered, which is inside the ring road S100.
- The thesis project will concentrate on the transportation of construction materials and equipment, but transport of personnel will not be taken into account.
- Only transportation via road and over water are considered in this thesis project, which means no other freight transport options are in scope.
- The focus of this thesis project is on the consequences of *waterborne* transport. In order to evaluate the consequences of performing construction logistics via water, several water scenarios will be compared with another. To make the evaluation complete, a high over comparison will be made with road transport. However, no extensive analysis has been performed on a road transport system, since the municipality of Amsterdam focuses on a complete shift to water transport for quay wall renovations
- The results from this thesis project are applicable for quay wall renovations, with the conventional way of reconstruction, that will be executed up to 2030. It is assumed that in the upcoming years no major technologies will be introduced and produced that can replace the complete vessel fleet of Amsterdam. The current infrastructure and fleet will be relevant until at least 2030, but after 2030 part of the fleet must be replaced due to the implementation of an emission-free area (Gemeente Amsterdam, 2019).
- Finally, the impact of additional construction related movements on current waterway users is not taken into consideration.

## 1.6. Outline of the report and deliverables

The deliverables of this thesis project consist of a presented design of the waterborne construction logistics system for quay wall renovation projects in Chapter 4. In addition, a decision support tool will be developed in Chapter 5 that quantifies the consequences of initiating waterborne construction logistics for quay wall renovations in Amsterdam. This tool can support actors in making decisions considering the waterborne construction logistics system, which will be explained in Chapter 6.

The outline of this thesis project is shown in Figure 1.4. A more detailed overview is incorporated in Figure 2.3 of Chapter 2.

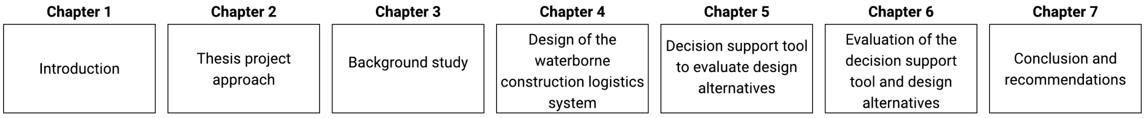



Figure 1.4: Thesis project outline

# 2

# Thesis project approach

In order to answer the research questions mentioned in Section 1, several methods will be used. For the development of the desired tool, the design steps are adapted from the basic design cycle of Roozenburg and Eekels (2002). The thesis project is divided in a qualitative and a quantitative part and the corresponding methods will be shortly discussed. In Section 2.1.1 the used methods will be shortly discussed.

## 2.1. Design methodology

As discussed in the introduction of Chapter 1 a need arises for the design of a waterborne construction logistics system for quay wall renovations and the corresponding consequences of this system. The main objective (MO) of this thesis project is therefore a design objective (DO) rather than a main research question (RQ) that needs to be answered and is as follows:

MO *To design a waterborne construction logistics system for quay wall renovations in the inner city of Amsterdam and to provide insight into the consequences of this system*

In order to meet this objective, a design methodology is chosen for the execution of this thesis project. As stated in Roozenburg and Eekels (2002) the basic design cycle of Roozenburg and Eekels (2002) is considered the most fundamental model of designing. Even though this design methodology is normally applied to product design, this basic design cycle is often used as a framework for the designing in general (Roozenburg & Eekels, 2002) and is therefore chosen as guideline for this thesis project. In Figure 2.1 a visualisation of the adaptation of the basic design cycle for this thesis project is shown, in which the most remarkable adjustment is the extra design loop for the development of a decision support tool. In the following subsections the different steps of the adapted basic design cycle are discussed. For every step is indicated which research questions are answered or design objectives are met. But firstly, an overview of the research questions and design objectives will be presented below as thesis project activities.

### 2.1.1. Thesis project activities

To meet the main objective, several research questions and design objectives are drafted. These questions and objectives, as stated below, contribute directly and indirectly to obtaining the thesis project objective. In Section 2.2, an overview shall be given of how the questions and objectives relate to the main objective of this thesis project.

RQ1 *What characteristics of a quay wall renovation project need to be taken into account for designing a waterborne construction logistics system?*

RQ2 *What are the performance indicators of interest for designing a waterborne construction logistics system and how do they influence the stakeholders of this system?*

RQ3 *What are the waterborne construction logistics building blocks that need to be considered in the design problem?*

DO1 *To design a waterborne construction logistics system for quay wall renovation projects.*

DO2 *To develop a decision support tool that can quantify the consequences of transport over water on relevant performance indicators.*

RQ4 *How can the decision support tool support decision makers in the shift to the waterborne construction logistics system?*

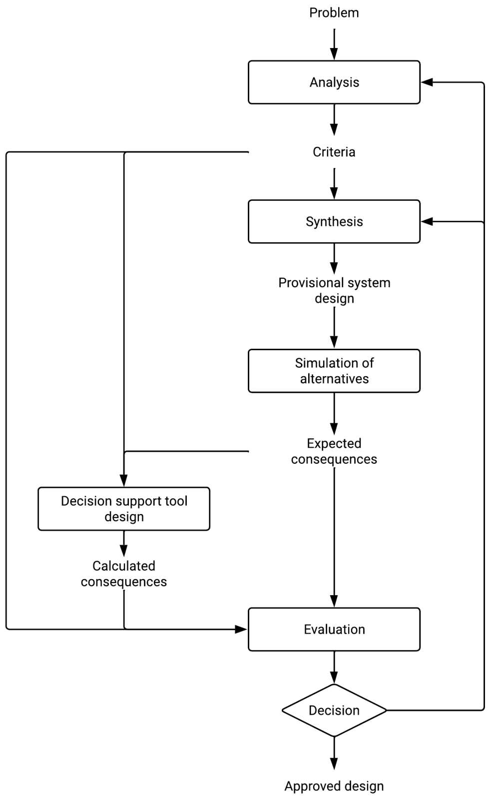



Figure 2.1: Thesis project design cycle. Adapted from (Roozenburg & Eekels, 2002)

### 2.1.2. Analysis

The goal of the analysis step is to get a deeper understanding of the thesis project problem by diving into desk research, including literature research, interviews with stakeholders and experts. From this, requirements and criteria can be deducted which will form a basis for the following design steps.

**Desk research**

First, a literature study is conducted to get a better understanding of the state-of-the-art of this topic. With help of this extensive literature study, the current state of the subject will be determined. Also, based on the literature and desk research, a quick stakeholder overview will be created in order to define relevant stakeholders for the interviews and corresponding relevant interview questions. Construction logistics applied to different use-cases and best practises will be evaluated. From these evaluations, part of the performance indicators for the evaluation of the waterborne construction logistics system can be identified.

**Expert interviews**

Based on the created stakeholder overview different stakeholders will be contacted for interviews. Interviews will include a variety of parties like the municipality of Amsterdam, (sub)contractors, research institutes, waterway users (passengers and freight), logistics providers and companies with innovative ideas for transportation via waterways. The aim of the interviews is to get a better understanding of the current situation on the canals, the preferences of stakeholders, and to finally determine and collect required data of planned construction projects and to add relevant performance indicators for construction logistics.

The interviews will be held in semi-structured form, which is usually used for data collection in qualitative research (Harvey-Jordan & Long, 2001). Preferably face-to-face interviews will be held, but due to Covid-19 measures during the course of this thesis project, online interviews are satisfactory as well. Since for the problem of this thesis project, success of implementation is highly related to stakeholder perspectives, qualitative research needs to be done first in order to determine data that can be used in a quantitative model. An overview of interviewees can be found in Table 2.1.

Table 2.1: Interviewees overview

| # | Role | Institution |
|---|---|---|
| 1 | Head innovation & development, Programme Bridges & Quays | Gemeente Amsterdam |
| 2 | Project manager 'Vernieuwingsopgave Kademuren' | Gemeente Amsterdam |
| 3 | Assistant project manager 'Vernieuwingsopgave Kademuren' | Gemeente Amsterdam |
| 4 | Project manager 'Innovatieparnerschap Kademuren' (IPK) | Gemeente Amsterdam |
| 5 | Project manager | Gemeente Amsterdam |
| 6 | Programma manager 'Programme Bridges & Quays' | Gemeente Amsterdam |
| 7 | Environment manager | Gemeente Amsterdam |
| 8 | Strategic advisor Programme Bridges & Quays, Programma Varen | Gemeente Amsterdam/Royal Haskoning DHV |
| 9 | Senior policy advisor logistics | Gemeente Amsterdam |
| 10 | Senior project manager Quay wall renovation Herengracht 1-103 | Gemeente Amsterdam |
| 11 | Amsterdam Vaart! project manager | Gemeente Amsterdam |
| 12 | Program manager (future) waste solutions city center Amsterdam | Gemeente Amsterdam |
| 13 | Junior manager | H. van Wijk |
| 14 | Program manager research | AMS Institute |
| 15 | Project coordinator Roboat | AMS Institute |
| 16 | Founder | ZOEV City & PK Waterbouw |
| 17 | Project lead Amsterdam Vaart! | Port of Amsterdam |
| 18 | Consultant Logistics, responsible for Amsterdam Vaart! calculation tool | TNO |
| 19 | Commercial manager | Van Keulen Hout en Bouwmaterialen |
| 20 | Manager logistics | Bouwbedrijf de Nijs |
| 21 | Assistant Professor, research into using the urban waterways of Amsterdam for city logistics | Delft University of Technology |

Based on the conducted literature study, desk research and interviews, at the end of the analysis phase the answered to the following research questions can be given.

RQ1 *What characteristics of a quay wall renovation project need to be taken into account for designing a waterborne construction logistics system?*

RQ2 *What are the performance indicators of interest for designing a waterborne construction logistics system and how do they influence the stakeholders of this system?*

RQ3 *What are the waterborne construction logistics building blocks that need to be considered in the design problem?*

The analysis performed to answer these three research questions are presented in Chapter 3. An important deliverable from this design step, is the overview of relevant evaluation criteria, which will be used for the evaluation of the design alternatives and the development of the decision support tool, as can be seen in Figure 2.1.

### 2.1.3. Synthesis

**Morphological chart**

Roozenburg and Eekels (2002) state that one of the creativity techniques for coming up with conceptual designs is making use of a morphological chart. A morphological chart, in essence, is a table of functions and solutions for each function. Normal convention is to list the functions in a column in the left hand side of the table, and list the solutions to each function to the right of the function. Various terms exist for these solutions. Dym and Little use the term "means" (Dym, 2013), Suh (Suh & Suh, 2001) uses "design parameters" for software design and Beitz, Pahl, and Grote (1996) use a term which can be translated to "working principles". In this thesis project, the names components and means are used for the construction of the morphological design, which will appear as the table shown in Figure 2.2.

| Functions | Means | | | | |
|---|---|---|---|---|---|
| $F_1$ | $M_{1.1}$ | $M_{1.2}$ | $M_{1.3}$ | ... | $M_{1.m}$ |
| $F_2$ | $M_{2.1}$ | $M_{2.2}$ | $M_{2.3}$ | ... | $M_{2.m}$ |
| $F_3$ | $M_{3.1}$ | $M_{3.2}$ | $M_{3.3}$ | ... | $M_{3.m}$ |
| ... | ... | ... | ... | ... | ... |
| $F_n$ | $M_{n.1}$ | $M_{n.2}$ | $M_{n.3}$ | ... | $M_{n.m}$ |

Figure 2.2: Principle of morphological chart (Smith, 2007)

For this thesis project the morphological chart will be filled with listing the sub-functions of the waterborne construction logistics system in the first column. For this step, a functional and requirements analysis will be performed, where it is important to keep the sub-functions as independent of each other as possible to generate the means (Börekçi, 2018). For the generation of the means of the system, brainstorming will be used to define all possible means per subfunction. These are mostly physical elements, or building blocks, as defined in Chapter 3.

With the construction of the morphological chart, the provisional design of the waterborne construction logistics system for quay wall renovations is defined and the first design objective is reached:

DO1 *To design a waterborne construction logistics system for quay wall renovation projects.*

### 2.1.4. Simulation of alternatives

Finally from the morphological chart, final design alternatives will be generated by challenging them to the requirements. These design alternatives are not the only solutions of this design cycle, but these will be the alternatives used for further evaluation of the waterborne construction logistics system.

Subsequently, the design alternatives will be presented in visual form, called the physical design alternatives. Next to a visualisation of the alternatives, an extensive description of the expected consequences per design alternative are discussed.

### 2.1.5. Decision support tool design

The following step of the design cycle, is the development of a decision support tool. As stated in the main objective of this thesis project, a need arises for insight into the consequences of the waterborne construction logistics system. To meet the design objective:

DO2 *To develop a decision support tool that can quantify the consequences of transport over water on relevant performance indicators.*

A quantification of the potential consequences will be generated through the development of a decision support tool. It is important to make sure the decision support tool can be applied to all possible design alternatives in order to evaluate and validate the system outcomes. For this decision support tool, it is chosen to use the Activity based costing approach (Fang & Ng, 2011) for the quantification of consequences of the design alternatives. The deliverable of this design step are calculated consequences of the design alternatives.

### 2.1.6. Evaluation

During the evaluation of the design cycle, the calculated consequences of the design alternatives from the waterborne construction logistics system are compared with the expected consequences. For this step, trade-off and sensitivity analyses are used to gather more insight into the relations of the alternatives and system components. Since it is difficult to obtain reliable data within the construction industry, an existing case study is selected in order to validate the model. In addition, this section will give an answer to the last research question:

RQ4 *How can the decision support tool support decision makers in the shift to the waterborne construction logistics system?*

### 2.1.7. Decision

After the iterative process of the design cycle, the approved design will be presented together with a discussion on the results and recommendations for further research. In this section a final answer to the main thesis project objective will be given as well.

## 2.2. Design methodology overview

In Figure 2.3 an overview of the methodology of this thesis project, including used methods and answered research questions per design step is shown.

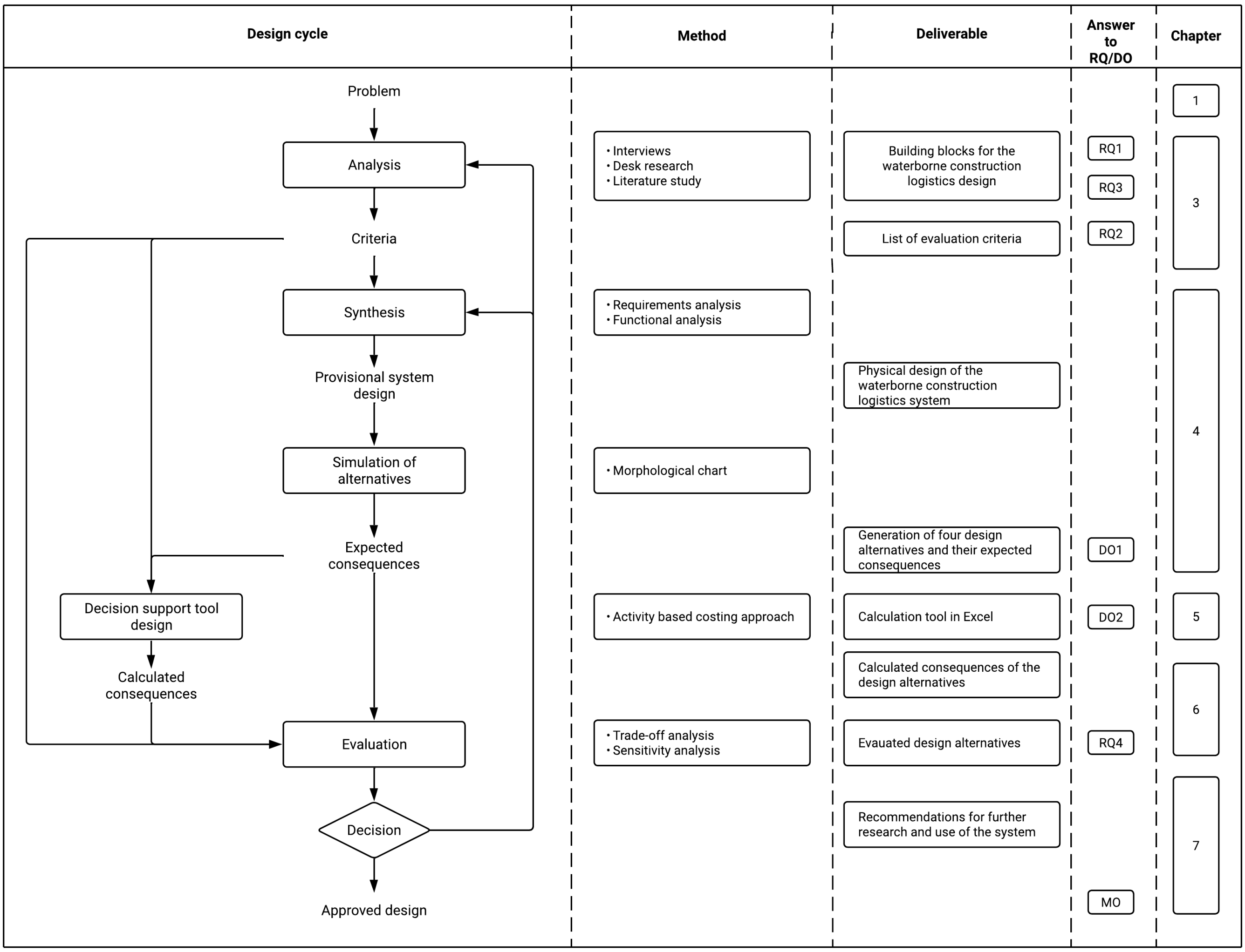



Figure 2.3: Design methodology used in this thesis project, including methods and deliverables per chapter

# 3
# Background study

In this chapter a background study will be performed in order to get a better understanding of quay wall renovation projects and the construction logistics requirements. Drivers and barriers for the to be designed waterborne construction logistics system will be discussed and finally the building blocks forming the base of the waterborne construction logistics system will be introduced. In this Section an answer will be given to the following research questions:

RQ1 *What characteristics of a quay wall renovation project need to be taken into account for designing a waterborne construction logistics system?*
RQ2 *What are the performance indicators of interest for designing a waterborne construction logistics system and how do they influence the stakeholders of this system?*
RQ3 *What are the waterborne construction logistics building blocks that need to be considered in the design problem?*

## 3.1. Background of construction logistics in urban areas

In this subsection, an overview is given of the consequences that executing the construction logistics of quay wall renovations via water instead of the conventional way of transport might incur. This Section starts with a brief introduction to construction logistics in cities. Subsequently, a literature study about research that already has been conducted on executing construction logistics over water and relevant consequences that need to be taken into account will be discussed. Hereafter the stakeholders for quay wall renovations specifically are analysed and potential consequences of a shift from road to waterborne transport will be elaborated upon.

### 3.1.1. Construction logistics

As earlier stated in Chapter 1 in this thesis project the following definition for construction logistics, stated by van Amstel et al. (2015), is used: "the scope of construction logistics concerns all supply and disposal shipments of building materials, construction equipment and construction personnel to and from the construction site (van Amstel et al., 2015)".

Construction logistics is a field that gets less attention and is less studied than other freight flows in urban areas and therefore transport related to construction is sometimes referred to as 'hidden' logistics (van Amstel et al., 2015). This can be explained by the fact that construction logistics do have some distinctive characteristics in comparison with movement of consumer goods or other sorts of freight. According to Balm et al. (2018) the distinctive character of construction logistics can be described as follows:

- Since every location of a construction project is unique and temporary, every construction project needs its own logistics setup. Besides, since construction activities happen on a project basis there is the possibility to plan them in advance based on certain requirements like required material and equipment and time constraints.

- Construction projects are material intensive (Quak et al., 2011), which often means that heavy vehicles or quite some light commercial vehicles corresponding to the volume are necessary for shipment. These large sized vehicles and the heavy loads could cause damage to infrastructure and could give an unsafe experience for pedestrians and cyclists on the road (van Amstel et al., 2015).
- Due to the fact that activities are construction phase bounded, they are interdependent and delay of one activity means a delay for all following activities. Therefore, it is a logistic challenge to make sure materials are delivered Just-in-Time with the right quantity.
- The construction industry is also characterised by its fragmented nature, which causes a lot of not optimized freight movements to and from construction sites.

According to van Amstel et al. (2015) and Vidalakis, Tookey, and Sommerville (2011) savings of 10-30% in project costs can be saved with improving construction logistics. According to Lundesjö (2015) transportation costs have been researched extensively over the past years, but transportation costs in the construction industry have been described by Shakantu et al. (2008) as 'hidden cost', while this can lead up to an amount of 10-20 % of the total construction cost of a project (Lundesjö, 2015). Therefore, efficient construction related transport moves to and from construction sites, might have a big impact on the overall construction logistics performance.

### 3.1.2. Construction logistics and the urban transport problem

As Janné (2018) describes in this study, transporting goods plays an important role in the development of urban areas, but at the same time causes issues such as congestion, emissions, noise and other nuisance. The urban transport system is, as stated by Janné (2018), a complex transport system where a limited infrastructure is utilized by both goods as passengers. Next to the earlier mentioned issues, also the risk of accidents increases in densely populated cities with a mix of vehicles and vessels being used.

Although urban freight transport activities has been researched extensively over the past few years, the attention to construction logistics has lagged behind Guerlain, Renault, and Ferrero (2019). Yet, the construction industry contributes for an enormous share in the amount of transport movements in cities, causing the earlier mentioned environmental issues.

Within construction logistics the flows of both materials and equipment as waste are uncoordinated and mostly performed on an ad hoc basis. Construction material suppliers and waste management operators have their own vehicles and schedules. The fact that these parties do not synchronise their activities results in congestion on the road (Shakantu et al., 2008). Especially in city centers this is managed by stipulating delivery time slots, but causes the fact that delivery vehicles now arrive well in time and have to wait or drive around to kill the extra time and contribute to congestion and environmental issues (Sullivan, Barthorpe, & Robbins, 2011). Since efficient construction logistics relies heavily on the transportation to and from sites, there is a need for improvement.

In several case studies performed by among others Van Merrienboer (2013) and Quak et al. (2011), concepts to improve construction logistics are studied. Examples of these concepts are local traffic control measures, urban consolidation centres or consolidation earlier in the supply chain, combining construction deliveries and waste pickups, but also making use of waterways for transportation moves (van Amstel et al., 2015). These case studies are applied to individual projects and according to van Amstel et al. (2015) a large-scale coordination across multiple projects is needed in order to achieve a successful implementation. Improving construction logistics by e.g. reducing congestion and optimize flows, between 10-30% could be saved in project costs (van Amstel et al. (2015);Vidalakis et al. (2011)). Not only cost reductions, but also improvements in project duration and thus for example noise nuisance and emissions could be achieved.

### 3.1.3. Waterborne logistics in urban areas

In literature, little can be found that dives deeper into construction logistics via waterways. In this Section some use cases and (grey) literature that is available, is discussed in more detail.

Maes, Sys, and Vanelslander (2015) and Janjevic and Ndiaye (2014) are examples of review studies of using inland waterways for city logistics. Best practises and initiatives throughout Europe are analysed and both studies showed that there is potential for using waterway networks in cities for the distribution of goods in several transport segments like waste collection and parcel delivery. In Janjevic and Ndiaye (2014) a case of transport of palletised construction material is reviewed. Although no extensive literature can be found concerning using waterways for construction logistics, Janjevic and Ndiaye (2014) concludes based on this case study that a promising amount of trucks and CO2 emissions per year are avoided by using the waterway network for construction logistics purposes.

Studies that have been conducted on using transport over water for construction logistics only investigate the impact on potential reduction in CO2 and truck movements. According to Van Merrienboer (2013), Quak et al. (2011) and Janjevic and Ndiaye (2014)) the concept of transport over water does indeed have the potency of having positive impact on vehicle movements and CO2 emissions in the city center. But what can also be concluded from practice, is the fact that transport over water from hub to construction site is often less cost effective than transport by road. Especially in the city of Amsterdam construction logistics transportation over water is a promising approach due to the large amount of construction sites on the water front and the addition of the quay-wall and bridge renovations in the coming years. Due to the fragmented nature of the construction industry, monitoring of construction logistics does often not occur and stakeholders have no clear overview of the different supply chain steps and the influencing factors on the performance.

Therefore more insight is needed in the consequences of the introduction of a waterborne construction logistics system in the city of Amsterdam. Literature diving into indicators, other than vehicle movements and CO2 emissions, that might influence the feasibility of using transport over water for construction logistics activities are not present. Due to the fact that different stakeholders have different objectives for transportation mode decision making, a need arises for more insights in the impact of transport over water on multiple criteria. Therefore, the development of a tool that assesses the impact of transport over water on stakeholder specific criteria and with that supports stakeholders in the decision making process of transportation mode choice, might be a large contribution to practice.

In literature several papers are dedicated to performance measurement of construction projects in general, in which relevant construction related performance indicators are introduced ((Cheung, Suen, & Cheung, 2004) ; (Ward, Curtis, & Chapman, 1991)). However, few literature or studies are found that focus on the performance measurement of construction logistics specifically. In Ward et al. (1991) a new framework for construction logistics measurement is introduced, but is mostly focused on the measurement system and its monitoring tools instead of the identification of relevant performance indicators. In Ying and Tookey (2017) using vehicle movements as a KPI for monitoring and improving construction logistics performance is proposed, which gives no insight in other relevant indicators that influences transportation mode choice. In Ying, Tookey, and Roberti (2014) a focus is on the practice and obstacles of efficient construction logistics transportation, but also from a vehicle movement point of view.

A recent study investigates the potential for the implementation of urban waterway transport in the canals of Amsterdam by determining and exploring success and failure factors of implementing this innovation (Roosmale Nepveu, 2020). According to Roosmale Nepveu (2020) freight flows characterised by heavy weights and large volumes, like e.g. construction materials and waste products, are most suitable to be successful. The study also states that it can only be implemented as a sustainable transport option when the road alternative becomes less attractive, which can be achieved by increasing congestion over the years, but it might also require political support like measures for road weight restrictions. Roosmale Nepveu (2020) concludes that reasons for failure can currently be pinpointed to a lack of logistic cooperation, supporting transport policy and of sufficient transshipment locations. One of the most critical recommendations of Roosmale Nepveu (2020) is further research into suitable transshipment locations for the loading and unloading of freight. The fact that construction sites for the renovations of the quay walls can already be used for those purposes, might be an opportunity and needs to be taken into account during this thesis project.

Since, as earlier mentioned, the transportation part of the construction supply chain can account for 10 - 20 % of the total construction project cost, more insight is needed in the assessment of the performance. Literature diving into indicators, other than vehicle movements and CO2 emissions, that might influence the feasibility of using transport over water for construction logistics activities are not present. Due to the fact that different stakeholders have different objectives for transportation mode decision making, a need arises for more insights in the impact of transport over water on multiple criteria.

## 3.2. Quay wall renovation projects in Amsterdam

Before diving into the construction logistics system of quay wall renovation projects, in this Section a brief introduction into the characteristics of these kind of projects will be presented. Firstly, an overview of the different methods and contractor combinations over time will be presented. Secondly, an elaboration on the different construction phases and activities will be presented and lastly the leading component for the construction logistics system, the to be transported construction materials, will be discussed.

### 3.2.1. Time frame and construction methods of quay wall renovation projects

The different construction methods and involved parties can be identified based on the time frame. In this subsection a quick overview of the different construction methods and contractor combinations are placed in time.

**January 2021 - onwards : Cooperation Agreement "Kademakers" (SOK)**
The municipality of Amsterdam has entered into a long-term commitment with three market parties for the renewal of quay walls in the city. On 11 January 2021, the contract was definitively awarded to Dura Vermeer Infra Regional Projects, Beens Groep and Aannemingsmaatschappij H. van Steenwijk (with Mobilis and Van Gelder as subcontractors). Within the Cooperation Agreement (SOK) Kademakers, these three parties will each be responsible for a minimum of 300 meters of quay wall renewal per year for the next six years at least, with an option for two two-year extensions. These parties will apply the conventional construction methods for quay wall renewal projects as discussed in Section 3.2.2. The study of Breederveld (2017) discusses the different quay wall renovation types that are used for the reconstruction of the quay walls in Amsterdam. Based on the circumstances of every construction project, the most convenient type is chosen. All three types are discussed in more detail in Appendix C, but will be briefly listed below:

- **L-Wall** The L-wall type is a quay wall with a relieving platform, which reduces horizontal load of the piles. Currently this type is applied to most quay walls in the city of Amsterdam (Breederveld, 2017). Usually the foundation piles are screwed into the soil and the L-wall is cast in-situ. A building pit with drainage is needed to replace the quay wall.
- **Combi-wall with inclined piles** The combi-wall with inclined piles consists of a vertical wall with sheet piles and steel piles combined with inclined piles in the direction of the canal, this design is favorable for locations with limited area behind the old quay wall. Another advantage of the inclined piles is that a building pit is not necessary.
- **Combined wall** The combined wall is a construction wall that consists of steel piles with sheet piles in between. A prefabricated concrete brick wall will be placed on top of the quay wall, which gives the quay wall the required characteristic appearance. The combined wall is much stiffer than a standard sheet pile wall and can bear higher (horizontal) loads.

**2022 - onwards : Addition of Innovation Partnerships for Quay walls (IPK)**
The innovation partnership means that the Municipality of Amsterdam has challenged market parties to use their innovative power to devise smart solutions for one or more of the following challenges:

- Accelerate the replacement of inner-city quay walls
- Reduce nuisance for the environment
- Sustainable solutions during execution of the renovation works and for the quays itself, possibly while preserving existing trees

The smart solution may consist of innovative implementation methods (construction method), innovative quay wall concept (object) or a combination of both. After a long selection phase the three parties that made the best offer were awarded the contract (March 31, 2020), which are the following combinations:

- G-force (Giken, van Gelder and Brothers de Koning)
- Quay 2.020 (CMD Civil Works, Oosterhof Holman Beton- en Waterbouw, Bouwadviesbureau Strackee, Sweco Nederland, Aannemingsbedrijf Verboon Maasland, Kroes Aannemingsbedrijf)

- Koningsgracht (BAM, Royal Haskoning DHV)

Since these combinations have introduced untried and untested construction methods (see Appendix B), firstly a pilot has started in 2021. When successful during the pilot, these combinations will take up to approximately 50% of the total amount of to be renewed quays in the inner city of Amsterdam.

### 3.2.2. Construction phases and activities

Since, as already mentioned in Section 3.2.1, the newly designed construction methods of the IPK combinations are not yet mature enough to be used in operation, in this thesis project it is chosen to focus on the conventional construction methods that are used nowadays. Nevertheless, in the design of the waterborne construction logistics system and calculation model of this thesis project, some space is left for potential additions of these smart solutions in the future. For now, we will focus on the general construction phases and activities retrieved by a quay wall renovation use case that was in operation during the execution of this thesis project.

The renovation activities of a quay wall in general is shown in Figure 3.1, and can be roughly divided into the following sections:

- Preparation of the construction site
- Removal of sewerage drains and looping through sewer
- Placing auxiliary sheet pile in roadway
- Removal and discharging of the existing quay construction
- Construction activities of the new quay wall
- Replacement of cables and pipelines
- Placement of new pavement
- Installation of street furniture and planting of trees

These activities can be included in five construction phases, which will be briefly discussed.

**Phase 0 - Preparatory work**
In this phase the work area is properly set up, necessary trees will be cut, breaking up and transporting current pavement, removing street furniture and public lighting. The duration of this phase is estimated to take approximately two weeks.
**Phase 1 - Placement of cutoff or auxiliary sheet pile**
During this phase sewerage drains will be removed and sewer will be looped through. After that, dependent on the construction type, an auxiliary sheet pile or a cutoff will be placed, which will give strength to the current construction and room for the next construction phase. Also the construction site will be provided by a temporary pavement. Duration is around 8 weeks for this phase.
**Phase 2 - Renovation of the quay wall**
This is one of the largest phases and will be divided into subphases

(a) Remove temporary pavement

(b) Remove old quay wall

(c) Place new quay wall

(d) Place new pavement

First, the temporary pavement will be removed, after which excavation works will be performed and the old quay wall will be broken down and material discharged. Next, the new quay wall will be placed and again a temporary pavement is placed. The approximated duration of this phase will be around a year, so 52 weeks.
**Phase 3 - Replacement of cables and pipelines**
The main focus of this phase, which will take approximately 16 weeks, is the replacement of the sewing system, cables and pipelines. Additionally, a temporary road surfacing needs to be replaced and applied.
**Phase 4 – Design ground level**
Design of ground level surface will be performed, which includes removal of temporary and placing of

permanent road pavement, placement of street furniture, trees and public lighting and will take around 5-10 weeks.

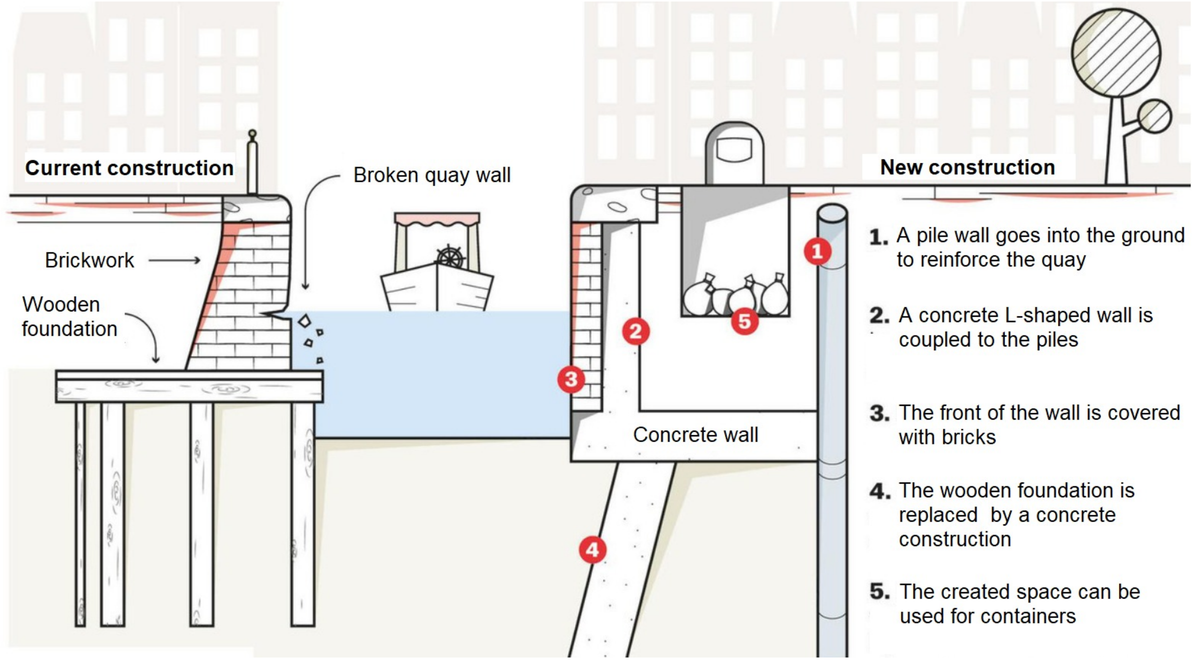



Figure 3.1: Overview of the different quay wall renovation steps

### 3.2.3. Construction materials

From interviews and desk research, it can be concluded that due to large amounts of material to be transported for quay wall reconstruction projects, mostly material specific flows (monoflows) can be identified.

During the construction activities of quay wall renovation projects, seven material type categories can be distinguished. These categories, which are introduced in Table 3.1, are defined based on interviews, historic data of finished renovation projects and building specifications of future projects. In the second column of Table 3.1 examples of the different material types can be seen.

Table 3.1: Material types quay wall renovation project

| Material type | Examples | Short explanation |
|---|---|---|
| Bulk material | - Soil<br>- Sand<br>- Demolition waste | Dry materials that are granular, powdery or lumpy in nature and stored in heaps. |
| Palletised material | - Bricks<br>- Kerb units | Construction materials that are arranged and transported on pallets. |
| Prefab elements | - Concrete walls<br>- Prefab elements | Dependent on the construction method, large prefab (concrete) elements will be transported to site. |
| Long materials | - Sheet piles<br>- Wooden piles<br>- Props<br>- Cast iron masts | Materials that have a length of >5 meters |
| Machinery and equipment | - Hydraulic excavator<br>- Wheel loader | Machinery that needs to be transported to the construction site |
| Time critical material | - Concrete<br>- Cement<br>- Mortar | These are wet materials that are time sensitive in terms of material properties (e.g. concrete). |
| Other goods | - Tree stumps<br>- Barrier posts | These materials can not be accommodated with the other material type categories. |

These material types are not dedicated to a specific construction phase of a project, but some material types are supplied or discharged more often in specific phases. Examples are discharging demolition waste after excavation and demolition works in phase 2 and the supply of palletised bricks during phase 4, when road pavements are being applied.

**Quantification**

To give a quantification to the share of material type in a project as a whole, the building specifications of the renovation of Herengracht 1-103 are used as a general case. In the building specifications all project activities are listed in a descriptive way, after which the associated obligated quantities are mentioned and their corresponding units. All these quantities of to be handled and transported material and equipment are converted to tonnes. All listed materials are then classified into the right material type category and whether it will be supplied or discharged, from which the overview of share percentages for a quay wall renovation project are defined as shown in Table 3.2.

Table 3.2: Share of material types in a general renovation project

| Material type | Share supply streams [%] | Share discharge streams [%] |
|---|---|---|
| Bulk material | 42.2 | 98.9 |
| Palletised material | 14.4 | 0.0 |
| Prefab elements | 28.0 | 0.0 |
| Long materials | 1.2 | 0.4 |
| Machinery and equipment | 1.1 | 0.7 |
| Time critical material | 8.5 | 0.0 |
| Other goods | 4.4 | 0.0 |

It is remarkable that large differences between supply and discharge streams are present. The logical explanation is the fact that most discharge streams consist of waste after demolition of old parts of the quay regardless of the type of material present in the wall. Also, it is evident that prefab material and time critical materials will not be returned in the same composition as it would during supply streams. Next to that, materials that are normally transported in pallet form, will in most cases be discharged in bulk form.

As earlier indicated, the material flows are all converted into tonnages for further calculations. For these calculations the material types that were presented as volumes are converted with help of specific weights to tonnes. From multiple interviews and performed calculations is concluded that weight is normative for transport of construction materials due to the relatively high specific weights.

### 3.2.4. The execution of corresponding construction logistics

In this Section a brief explanation will be given of the circumstances that are forcing stakeholders to perform the quay wall renovation related construction logistics over water instead of the conventional way via road.

**Measures of Municipality of Amsterdam to decrease impact** The Municipality of Amsterdam (MoA) is actively working on policies reducing the impact of freight operations in the city. In this subsection the most relevant initiatives are discussed in more detail.

**Focus on sustainable urban logistics**

To be able to adequately support the city in the future supply, it is important that urban logistics become cleaner, becomes lighter and more efficient. The ambition is an emission-free area for delivery vans and trucks within the ring road A10 in 2025. The implementation of this ambition is part of the Clean Air Action Plan. Jointly with the logistics and industry program is being worked on carrying out this ambition. Vehicle weight reduction is an important element of the Bridges and Quay Walls Action Plan. Making urban logistics more efficient is part of the Agenda Amsterdam Low-traffic, because logistics use flows like other traffic flows of the same limited public space. There is a strong link with the planned hubs near the city and in the region. In area development, the unique chance to arrange the logistics right immediately and profit from it for years, as in the existing city cannot. The logistics flows become in area development an integral part of the design. There is continuous focused attention from the Municipality of Amsterdam necessary for the specific dynamics of the logistics sector. Collaboration with parties from the logistics sector chain and with knowledge institutions is a precondition to take appropriate measures. Together we learn more and more about how logistics in the city functions. This is much needed because both the development of transport concepts such as the developments in the field of data and ordering behaviour go very fast.

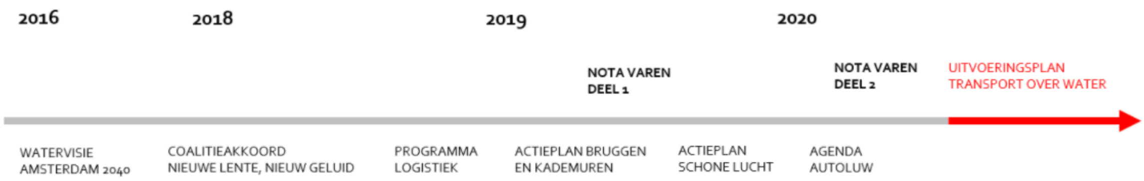



Figure 3.2: Timeline measures Municipality of Amsterdam

**Plan of Action for Clear Air**

The following are the main goals of this Plan of Action for Clean Air (Gemeente Amsterdam, 2019):

2020 Realisation of the environmental zone (for diesel) within the geographical boundaries of the ringroad A10 as of EURO4 passenger vehicles and a geographical extension of the environmental zones.

2022 Emission-free area within the boundaries of the S100 on the southern side of the train rails for public transportation vehicles and touring cars. Next to that the environmental zone will be tightened to EURO6 freight vehicles.

2025 Emission-free area by size of the built-up area for mopeds. An emission-free zone within the ring road A10 for trucks, vans, taxis, public transport buses and touring cars. And an emission-free area for passenger and pleasure craft and GVB ferries.

2030 Emission-free area for all modalities by the size of the entire built-up area.

**Programma Varen**

One of the main goals of this program is stimulating transport over water for all purposes in order to relieve the roadways, quays and bridges in the city. Since cargo transport over water is still in its infancy, the MoA will start with pilots and research to get more insights into the market needs. The Nota Varen contains the city of Amsterdam's new navigation policy with a long-term view on low-cost use of the shores and the water by a variety of users. Especially in Nota Varen Deel 2 (Gemeente Amsterdam, 2020b) a more advanced implementation strategy is discussed, including stimulation of transport over water. The main goal is to improve the city logistics by using water more intensively.

**Stimulating Transport over water in the *BLVC-kader***
The *BLVC-kader* focuses on four points regarding the surroundings of a quay wall renovation project. These focus areas are accessibility, liveability, safety and communication. This plan describes how the nuisance to the environment can be limited to the environment. In this document, next to an explanation of the project, description of the environment, contact persons and risk analyses, there is also the possibility to enforce parties to follow certain environmental measures. Fixed routes to and from construction sites is an example of a measure that could be added.

**Main outcome policy MoA**
For all quay wall renovations within scope it is decided that all construction logistics should take place via water from a transfer point outside the Centrumring S100. If equipment or material cannot be supplied and/or removed by water, the contractor must obtain permission from the management to deviate from this. The contractor independently arranges and coordinates the process surrounding construction logistics or logistics chain for the benefit of the construction process.

Quay wall renovations seem to be the ideal construction projects for doing the logistics via water, mostly because of the convenient construction site at the waterfront. The Municipality wants to enforce this type of waterborne construction logistics for all parties, but it is not yet clear what the impact might be for the stakeholders. This thesis project aims to give an answer to that gap. In Section 3.3.2 the expected drivers and barriers of the waterborne construction logistics system are discussed, which form a basis for the remaining part of this thesis project.

## 3.3. Attitude towards a waterborne construction logistics system

In this section a stakeholder analysis is performed to identify the relevant stakeholders, their interests and attitude towards using a waterborne construction logistics system. Based on interviews and site visits the drivers and barriers for implementation of this waterborne construction logistics system are discussed in this section as well. These form the basis for defining key performance indicators for the evaluation of the system in this thesis project.

### 3.3.1. Stakeholder analysis

In this section different stakeholders involved in the construction logistics system are identified and analysed. The different actors are introduced and their interests are discussed. One of the main reasons for the complexity of implementing construction logistics over water is the large amount of actors with conflicting stakes are involved in the problem. In this subsection the key stakeholders and their main interests are treated. These main interests will be used in this thesis project to define the evaluation criteria for evaluating the alternative scenarios of the waterborne construction logistics system.
For the evaluation of an UFT sustainability initiative Quak (2008) state that the key stakeholders to include are public authorities, shippers, freight transport operators, receivers and residents. In case of this system the Municipality of Amsterdam is the public authority of interest. Next to that, freight transport operators can be distinguished in both road as waterway transporters. Also, since construction projects are investigated, receivers in this particular case are the contractors at the construction site. And wholesalers, suppliers and hub operators need to be taken into account as key stakeholders as well.

**Municipality of Amsterdam**
For quay wall renovations in Amsterdam, the Municipality fulfills several roles, which will be enumerated and explained shortly below.

- *Principal*: in the particular case of a quay wall renovation project, the Municipality is the principal of the construction projects. For a large share of the quay walls they are the owner
- *Facilitator and key driver*: To stimulate initiatives for waterborne construction logistics, the municipality can regulate and create conditions in benefit of companies with sustainable initiatives. Examples are providing subsidies, and infrastructure for facilitating an easy to implement system
- *Legislative and directive*: The municipality has a formal role in supervising the use of public space, including roads and waterways in the historical center. This role can be filled in by setting up frames for policy that stimulate multimodal logistics. The municipality can steer the logistics process by the choice of granting permits for construction works and transportation over water. The same holds for permits regarding truck routes in the city center. Next to that, the municipality also the enforcer regarding compliance with permits
- *Public interest*: The Municipality takes care for its citizens and thus require solutions that mitigate accidents, nuisance and pollution and make sure the liveability and safety is high.

**Contractors** The contractor is responsible for the execution of the construction project. The entire construction process is lead by the contractor including keeping the client satisfied. They achieve for as high as possible project efficiency and are keen on on-time deliveries of materials, safety of personnel and effectiveness of the construction project.

**Suppliers and wholesalers** Suppliers and wholesalers of materials and equipment needed for the construction work are also key stakeholders. They will be interested in the reliability of the logistics system, as well as the potential impact on their business operations. Especially when they are located near the water side, it might become interesting to start the waterborne logistics from supplier to the site, reaping potential economies of scale.

**Hub operators** Hub operators responsible for managing the distribution of materials and equipment will also be key stakeholders. A waterborne construction logistics system creates an opportunity for hub operators located at the water front to involve more in the construction industry. They will mainly be interested in the efficiency and reliability of the logistics system and the impact on their operations.

**Logistics service provider** The logistics service company is responsible for the arrangement of construction material transport from supplier or wholesaler to the construction site. The company has the ability to outsource the operations to freight transporters or do the transport itself. The main aim of this stakeholder are profitable operations, which includes high on-time performance, flexibility, always keeping satisfaction of their clients into account.

**Waterborne freight transporter** Waterborne freight transporters for urban construction logistics is quite a new concept and not many companies offer this service. This is the stakeholder that provides the transport of construction materials via water from the supplier/wholesaler to the client. The new waterborne construction logistics system offers opportunities for scaling up their operations resulting in lower operational times and costs.

**Road freight transporter** Road freight transporters are the stakeholders that provide transport of construction materials via roads from the supplier/wholesaler to the client. An increase in attractiveness and a better proposition of waterborne transport, will have a negative effect on the operations of road freight transporters.

**Residents** Residents are the stakeholders living near the construction site and indirectly influenced by the construction activities. The wish of this group is as less nuisance as possible and a liveable city, including high safety perception and little noise and pollution.

In Table 3.3 an overview of the stakeholders with their primary and secondary evaluation criteria are presented. Additionally the impact of performing construction logistics via water on the stakeholder is indicated and the influence the stakeholder has on the to be designed system.

Table 3.3: Stakeholder evaluation matrix with evaluation criteria of a logistics system

| **Stakeholder** | **Primary Evaluation Criteria** | **Secondary Evaluation Criteria** | **Impact on Stakeholder** | **Influence of Stakeholder** |
|---|---|---|---|---|
| Municipality of Amsterdam | Relieving quay walls and bridges, reduction in vehicle movements and km's, accessibility of city centre, reduction of air pollution and greenhouse gas emissions, noise hindrance, liveability of citizens | Safety, low amount of complaints, sustainability of the transport system | High | High |
| Contractors | Reliability of deliveries, efficient operations and transport, low logistics costs, safety of employees, material and equipment, flexibility on the site | Profitable operations, flexibility of multimodal transport | High | High |
| Suppliers | High on-time performance of pick-ups and deliveries, satisfied clients (supplier/wholesaler and receivers), profitable operations, flexibility of multimodal transport | Cost-effectiveness of operations, easily accessible site | Medium | Medium |
| Logistics service providers | Low pick-up and delivery times (un)loading & transportation, cost-effectiveness of operations, flexible time schedule, client satisfaction, full barge loads, attractiveness of waterborne transport | Reliability of operations, profitable operations | Medium | Medium |
| Wholesalers | Low pick-up and delivery times (un)loading & transportation), cost-effectiveness of operations, flexible time schedule, client satisfaction, full truck loads, attractiveness of road transport | Reliability of operations, profitable operations | Medium | Medium |
| Hub operators | Reliability of operations, efficient use of hub facilities, profitability of operations, low congestion and waiting times, client satisfaction | Flexibility of operations, cost-effectiveness of operations | High | Medium |
| Waterborne freight transporters | Low emissions, low fuel consumption, safe operations, reliable schedules, profitable operations | Flexibility of operations, client satisfaction | High | Low |
| Road freight transporters | Low emissions, low fuel consumption, safe operations, reliable schedules, profitable operations | Flexibility of operations, client satisfaction | High | Low |
| Residents | Positive effects on liveability such as traffic safety, safety near the site, hindrance of noise/sight, reduction of air pollution, less vehicle movements and congestion | None identified | High | Low |

### 3.3.2. Drivers and barriers of waterborne construction logistics

In this subsection an overview of the potential drivers and barriers of using a waterborne construction logistics system is given. The information is retrieved from literature, desk research, site visits and interviews with stakeholders.

**Drivers**

**More accessible construction sites**

An advantage of using waterborne construction logistics is the fact that the canal infrastructure is already present. This infrastructure, together with the restrictions the Municipality of Amsterdam enforces for road transport, creates an opportunity to reach more construction locations than road transport could do.

**Improved conditions construction site**

According to multiple stakeholders, the conditions for construction works at the site will improve with the introduction of a waterborne construction logistics system. From interviews (M. Scheltinga, personal communication, August 25, 2020)(K. Borgmann, personal communication, July 2, 2020) can be deducted that the operations on site will go more efficiently due to more space on and around the construction site, no nuisance of waiting trucks, the possibility of material storage on vessels and more efficient handling due to an improved time schedule. Also there is the possibility to work directly from the transport type as a platform, which will leave directly afterwards, such as a vessel dumping concrete. This has a positive impact on the capacity of the operations. Next to that, the supply streams of material will become more predictable and therefore less ad hoc deliveries are expected, which will also provide rest on the construction site.

**Less load on cultural heritage**

Since the quays and bridges are already vulnerable, the Municipality wants as less load on the quays as possible. It is expected that executing construction logistics via water will have a large impact on decreasing the amount of movements through the city. Also, since the waterborne construction logistics elements can be used as a working platform as well, the quays are also relieved from heavy loads during the construction phases.

**Less movements through the city**

Due to the bulk volumes of materials, it is expected that less vessel movements are necessary than vehicles would have been used for transporting the same amount of material. This is mainly due to the fact that it is easier to bundle freight flows of the same material type, especially when it is bulk material, which causes a higher degree of consolidation resulting in i.e. lower logistics costs.

**Less vehicle movements**

Less vehicle movements, since for the new waterborne construction logistics system it is expected that all material and equipment flows will go via water, means positive impact on the environment in terms of accessibility, safety, reliability, livability of the citizens and sustainability. In Figure 3.3 the consequences of vehicle kilometres in a city center are shown. These relationships show that decreasing the amount of movements on the roads, will indeed have a positive impact on the environment as stated above.

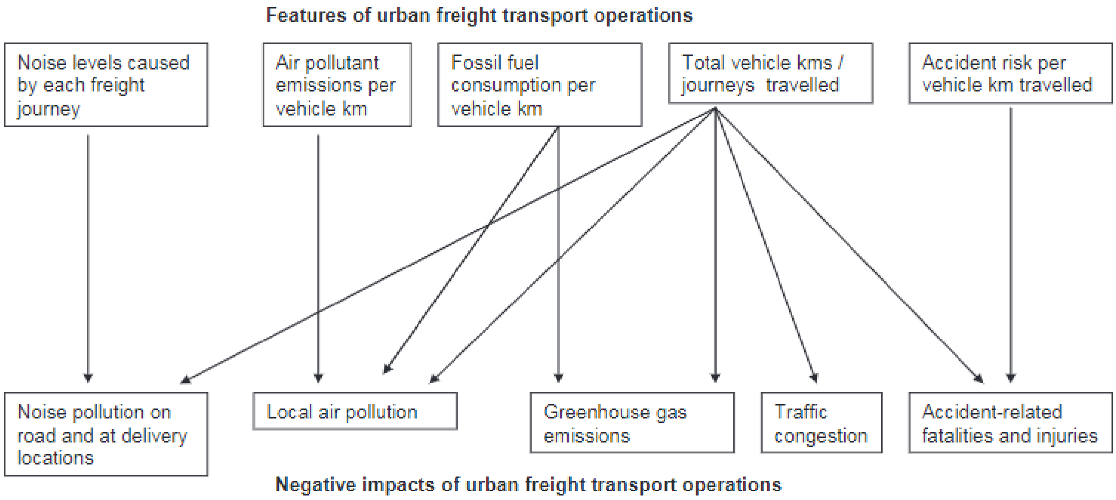



Figure 3.3: Relationship between features and negative impacts of urban freight transport (Browne et al., 2012)

First of all it is expected that less vehicle movements will cause less traffic congestion on the road network, resulting in a *better accessible network* for all users. This decrease of load on the road network also has a positive impact on the environment for residents, since there is *less nuisance* of noise, dust and crowdedness. Another large advantage is the diminished chance of accidents on the road between trucks and road users, and thus *increased safety*. It is not yet known what the exact impact is, and therefore this might be interesting to quantify for the to be designed system.

**Less emissions**
Not only the decrease in vessel kilometres might have a positive impact on the liveability of the city, it is expected to have a direct impact on the emissions of the construction logistics as well. From literature can be deducted that in most cases transport via water emits less $CO_2$, $PM_x$ and $NO_x$ than the alternative modality road.

**Barriers**
**Shortage of (un)loading places**
According to Nota Varen part 2 (Gemeente Amsterdam, 2020b) and the Analyses of the Transport over water policy of the Municipality of Amsterdam (Gemeente Amsterdam, 2020a), one of the main drawbacks of performing construction logistics over water, is the lack of sufficient (un)loading places throughout the city center. Next to that, when a quay wall is being renovated, the quays are that vulnerable that the quay can not be used as a working or storage platform for the construction project. What does happen nowadays, is that a working platform is constructed just above the water level, where all supplied construction material can be loaded and stored.

**Fairway profiles are restricting some canals**
In Section 3.4 some more information about the fairway profiles of the canals is given. It is important to understand that there are canals, mostly in the Wallen area with dimension restrictions because of the small canals, resulting in either lower maximum load capacity of vessels (-50%) or lower loading rates of vessels. This has direct impact on the amount of shipments needed to transport all material to and from the construction site.

**Effect on water traffic**
One of the first things that is remarkable when you have a look at the canals of Amsterdam, are the large amount of tour boats during the tourist seasons. At a peak moment, approximately 30-32 tour boats per hour (van der Does de Willebois, 2019) will sail past the busy canals in the city center. The addition of construction logistics to the waterways will have its effect on the accessibility of the waterways for other waterway users like distribution of consumer goods, pleasure craft and houseboats.

**No clear policy and guidelines for waterborne construction logistics**
There is still a lot of uncertainty about what is possible and allowed for stakeholders concerning waterborne construction logistics. For example, the passage profiles, enforcing a maximum transport combination length of 20 metres for fairway profile B, are not yet maintained everywhere (J.Tellingen, M. Roosmale Nepveu, personal communication, October 29, 2020). This is resulting in situations where the barge length is indeed less than 20 metres, but in combination with the tugboat the total transport combination reaches a length of around 35 metres.

**Less efficient routes due to one-way traffic on canals**
On quite some canals one-way traffic regulations apply, which means as a water transporter you are bound to fixed routes, which may not always be the fastest route.

**Extra houseboats removed because of working platforms on water**
Next to the houseboats that need to be removed in order to properly renovate the quay wall, some extra space needs to be freed up in order to perform the transport, handling and storage on water.

**Limited fleet availability**
The transport fleet available for waterborne transport is limited, since there are only few parties offering barges with the right specifications. For the current operations the fleet seems to be sufficient, but when the Municipality of Amsterdam wants to scale up the amount of simultaneously executed construction projects, this might be a blocker. Also, even though market parties are working hard on generating alternatives to diesel boats, most propelled vessels are not yet ready to navigate electrically.

**Logistics cost**
From interviews with several stakeholders can be concluded that it is expected that total logistics cost will increase significantly compared to road transport. This is underpinned with the fact, which is also confirmed by waterborne transport companies, that the hourly transport costs are approximately 25-30% higher ((B. Verweijen, personal communication, October 30, 2020). The total logistics cost are highly dependent on the amount of shipments and thus on the size of the transport carrier, but also on the restrictions on the waterways.

The increase in total logistics cost can be assigned to longer transportation times and more costly equipment and fleet. Next to that, for waterborne construction logistics in most cases extra handling activities at transshipment points and at the construction sites need to be performed. The costs associated with these extra handling activities need to be quantified in order to draw conclusions.

### 3.3.3. KPIs to evaluate the waterborne construction logistics system
In this subsection the KPIs derived from literature, desk research, site visits and conducted interviews are presented. Since this thesis project focuses on the design of a logistics system, logistics parameters are identified from which relevant indicators for all stakeholders can be derived as shown in Figure 3.4. From interviews it became clear that mostly the indicators on the left side of the figure are of interest for stakeholders. These indicators can all be bundled in the following logistical parameters, which will be used in the continuation of this thesis project.

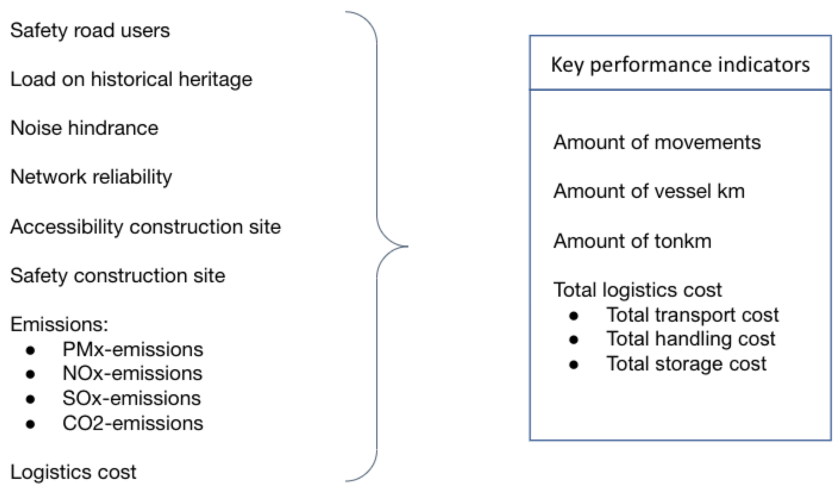



Figure 3.4: KPI overview

In Table 3.4 the final overview of the KPIs in scope for the continuation of this thesis project are depicted with their units and explanation below.

Table 3.4: Model parameters of the evaluation model

| Key performance indicators | Unit |
|---|---|
| Total transport cost water | € |
| Total handling cost water | € |
| Total storage cost water | € |
| Total logistics cost water | € |
| Amount of vessel movements | [-] |
| Amount of water vessel kilometres | vesselkm |
| Amount of road tonkm | tonkm |

- **Total transport cost**: The cost associated with the transportation of material to and from the construction site
- **Total handling cost**: The cost associated with the handling of material at the construction site
- **Total storage cost**: The cost associated with the storage of material at the construction site
- **Total logistics cost**: The cost associated with all logistics cost of transport over water. This is the combination of transport, handling and storage cost
- **Amount of vessel movements**: The amount of movements a vessel need to do in order to transport all material to and from the construction site
- **Amount of vessel kilometres**: The amount of movements for transporting all material times the distance the vessel covers in total vessel km
- **Amount of tonkm**: The amount of tonnes of material that are transported over the total distance covered by the vessels

## 3.4. Building blocks for designing a waterborne construction logistics system

In this section the to be designed system will be diverted into essential elements that need to be considered. In order to break the design problem down in the right building blocks, the characteristics of the design problem are discussed in more detail in this Section.

Overall, the design of the waterborne construction logistics system for quay wall renovations involves the integration of various elements to ensure that the system is safe, efficient, and sustainable. The goal of this Section is to provide a detailed understanding of the different elements and characteristics of the system to support the design process.

In Figure 3.5, a schematic overview of the transport chain and the corresponding modes is depicted. In the scope of this thesis project, the transport chain from the supplier to the construction site is included. As can be seen in Figure 3.5, there are a lot of transport mode options during different phases of the transport chain.

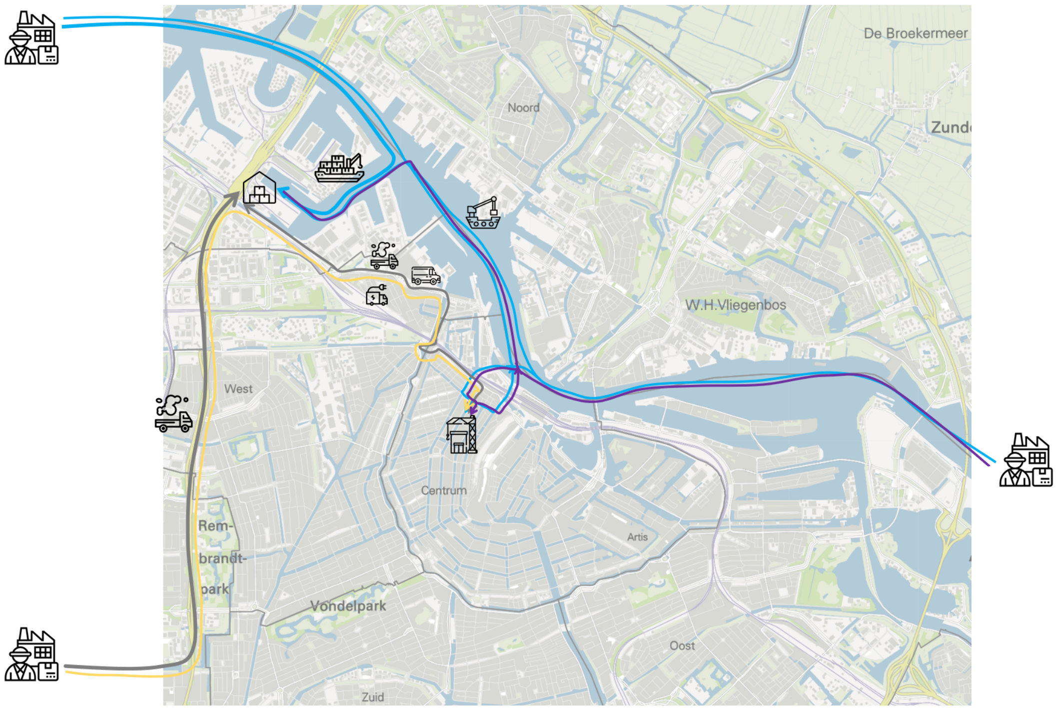



Figure 3.5: Schematic overview of the logistics transport chain (own work)

There is the option to transport materials and equipment via road, via waterways or a combination of both. A choice can be made for a specific fuel type and whether or not to use a hub for transshipment to other modes or consolidation of goods. This thesis project is focused on the enforcement of waterborne transport for transporting construction materials to the construction sites in the inner city of Amsterdam. Therefore the yellow and grey lined connections between hub and construction site will only be used in exceptional cases.

From the overview of the transport chain, two important pillars can be distinguished that generate choices for the design of the system, which are transport choices and handling or storage choices. These are the elements discussed in more detail in the following paragraphs.

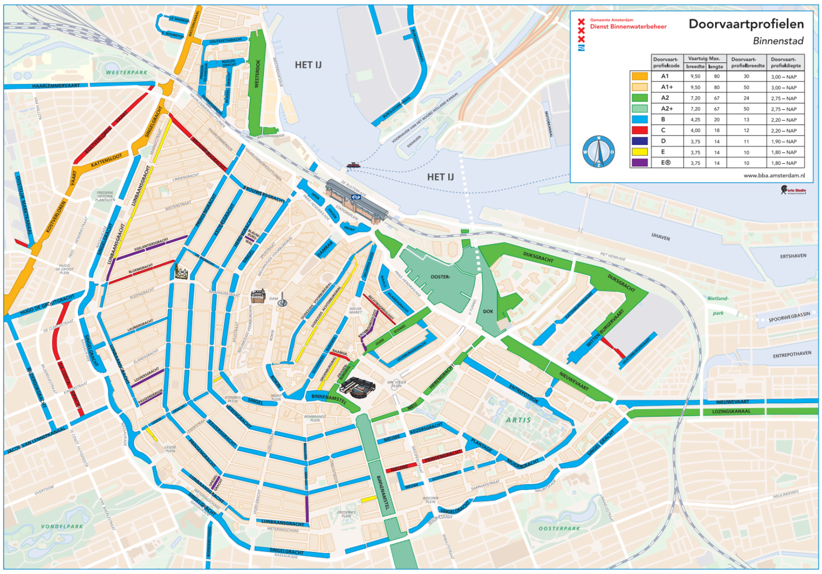
### 3.4.1. Transport elements

The transport elements that need to be taken into account are infrastructural boundaries like the fairway profiles and capacity profiles. Also, the physical elements are considered such as transport types from supplier to hub, transport types from hub to construction site, importance of vessel load and fuel types.

**Fairway profiles**

Based on fairway profiles, conditions apply regarding a maximum width, length and draft of vessels through the canals. The restricted sizes are set for the complete transport combination, which means that for example tugboats need to be subtracted from the total. In Figure 3.6, it can be seen that the majority of the current network, the canals depicted in light-blue, has a passage profile whereby vessels with a length of up to 20 meters and a width of up to 4.25 meters (Gemeente Amsterdam, 2020d) can be facilitated to ensure smooth and safe passage. When a canal has stricter conditions regarding the dimensions, vessels that fall outside the profile are still allowed to sail, but only with a separate test and permit. This oversized navigation is only possible with exemption and demonstrable evidence of necessity of transporting the freight. A possible result of this restriction is that the standard size vessel is allowed to sail to a construction site with a tight fairway profile, but is restricted concerning the loading capacity.

Another nautical bottleneck that might be interesting is the height of bridges, but based on what is seen during site visits, it is assumed that the passage profiles are more critical than the bridge height and therefore it is chosen to exclude it from the scope of this thesis project.




Fairway profiles for the innercity of Amsterdam

| Profiles | Color | Minimum passage width (m) | Maximum length vessels (m) | Maximum width vessels (m) | Fairway depth (m) |
|---|---|---|---|---|---|
| A1 | | 30 | 80 | 9.5 | 3.00 - NAP |
| A1+ | | 50 | 80 | 9.5 | 3.00 - NAP |
| A2 | | 24 | 67 | 7.2 | 2.75 - NAP |
| A2+ | | 50 | 67 | 7.2 | 2.75 - NAP |
| B | | 13 | 20 | 4.25 | 2.20 - NAP |
| C | | 12 | 18 | 4 | 2.20 - NAP |
| D | | 11 | 14 | 3.75 | 1.90 - NAP |
| E | | 10 | 14 | 3.75 | 1.80 - NAP |
| E* | | 10 | 14 | 3.75 | 1.80 - NAP |

Figure 3.6: Fairway profiles for vessels on the inner city canals of Amsterdam (Gemeente Amsterdam, 2020d)

**Capacity on the water**

The starting point is that the general pressure on the water does not increase further and that the share of passenger traffic aimed at visitors does not increase further. Passenger shipping licenses are issued for up to 550 vessels. In a general sense, it can be said that before 10:00AM and after 8:00PM (Gemeente Amsterdam, 2020a) there is sufficient space for water transport. In the long term, the municipality will use data to determine how to differentiate in flows, times and days. As can be seen in Figure 3.7 for most canals, indicated in blue, only capacity issues might arise during weekend days and do not pose a threat on the feasibility of using waterborne transport for construction logistics.

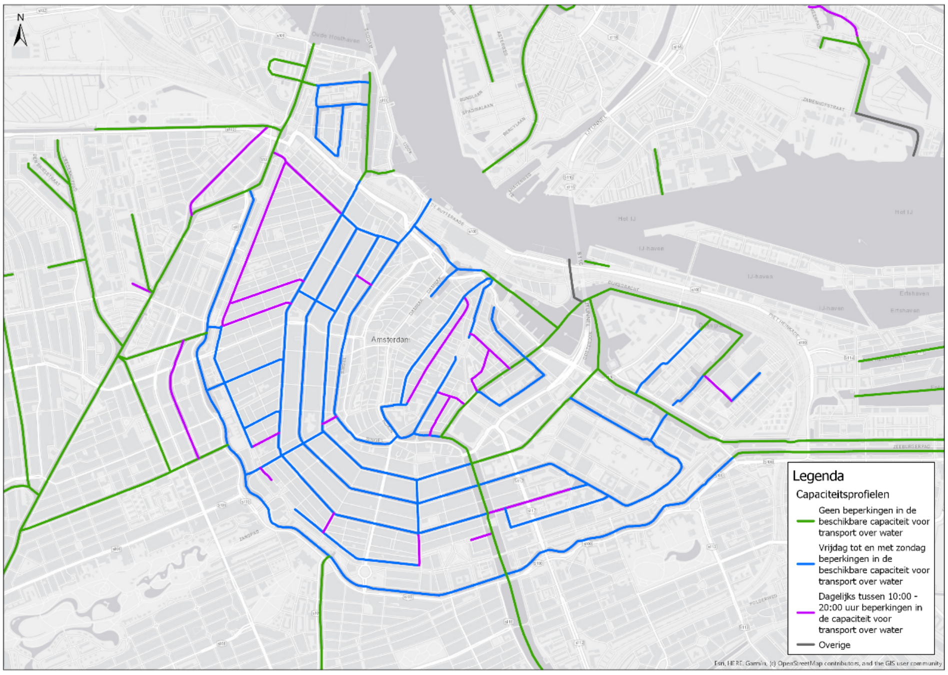



Figure 3.7: Capacity profiles on the canals in the inner city of Amsterdam (Gemeente Amsterdam, 2020a)

**Fuel Types**

The choice of fuel for the vessels used in waterborne construction logistics is an important consideration. The most common types of fuel used for vessels are diesel and gasoline. However, there is increasing interest in alternative fuels, such as liquefied natural gas (LNG), hydrogen, and electric power. For example, the Port of Rotterdam is implementing LNG-powered vessels in its fleet to reduce emissions and improve air quality in the port area. The choice of fuel will depend on a range of factors, including the availability and cost of different fuels, the environmental impact of the fuel, and the requirements of local regulations.

**Transport types**

The transport types are considered as one of the most important building blocks of the waterborne construction logistics system. In Table 3.5 an overview of the identified transport types for the to be designed system is presented. All transport type dimensions are based on the PK Waterbouw or ZOEV city fleet (PK Waterbouw, 2022)(ZOEV city, 2022) retrieved from their web page. The hourly cost estimations are retrieved from interviews held in 2020 with H. Van Wijk infra (L. Van Wijk, personal communication, November 23, 2020) and PK Waterbouw (B. Verweijen, personal communication, October 30, 2020).

Table 3.5: Transport types of the waterborne construction logistics system

| Transport types | Description and usage | Characteristics |
|---|---|---|
| Hopper barge | Barge with a cargo hold, which can be both open and covered up These barges can be used for transportation only, but can also be commissioned as storage facility during operation. Due to the fact that these barges are not restricted in terms of height, they also have storage capacity beneath the water line. Therefore the average loading capacity is higher than for other vessels. | - Non motorised<br>- Available as temporary storage facility<br>- Avg. dimensions: L = 19 - 24m B = ca. 4.8 m, D = 1.85 m, H = 2.2m<br>- Loading capacity = ca. 80 - 90 ton<br>Costs: €400 per week |
| Deck barge | Barge on which material is loaded on deck. Although some deck barges can carry heavy loads, restrictions are mostly caused by the maximum height on deck due to bridge heights in the city center of Amsterdam. Deck barges can also be used as a temporary storage facility during construction works. | - Non motorised<br>- Available as temporary storage facility<br>- Categories: L < 18 m, L = 18 - 22 m, L = 22-30m, L > 30m, B = 4 - 7 m, B = - Load capacity: 25 - 250 ton, Avg in first two categories: 45 - 48 ton<br>Costs: €400 per week |
| Barge with crane | Almost all waterborne transport companies also offer barges with a crane or other handling equipment attached to it. This could give advantages in terms of more efficient handling at transshipment and construction location and excluding rental costs of fixed handling equipment at the construction site. | - No need for separate handling equipment rent<br>- Costs: €150 per hour |
| Push/tugboat | Vessels that are used to transport non-motorised barges to their destination. | - Costs: €130 per hour<br>- Transport time = ca. 1.33 h from hub to city center |
| Motorised barge with crane | There are a few waterborne transport companies that provide motorised barges with a crane attached. This could give advantages in terms of more efficient handling at transshipment and construction location. | - Transport costs are including propelling, so no need to rent separate tugboat<br>- No need for separate handling equipment rent<br>- Costs: €165 per hour |
| (Coupling) pontoon | Pontoons are mostly used as a platform from which construction activities can be performed. They are often offered as coupling pontoons, which means multiple pontoons can be bundled and attached to create a larger platform or it can be composed in a modular way. Pontoons can also be used as a means to transport materials, since it has the smallest dimensions of all non motorised transport options | - Non motorised<br>- Ability to couple pontoons and play with dimensions<br>- Can be used as construction platform and storage location<br>L: > 6 m, B > 2 m<br>Costs: €1250 per week |
| Ferry | Used for large and heavy load transport. Dimensions too large for transporting materials through the canals of Amsterdam and therefore not taken into consideration for the design of this model | - Dimensions L49.3 x B13.5 x D2.3 x H9.4m<br>Load capacity: 126 ton |
| Autonomous vessel (with crane) | Autonomous shipping has the potential to lower the transportation costs for moving construction material mostly due to less personnel costs and increased safety. Although technology is not mature enough to use autonomous vessels for construction logistics, it is something to keep in mind for the future. | - Technically infeasible<br>- Potency for the future |

### 3.4.2. Handling & Storage elements

**Transshipment and storage locations**
In Figure 3.8 the identified hub locations within scope of this system are depicted including their location. As can be seen, all relevant transporters are based in the Western port area of the port of Amsterdam and are, as can be expected, all located near a water front. At these hubs, materials and equipment can be transshipped from other modalities to transort types suitable for waterborne transport. Additionally, material can be bundled for more efficient transportation. In the following Sections, these centres will be referred to as hubs. The identified hubs in Figure 3.8 have a sailing distance to the city center of Amsterdam between 7.5 and 15 kilometres and the sailing distances are comparable with the shortest route distance for road transport. However, due to congestion issues, trucks often choose a longer route in distance in order to reach the construction site in time.

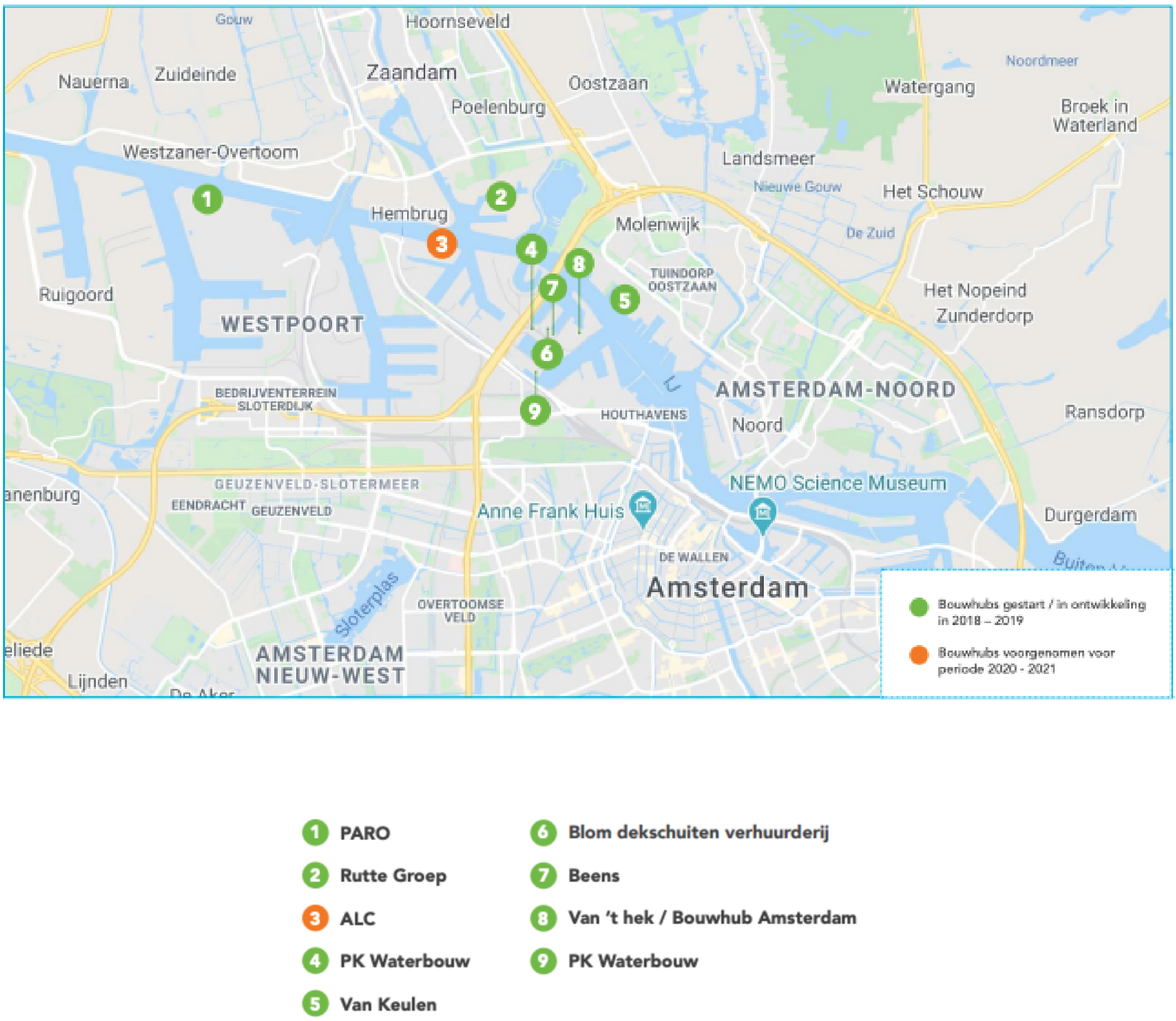



Figure 3.8: Hub locations for consolidation and transshipment of modalities. Retrieved from Port of Amsterdam (2020)

**Handling equipment**
The handling equipment is an important element of the waterborne construction logistics system. All equipment is adapted on the needs of the materials to be handled. Therefore some handling equipment might be suitable for only one material type. An overview of the handling equipment interesting for the to be designed system is provided in Table 3.6. For defining the specifications the average values from web pages selling handling equipment are taken as input for this table.

Table 3.6: Handling Equipment Specifications

| **Handling Equipment** | **Description** | **Specifications** |
|---|---|---|
| Crane | A machine used for lifting and moving heavy construction materials, such as steel, concrete, and prefabricated building components. | Handling speed: 20-50 tonnes/hour. Price per hour: 200-400 euros. Personnel needed: 1-3 operators. Maximum load per movement: 100-1000 tonnes. |
| Mobile Crane | A crane that is mounted on a mobile platform, allowing it to be easily moved from one location to another. It is used for lifting and moving heavy materials and often seen at quay wall renovation sites. | Handling speed: 20-50 tonnes/hour. Price per hour: 200-400 euros. Personnel needed: 1-3 operators. Maximum load per movement: 100-1000 tonnes. |
| Gantry Crane | A type of crane that is supported by a structure spanning an area, such as a manufacturing plant or construction site. It is used for lifting and moving heavy materials. | Handling speed: 20-50 tonnes/hour. Price per hour: 200-400 euros. Personnel needed: 1-3 operators. Maximum load per movement: 100-1000 tonnes. |
| Wheel Loader | A machine used for transporting loose construction materials, such as gravel, sand, and dirt. | Handling speed: 50-100 tonnes/hour. Price per hour: 100-200 euros. Personnel needed: 1 operator. Maximum load per movement: 5-20 tonnes. |
| Hydraulic Excavator | A machine used for digging and excavating soil and other construction materials and is often seen at quay wall renovation platforms. | Handling speed: 20-50 tonnes/hour. Price per hour: 100-300 euros. Personnel needed: 1-2 operators. Maximum load per movement: 2-5 tonnes. |
| Forklift Truck | A machine used for transporting and stacking materials in warehouses and construction sites. | Handling speed: 10-20 tonnes/hour. Price per hour: 50-100 euros. Personnel needed: 1 operator. Maximum load per movement: 1-5 tonnes. |
| Hydraulic Jack System | A system used for lifting heavy objects, such as vehicles and machinery, for maintenance and repair purposes. | Handling speed: N/A. Price per hour: 50-100 euros. Personnel needed: 1-2 operators. Maximum load per movement: 10-50 tonnes. |
| Conveyor Belt | A system used for transporting construction materials over long distances. | Handling speed: 100-1000 tonnes/hour. Price per hour: 100-300 euros. Personnel needed: 1 operator. Maximum load per movement: N/A. |
| Pump System | A system used for transporting liquids, such as concrete, over long distances. | Handling speed: 5-20 cubic meters/hour. Price per hour: 100-300 euros. Personnel needed: 1 operator. Maximum load per movement: N/A. |
| Crane + Concrete Hopper | A combination of a crane and a hopper used for transporting and pouring concrete at construction sites. | Handling speed: 5-10 cubic meters/hour. Price per hour: 300-500 euros. Personnel needed: 1-3 operators. Maximum load per movement: 5-10 cubic meters. |
| Dump System | A system used for transporting loose construction materials, such as soil and gravel, over long distances. | Handling speed: 50-100 tonnes/hour. Price per hour: 100-200 euros. Personnel needed: 1 operator. Maximum load per movement: 20-50 tonnes. |
| Chute | A system used for pouring and distributing concrete or other construction materials at a construction site. | Handling speed: N/A. Price per hour: 50-100 euros. Personnel needed: 1 operator. Maximum load per movement: N/A. |

**Load carrier**

In order to load and unload the construction material types defined in Section 3.2.3, the used load carrier needs to be defined with their corresponding dimensions and characteristics. In Table 3.7 an overview of the identified load carriers in scope of this thesis project are listed.

Table 3.7: tab:Load carriers

| Load carrier | Explanation | Characteristics |
|---|---|---|
| Pallet | In this thesis project Europallet sizes are used. Pallets are standardized | - B x L x H = 0.8 x 1.2 x 1 = 0.96 m3<br>- Height can vary |
| Flatrack | Construction to carry three or more pallets. | - 3 x 0.96 m3 = 2.88 m3<br>- Weight of the flatrack construction should be taken into account |
| Skips & containers | Unit load or demolition waste carrier, often used in construction logistics. | - 20 ft container (33.2 m3)<br>- Demolition waste container 6 m3<br>- Demolition waste container 10 m3 |
| Bigbags | A big bag is an industrial container made of flexible fabric. With these bags dry material, like sand, soil or demolition waste The standard dimensions are 0.9 x 0.9 m (B x L), where the depth of the bag can vary, which means no standard bigbag size is used in the construction industry. | - Dimensions varying between 0.81 - 1.377 m3 |
| No load carrier | In the case of construction logistics, mostly monoflows are present and in most cases bulk material. Since transport types are present that are able to carry loose bulk material, it often happens that material is transported without a load carrier. | - Loose material |

**Storage decisions**
For the storage decisions of the waterborne construction logistics system, there is a difference compared to the conventional way of construction logistics. Quays do not often have space to store material at the site, but in this particular situation, it might be interesting to store material on the transport carrier for a couple of days. The construction projects are material intensive and a trade-off can be made between direct unloading at the site or leaving the transport carrier to support efficient and smooth operations at the site.

## 3.5. Subconclusion

In this chapter a theoretical framework is used to give an answer to the following three research questions

RQ1 *What characteristics of a quay wall renovation project need to be taken into account for designing a waterborne construction logistics system?*

The key takeaway from this analysis is that the construction materials for quay wall renovation are mostly transported in monoflows, in particular more than 50% is identified als dry bulk material.

RQ2 *What are the performance indicators of interest for designing a waterborne construction logistics system and how do they influence the stakeholders of this system?*

Based on a stakeholder analysis, the evaluation criteria of the key stakeholders are defined and accordingly, the logistical performance indicators that provide insight into the consequences of the system on the stakeholders are defined. These KPIs are the amount of movements, the amount of vessel km, the amount of tonkm and the total logistics cost, consisting of transport, handling and storage cost.

RQ3 *What are the waterborne construction logistics building blocks that need to be considered in the design problem?*

In the last part of this section the building blocks of the waterborne construction logistics system are defined and discussed. These building blocks can be divided into transport related elements and handling and storage related elements.

# 4

# Design of the waterborne construction logistics system

In Chapter 3 an extensive background study is performed that will form the basis of the design of the waterborne construction logistics system as presented in this chapter. Both the background of a quay wall renovation project (3.2), the criteria of stakeholders of the waterborne construction logistics system (3.3) and the building blocks that need to be considered (3.4), will serve as a base for constructing the conceptual design in this chapter. First, based on Section 3 design requirements and evaluation criteria will be introduced, which the design should meet. After that, an introduction into creativity techniques and a morphological chart will be presented, that is constructed based on the building blocks defined in 3.4. Thereafter, the designed morphological chart and the final chosen building blocks are elaborated upon in Section 4.2.1. In Section 4.2.3, the design alternatives are generated and introduced, including the physical designs and their explanation. The presented design alternatives will be used as scenarios in the calculation model of Section 5 in order to evaluate the designed system, which will be discussed in more detail in Chapter 6.

## 4.1. Design requirements

In order to design the waterborne construction logistics system, requirements and evaluation criteria need to be defined. In this Section it will be discussed in more detail. The input is mostly gathered through the background analysis of Section 3.

### 4.1.1. Requirements

The requirements for designing the waterborne construction logistics are divided into functional and non-functional requirements. These are chosen based on the background analysis performed in Chapter 3 and the building blocks discussed in Section 3.4. The functional requirements describe the functionalities the system should have. Therefore a list of the general steps of waterborne construction logistics is generated, which is shown below and used as a base for the functional requirements of Table 4.1.

- Transport from supplier to hub
- Transshipment of material to vessel
- Transport to construction site
- Unload material from vessel to site
- Store material at construction site
- Load material/equipment/waste back on vessel
- Transport back to hub or end location

Table 4.1: Functional requirements

| No. | Functional requirement | Underpinning |
|---|---|---|
| FR1 | The waterborne construction logistics system shall be able to transport construction material for quay wall renovation project from supplier to transshipment location | All construction materials (3.2.3) can be moved from supplier to transshipment location (3.4) |
| FR2 | The waterborne construction logistics system shall be able to transship construction material from transshipment location to the used transport carrier | The ability to transship all materials from one transport type to the other at the transshipment location is essential for an efficient transport chain and desires the right handling equipment (3.4.2). |
| FR3 | The waterborne construction logistics system shall be able to transport all construction material from transshipment location to construction site | It is important that the system facilitates a transport (combination) that can move all material types from the transshipment location to the site (3.2.3) |
| FR4 | The waterborne construction logistics system shall be able to unload and load construction material from the used transport type to a storage location and vice versa | Suitable handling equipment is necessary at the construction site to transship the construction materials to the right location (3.4.2) |
| FR5 | The waterborne construction logistics system shall be able to store construction material at the construction site | Due to the large amounts, the construction site there needs to be a storage facility to store construction materials at or around the construction site (3.4.2) |
| FR6 | The waterborne construction logistics system shall be able to take up return flows | In order to have an efficient transport chain, it is important that waste or other return flows can be taken up by the system (3.2.3). |
| FR7 | The waterborne construction logistics system shall have the ability to directly transport construction material from supplier to construction site and vice versa | It should be possible to have a direct connection between supplier and the construction site when the supplier is located near the waterfront (3.3.1). |

The non-functional requirements are quite high over as the system is rather complex and large and design alternatives from the system might face different regulations or standards depending on the choices made. However, all design scenarios should always comply to local laws and regulations and should not cause safety hazards or inefficient operations. The corresponding requirements are presented in Table 4.2.

Table 4.2: Non-functional requirements

| No. | Non-functional requirement | Underpinning |
|---|---|---|
| NFR1 | The waterborne construction logistics system shall respect local laws and regulations | In order for the system to be successful, it should respect local laws and regulations |
| NFR2 | The waterborne construction logistics system shall comply with water traffic regulations | The system shall have to follow the regulations concerning fairway profiles and capacity restrictions (3.4.1). |
| NFR2 | The waterborne construction logistics system shall comply with safety standards | The system will have to follow the safety regulations that are applied by the Municipality of Amsterdam, such as speed restrictions (Gemeente Amsterdam, 2023b). |
| NFR3 | The waterborne construction logistics system shall not cause a bottleneck on crucial parts of the waterways | The system must follow the guidelines of the Municipality and i.e. not navigate through the canals on weekend days (3.4.1). |
| FR4 | The waterborne construction logistics system shall be energy efficient | The system should use its resources as best as possible in order to be successful. |
| FR5 | The waterborne construction logistics system shall have sufficient energy reserve for a complete trip | There is a lack of fuel possibilities in the inner city of Amsterdam (Gemeente Amsterdam, 2020a). |

### 4.1.2. Evaluation criteria

Based on the stakeholder analysis conducted in Section 3.3.1, the evaluation criteria can be derived for the stakeholders to evaluate the waterborne construction logistics system. In Table 4.3 this overview is shown, which are based on the KPIs discussed in Section 3.3.3.

Table 4.3: Overview of evaluation criteria

| Objective | Description |
|---|---|
| O1 | Have as less vessel movements as possible |
| O2 | Cause as less vessel kilometres as possible |
| O3 | Cause as less tonkilometres as possible |
| O4 | Have as low total logistics cost as possible |
| O5 | Have as low total transport cost as possible |
| O6 | Have as low total handling cost as possible |
| O7 | Have as low total storage cost as possible |

## 4.2. Functional design

In this section the functional design is presented, which will be shortly introduced below.

### 4.2.1. Setting up the functions

In order to define the functions the design should comply with, a main success scenario is constructed to get a better understanding. This main success scenario encompasses the following steps, which are also shown in Figure 4.1 in the form of a functional flow block diagram:

1. Identify material type to be transported [pre-step]
2. Transport from supplier
3. Arrival of materials at hub
4. Transshipment of material to vessel
5. Transport to construction site
6. Arrival of material at construction location
7. Move material from vessel
8. Store material at construction site
9. Pick material from storage location
10. Use material for renovation step
11. Store material/equipment/waste at storage location
12. Move material/equipment/waste on vessel
13. Transport vessel away from construction site
14. Arrival of return flow at hub [end use case]

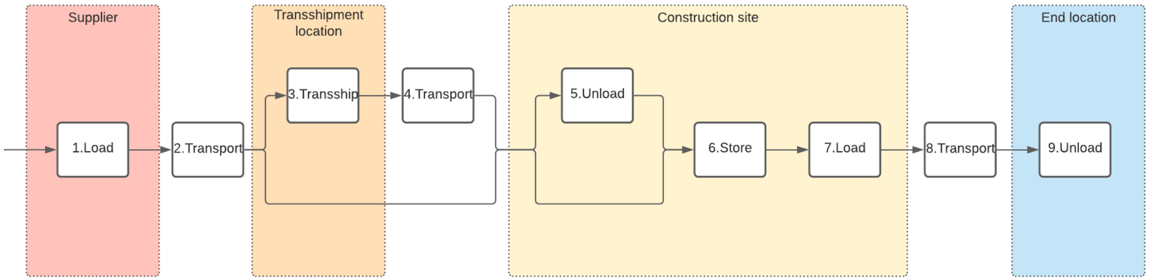



Figure 4.1: Functional flow block diagram

From this main success scenario and its visualisation, a better understanding of the functions or according to Dym and Little (1999) components is retrieved and added to the left side of the morphological chart in Figure 4.2.

### 4.2.2. Morphological chart

A morphological chart is used to construct an overview of all design possibilities. In the rows of the morphological chart the functions discussed in subsection 4.2.1 of the system are listed as components for the waterborne construction logistics system. For the means of the morphological chart, physical elements are listed that represent possible solutions for executing the function listed in the most left column. The means are generated through brainstorming. Based on the background analysis of Chapter 3 for every component all possible means are listed in a brainstorming session with fellow students. Hereafter, a selection is made of potential solutions that are already used or might be used in the future.

| MEANS<br>COMPONENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material to be transported to site** | Dry bulk | Palletised materials | Prefab elements | Long materials | Liquid bulk | Machinery and equipment | Miscellaneous | | | |
| **Transport type from supplier to hub** | Truck/Trailer | Inland waterway barge | LHV | Concrete mixer truck | Dump truck | | | | | |
| **Transshipment to vessel** | Grabber crane | Crane | Wheel loader | Conveyor belt | Dump | Chute | | | | |
| **Load carrier to site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | Concrete mixer | | | |
| **Transport type to and from site** | Push/tugboat + deck barge | Push/tugboat + hopper barge | Push/tugboat + (coupling)pontoon | Push/tugboat + barge with crane | Push/tugboat + barge with concrete mixer | Self-propelled deck barge | Self-propelled barge with crane | Roll-on/Roll-off barge | Ferry | Autonomous vessel |
| **Vessel load** | < 30 tonnes | 30 tonnes | 40 tonnes | 50 tonnes | 60 tonnes | 70 tonnes | 80 tonnes | 90 tonnes | > 90 tonnes | |
| **Fuel type** | Diesel | Electric | Biodiesel | Biofuel (HVO) | Hybrid | GTL | Hydrogen fuel | | | |
| **Unloading equipment** | Crane | Vessel mounted crane | Wheel loader | Hydraulic excavator | Forklift truck | Hydraulic jack system | Conveyor belt | Pump system | Crane + concrete hopper | None |
| **Store material at site** | Direct to work platform/pontoon | Chosen transport type > 1 day | Chosen transport type ≤ 1 day | No storage, direct usage | | | | | | |
| **Choose material to be transported back** | Dry bulk (demolition waste) | Palletised materials | Long materials | Machinery and equipment | Contaminated waste | Miscellaneous | | | | |
| **Load carrier from site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | | | | |

Figure 4.2: Morphological chart overview

During the brainstorm phase of creating input for the means of the morphological chart, it became clear that the initial material type is leading in both the creation of means to the components (or system functions) and the later to be chosen alternatives. Chosen load carriers, transport combinations and handling equipment are dependent on the material to be transported. Also the material to be transported for the return flow is dependent on the transport type that arrived at the construction site. To create a better understanding of the interdependency between the sub-components of the system, in Figure 4.3 a dependency structure matrix is shown.

| | Material to be transported to site | Transport type from supplier to hub | Transshipment to vessel | Load carrier to site | Transport type to and from construction site | Vessel loading capacity | Fuel type | Unloading equipment | Store material at site | Choose material to be transported back | Load carrier from site |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Material to be transported to site | | | | | | | | | | | |
| Transport type from supplier to hub | 1 | | | | | | | | | | |
| Transshipment to vessel | 1 | 1 | | 1 | 1 | | | | | | |
| Load carrier to site | 1 | | 1 | | 1 | | | | | | |
| Transport type to and from construction site | 1 | | | | | | | 1 | | | |
| Vessel loading capacity | | | | 1 | 1 | | | | | | |
| Fuel type | | | | | 1 | | | | | | |
| Unloading equipment | 1 | | | 1 | 1 | | | | 1 | | |
| Store material at site | 1 | | | | 1 | | | | | | |
| Choose material to be transported back | | | | | 1 | 1 | | 1 | | | |
| Load carrier from site | | | | 1 | 1 | 1 | | 1 | | 1 | |

Figure 4.3: Dependency structure matrix

### 4.2.3. Generation of alternatives

The morphological chart can be used as a tool for the generation of design alternatives. As mentioned in the previous Section, the material type that needs to be transported to the construction site is leading in the consecutive means decisions. Another very important component that needs to be chosen right after the material type is the load carrier. This is caused by the fact that a combination of both components, narrows down a lot of possible design alternatives. This will be demonstrated by means of the following example.

*Example – Material type only*

For a project a lot of dry bulk needs to be transported to the construction site. When we make this decision in the morphological chart without any other information, still a lot of means could be possible. Even though quite some means can be excluded on basis of knowledge retrieved in Section 3 and common sense, still endless options are possible as can be seen in Figure 4.4. Since it is unknown whether the dry bulk will be transported as loose material or in big bags or skips, almost all transport types are still optional. The big bags or skips could easily be transported on a pontoon or a deck barge and both a crane for the big bags as an hydraulic excavator for loose material could be used for handling at the site.

| MEANS<br>COMPONENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material to be transported to site** | Dry bulk | Palletised materials | Prefab elements | Long materials | Liquid bulk | Machinery and equipment | Miscellaneous | | | |
| **Transport type from supplier to hub** | Truck/Trailer | Inland waterway barge | LHV | Concrete mixer truck | Dump truck | | | | | |
| **Transshipment to vessel** | Grabber crane | Crane | Wheel loader | Conveyor belt | Dump | Chute | | | | |
| **Load carrier to site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | Concrete mixer | | | |
| **Transport type to and from site** | Push/tugboat + deck barge | Push/tugboat + hopper barge | Push/tugboat + (coupling)pontoon | Push/tugboat + barge with crane | Push/tugboat + barge with concrete mixer | Self-propelled deck barge | Self-propelled barge with crane | Roll-on/Roll-off barge | Ferry | Autonomous vessel |
| **Vessel load** | < 30 tonnes | 30 tonnes | 40 tonnes | 50 tonnes | 60 tonnes | 70 tonnes | 80 tonnes | 90 tonnes | > 90 tonnes | |
| **Fuel type** | Diesel | Electric | Biodiesel | Biofuel (HVO) | Hybrid | GTL | Hydrogen fuel | | | |
| **Unloading equipment** | Crane | Vessel mounted crane | Wheel loader | Hydraulic excavator | Forklift truck | Hydraulic jack system | Conveyor belt | Pump system | Crane + concrete hopper | None |
| **Store material at site** | Direct to work platform/pontoon | Chosen transport type > 1 day | Chosen transport type ≤ 1 day | No storage, direct usage | | | | | | |
| **Choose material to be transported back** | Dry bulk (demolition waste) | Palletised materials | Long materials | Machinery and equipment | Contaminated waste | Miscellaneous | | | | |
| **Load carrier from site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | | | | |

Figure 4.4: Alternative overview material type - Dry bulk

*Example – Material type + load carrier*
When we specify the load carrier as well, the spectrum of possibilities will be narrowed down, as can be seen in Figure 4.5. Here it is assumed that the bulk will be transported as loose material, resulting in a few logical consequences for the system. First of all only one transport type remains, the push/tugboat with hopper barge. This can be explained by the fact that loose material could blow off a vessel when it is on a deck. The only options left would be the hopper barges. When we look at the hopper barge options, two of the three means are with an attached crane. Because in this case loose material is transported, it is more logical to use an hydraulic excavator as unloading equipment, resulting in the consequence that only one transport type can be chosen. Also with dry bulk as material, more volume and thereby tonnes can be loaded onto the vessel. Since the hopper barge can still be pushed or towed by any kind of boat, the fuel type is difficult to define on beforehand.

Since loose material, and especially in large tonnage, is transported to the site, it must be a just-in-time delivery of the vessel when it is chosen to store it on-site on the fixed working construction or the pontoon. Even if the load can be used for construction right away, the push- or tugboat needs to wait, which will probably result in high waiting cost. Therefore it would be more convenient to store the material in the hopper barge itself or potentially transship it to another hopper barge near the construction site. For the return flow, it can be assumed that bulky demolition waste will be taken back. It is good to keep in mind that these decisions could still be influenced by external factors like weather conditions, restrictions at the construction site, fairway profiles, availability of the fleet et cetera. These influences can cause changes to the possible means and thus change a system alternative.

| MEANS COMPONENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material to be transported to site** | Dry bulk | Palletised materials | Prefab elements | Long materials | Liquid bulk | Machinery and equipment | Miscellaneous | | | |
| **Transport type from supplier to hub** | Truck/Trailer | Inland waterway barge | LHV | Concrete mixer truck | Dump truck | | | | | |
| **Transshipment to vessel** | Grabber crane | Crane | Wheel loader | Conveyor belt | Dump | Chute | | | | |
| **Load carrier to site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | Concrete mixer | | | |
| **Transport type to and from site** | Push/tugboat + deck barge | Push/tugboat + hopper barge | Push/tugboat + (coupling)pontoon | Push/tugboat + barge with crane | Push/tugboat + barge with concrete mixer | Self-propelled deck barge | Self-propelled barge with crane | Roll-on/Roll-off barge | Ferry | Autonomous vessel |
| **Vessel load** | < 30 tonnes | 30 tonnes | 40 tonnes | 50 tonnes | 60 tonnes | 70 tonnes | 80 tonnes | 90 tonnes | > 90 tonnes | |
| **Fuel type** | Diesel | Electric | Biodiesel | Biofuel (HVO) | Hybrid | GTL | Hydrogen fuel | | | |
| **Unloading equipment** | Crane | Vessel mounted crane | Wheel loader | Hydraulic excavator | Forklift truck | Hydraulic jack system | Conveyor belt | Pump system | Crane + concrete hopper | None |
| **Store material at site** | Direct to work platform/pontoon | Chosen transport type > 1 day | Chosen transport type ≤ 1 day | No storage, direct usage | | | | | | |
| **Choose material to be transported back** | Dry bulk (demolition waste) | Palletised materials | Long materials | Machinery and equipment | Contaminated waste | Miscellaneous | | | | |
| **Load carrier from site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | | | | |

Figure 4.5: Alternative overview - Dry bulk + Loose material

**Choosing alternatives**

Since it can be concluded from Section 3.2.3 that around 50% of the total amount of transported construction materials to the construction site is dry bulk, it is chosen to use this material type as a starting point for the generation of alternatives. The baseline will serve as a reasonable starting point for the evaluation of the design alternatives and measuring the difference in effects.

**Baseline of the system**

Based on the background analysis performed in Section 3 the most probable scenario can be derived that will be applied in most cases for quay wall renovation projects.

| MEANS / COMPONENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material to be transported to site** | Dry bulk | Palletised materials | Prefab elements | Long materials | Liquid bulk | Machinery and equipment | Miscellaneous | | | |
| **Transport type from supplier to hub** | Truck/Trailer | Inland waterway barge | LHV | Concrete mixer truck | Dump truck | | | | | |
| **Transshipment to vessel** | Grabber crane | Crane | Wheel loader | Conveyor belt | Dump | Chute | | | | |
| **Load carrier to site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | Concrete mixer | | | |
| **Transport type to and from site** | Push/tugboat + deck barge | Push/tugboat + hopper barge | Push/tugboat + (coupling)pontoon | Push/tugboat + barge with crane | Push/tugboat + barge with concrete mixer | Self-propelled deck barge | Self-propelled barge with crane | Roll-on/Roll-off barge | Ferry | Autonomous vessel |
| **Vessel load** | < 30 tonnes | 30 tonnes | 40 tonnes | 50 tonnes | 60 tonnes | 70 tonnes | 80 tonnes | 90 tonnes | > 90 tonnes | |
| **Fuel type** | Diesel | Electric | Biodiesel | Biofuel (HVO) | Hybrid | GTL | Hydrogen fuel | | | |
| **Unloading equipment** | Crane | Vessel mounted crane | Wheel loader | Hydraulic excavator | Forklift truck | Hydraulic jack system | Conveyor belt | Pump system | Crane + concrete hopper | None |
| **Store material at site** | Direct to work platform/pontoon | Chosen transport type > 1 day | Chosen transport type ≤ 1 day | No storage, direct usage | | | | | | |
| **Choose material to be transported back** | Dry bulk (demolition waste) | Palletised materials | Long materials | Machinery and equipment | Contaminated waste | Miscellaneous | | | | |
| **Load carrier from site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | | | | |

Figure 4.6: Baseline of the design

As already mentioned in Section 3.2.3 more than 50% of the construction materials is dry bulk. Although the system is gradually changing, the most commonly used way of transporting dry bulk is still road transport by truck. Dry bulk is often transported in bulk form and thus not restricted by a load carrier, which can be easily handled by a grabber crane near the water side. A hopper barge is easiest to dump bulk material in, since on a deck barge the granular material could get blown away by the wind. Since the fleet is not yet large and extensive enough with motorised hopper barges, the barge needs to be towed by a motorised tugboat. Also, not all tugboats are suited with hybrid or electrical engines, resulting in a first assumption that the current most plausible scenario is that the parties will make use of a diesel engine. Since most of the fairway profiles within the city center of Amsterdam are restricting vessels to a maximum length of 20 metres, it is plausible to assume that an average shipment is able to transport 40 ton of material. As often seen on quay wall renovation construction sites, hydraulic excavators are present for bulk handling at the site. Since not all bulk can be handled immediately, it is often seen that the hopper barge that is used for transportation is also used as a storage location until all material has been collected for operation. Since around 95% of the return flow seems to consist of dry bulk material, mostly in the form of demolition waste and soil, it is very plausible that the chosen material for the return flow will be bulk material in loose material form.

### 4.2.4. Physical design concept

It is chosen to create the physical designs in the form of the complete transport chain with the chosen means, or variables, in visual form. In Figure 4.7 the general overview is shown with on the left the supplier, in the middle the transshipment location, or hub, and on the right side the construction site. In orange the different means that need to be chosen per alternative are depicted.

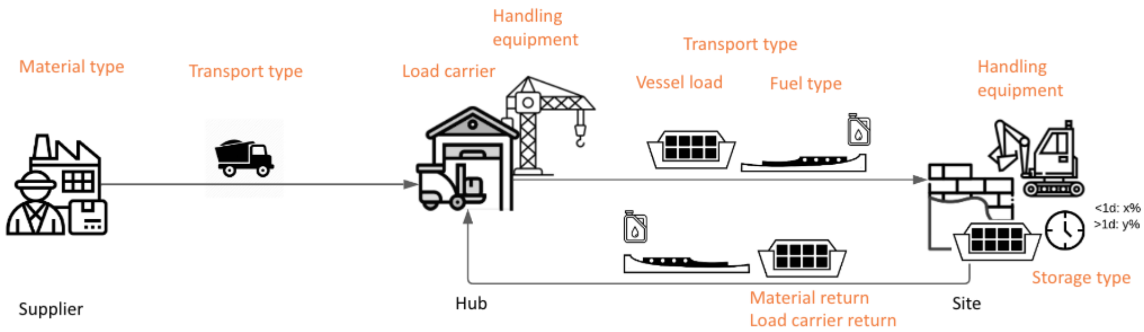



Figure 4.7: Physical design overview

**Physical design of the Baseline**

Based on the earlier described baseline of the system, the physical design can be defined by combining all highlighted means in a visualisation of the supply chain. This is shown in Figure 4.8, in which the elements are depicted in the icons, such as the average vessel load, the handling equipment and storage type.

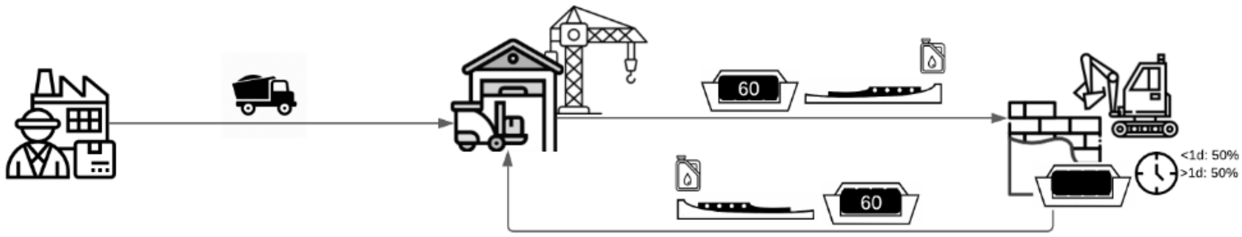



Figure 4.8: Physical design - Baseline

### 4.2.5. Physical design alternatives

In this Section the design alternatives will be introduced, explained and presented in a visual way. These alternatives are derived from the options in the morphological chart. It is important to mention that due to the large amount of design possibilities, it is chosen to take dry bulk as a starting material for all design alternatives in this thesis. Dry bulk takes up the largest share of the total logistics movements and in this way it is easier to compare the alternatives. The alternatives can be compared with the baseline scenario described in the previous Section.

**Design alternative 1 - Self-propelled electrical barge with mounted crane**

From a transporter and contractor point of view, it might be interesting to use a self-propelled barge with a crane mounted on it. This could potentially be advantageous with respect to transport costs (no tugboat needed), handling time and costs (no extra handling equipment needed). But also for the municipality this alternative might be interesting due to less nuisance on the waterways (the total length of transport is shorter than average) and less visual nuisance on the construction site due to less handling equipment being present. For this design alternative a specific use case can give some direction to the choices, since there is a specific vessel in Amsterdam called the "City supplier", which is operating as a construction material supplier since 2010. This is a self-propelled barge, sailing electrically and has a crane mounted on deck. The average vessel load is estimated to be 40 tonnes, which is around 50% less than a comparable sized vessel without handling equipment on board. In Figure 4.9 an overview of this design alternative is shown.

| MEANS<br>COMPONENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material to be transported to site** | Dry bulk | Palletised materials | Prefab elements | Long materials | Liquid bulk | Machinery and equipment | Miscellaneous | | | |
| **Transport type from supplier to hub** | Truck/Trailer | Inland waterway barge | LHV | Concrete mixer truck | Dump truck | | | | | |
| **Transshipment to vessel** | Grabber crane | Crane | Wheel loader | Conveyor belt | Dump | Chute | | | | |
| **Load carrier to site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | Concrete mixer | | | |
| **Transport type to and from site** | Push/tugboat + deck barge | Push/tugboat + hopper barge | Push/tugboat + (coupling)pontoon | Push/tugboat + barge with crane | Push/tugboat + barge with concrete mixer | Self-propelled deck barge | Self-propelled barge with crane | Roll-on/Roll-off barge | Ferry | Autonomous vessel |
| **Vessel load** | < 30 tonnes | 30 tonnes | 40 tonnes | 50 tonnes | 60 tonnes | 70 tonnes | 80 tonnes | 90 tonnes | > 90 tonnes | |
| **Fuel type** | Diesel | Electric | Biodiesel | Biofuel (HVO) | Hybrid | GTL | Hydrogen fuel | | | |
| **Unloading equipment** | Crane | Vessel mounted crane | Wheel loader | Hydraulic excavator | Forklift truck | Hydraulic jack system | Conveyor belt | Pump system | Crane + concrete hopper | None |
| **Store material at site** | Direct to work platform/pontoon | Chosen transport type > 1 day | Chosen transport type ≤ 1 day | No storage, direct usage | | | | | | |
| **Choose material to be transported back** | Dry bulk (demolition waste) | Palletised materials | Long materials | Machinery and equipment | Contaminated waste | Miscellaneous | | | | |
| **Load carrier from site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | | | | |

Figure 4.9: Design alternative 1

This vessel is not suitable for bulky loose material and can therefore best be filled with big bags. Furthermore, with using big bags, it is guaranteed that the crane on board of the vessel is able to transship the bulk material to the construction site. Since the cost of the "City Supplier" is estimated to be around €165 +/- 20%, it is rather expensive to use the vessel as a temporary storage site or wait until the construction activities are finalised. Therefore it is a logical choice to directly load the material to the construction site and use the vessel for other purposes. Lastly, for the return flow also big bags will be used, since the crane can easily transship these units.

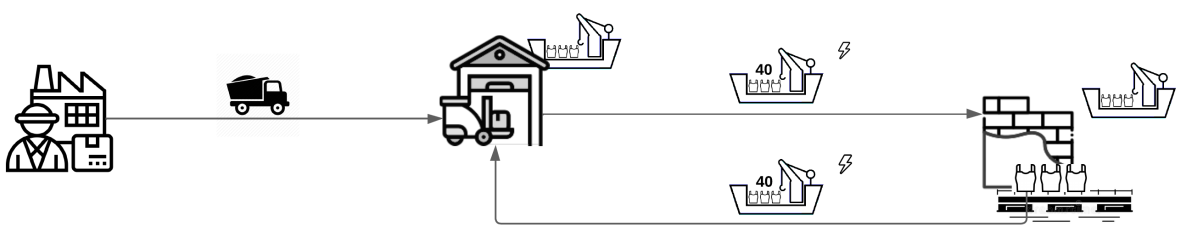



Figure 4.10: Physical design alternative 1

Expected consequences compared to the baseline scenario are as follows:

- Increase in vessel movements, since the average vessel load is a third lower than the vessel load of the baseline.
- Decrease in $CO_2$ emissions due to the electrically propelled motor

- Less handling costs due to no need for additional handling equipment, but at the same time also higher handling costs due to the fact that the motorised part of the transport type can not be disconnected like in the baseline and needs to wait during unloading and loading
- Higher transport costs due to the higher cost per hour of a self-propelled barge

**Design alternative 2 - Just-in-time delivery**
For this design alternative it is chosen to focus on Just-in-time delivery, where the trade-off can be made visible between transporting less load per shipment that can be processed immediately in the project or transporting large materials that can be processed during the day with the corresponding storage cost (Baseline scenario). In this design alternative it is chosen to transport less than 30 tonnes per shipment, waits till the supply material is unloaded and the waste flow is loaded. Hereafter the transport type, in this case a hopper barge and tugboat transports back to supply new material.

For all stakeholders this alternative is of relevance to test. The consequences of using vessels with a lower loading capacity for the construction logistics can be estimated by everyone, but the actual consequences are not generally known. Besides, it is not always possible to perform transport with large loads due to the fairway profiles in the canals of Amsterdam. In some cases a vessel is restricted to a maximum load of 25 ton per shipment. As can be seen in Figure 4.11 apart from the vessel load and the storing choice, the components stay the same as the baseline scenario. This is consciously chosen to make sure the immediate impact can be seen from the results.

| MEANS / COMPONENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material to be transported to site** | Dry bulk | Palletised materials | Prefab elements | Long materials | Liquid bulk | Machinery and equipment | Miscellaneous | | | |
| **Transport type from supplier to hub** | Truck/Trailer | Inland waterway barge | LHV | Concrete mixer truck | Dump truck | | | | | |
| **Transshipment to vessel** | Grabber crane | Crane | Wheel loader | Conveyor belt | Dump | Chute | | | | |
| **Load carrier to site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | Concrete mixer | | | |
| **Transport type to and from site** | Push/tugboat + deck barge | Push/tugboat + hopper barge | Push/tugboat + (coupling)pontoon | Push/tugboat + barge with crane | Push/tugboat + barge with concrete mixer | Self-propelled deck barge | Self-propelled barge with crane | Roll-on/Roll-off barge | Ferry | Autonomous vessel |
| **Vessel load** | < 30 tonnes | 30 tonnes | 40 tonnes | 50 tonnes | 60 tonnes | 70 tonnes | 80 tonnes | 90 tonnes | > 90 tonnes | |
| **Fuel type** | Diesel | Electric | Biodiesel | Biofuel (HVO) | Hybrid | GTL | Hydrogen fuel | | | |
| **Unloading equipment** | Crane | Vessel mounted crane | Wheel loader | Hydraulic excavator | Forklift truck | Hydraulic jack system | Conveyor belt | Pump system | Crane + concrete hopper | None |
| **Store material at site** | Direct to work platform/pontoon | Chosen transport type > 1 day | Chosen transport type ≤ 1 day | No storage, direct usage | | | | | | |
| **Choose material to be transported back** | Dry bulk (demolition waste) | Palletised materials | Long materials | Machinery and equipment | Contaminated waste | Miscellaneous | | | | |
| **Load carrier from site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | | | | |

Figure 4.11: Design alternative 2

In Figure 4.12 the physical design of this alternative is shown, in which can be seen that no storage activities are present at the construction site.

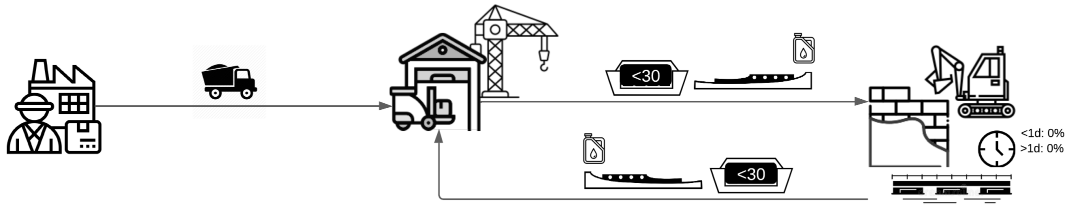



Figure 4.12: Physical design alternative 2

The expected consequences of this design alternative compared to the baseline scenario are as follows:

- Increase in movements and thus in vessel kilometres, because of the smaller vessel load per shipment
- Increase in transport cost due to the increase in movements
- Increase in handling cost, since the vessels are waiting on the handling of material at the construction site
- Decrease in storage cost, since no storage activities at the construction site take place. Whether the decrease in storage cost outweigh both the increase in transport as handling cost is difficult to predict

**Design alternative 3 - Use skips as storage location**

In the final design alternative generated from the waterborne construction logistics system (see Figure 4.13, it is decided to transport the dry bulk material in large skips of 9 m3. The available tonnage in such a skip is around 12 tonnes of dry bulk. It is assumed that three skips can be places on a deck barge. Therefore it is chosen to use a tugboat with deck barge for this alternative. When three skips fit on the vessel, around 36 tonnes can be taken as average vessel load per shipment. In this alternative biofuel is chosen as fuel type. The unloading at the site will be performed with a crane. Since it only has to carry three skips from the deck barge to the platform, the handling time is expected to be considerably lower than for other possible load carrier choices. However, due to the fact that it is chosen to store material at the site for more than one day, the efficiency of transshipment will decrease significantly due to the extra time.

| MEANS<br>COMPONENT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material to be transported to site** | Dry bulk | Palletised materials | Prefab elements | Long materials | Liquid bulk | Machinery and equipment | Miscellaneous | | | |
| **Transport type from supplier to hub** | Truck/Trailer | Inland waterway barge | LHV | Concrete mixer truck | Dump truck | | | | | |
| **Transshipment to vessel** | Grabber crane | Crane | Wheel loader | Conveyor belt | Dump | Chute | | | | |
| **Load carrier to site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | Concrete mixer | | | |
| **Transport type to and from site** | Push/tugboat + deck barge | Push/tugboat + hopper barge | Push/tugboat + (coupling)pontoon | Push/tugboat + barge with crane | Push/tugboat + barge with concrete mixer | Self-propelled deck barge | Self-propelled barge with crane | Roll-on/Roll-off barge | Ferry | Autonomous vessel |
| **Vessel load** | < 30 tonnes | 30 tonnes | 40 tonnes | 50 tonnes | 60 tonnes | 70 tonnes | 80 tonnes | 90 tonnes | > 90 tonnes | |
| **Fuel type** | Diesel | Electric | Biodiesel | Biofuel (HVO) | Hybrid | GTL | Hydrogen fuel | | | |
| **Unloading equipment** | Crane | Vessel mounted crane | Wheel loader | Hydraulic excavator | Forklift truck | Hydraulic jack system | Conveyor belt | Pump system | Crane + concrete hopper | None |
| **Store material at site** | Direct to work platform/pontoon | Chosen transport type > 1 day | Chosen transport type ≤ 1 day | No storage, direct usage | | | | | | |
| **Choose material to be transported back** | Dry bulk (demolition waste) | Palletised materials | Long materials | Machinery and equipment | Contaminated waste | Miscellaneous | | | | |
| **Load carrier from site** | Pallet | Flatrack | Skip 6 m3 | Skip 9 m3 | Big bags | Loose material | | | | |

Figure 4.13: Design alternative 3

The expected consequences of this design alternative, for which the The physical design is presented in Figure 4.13, are as follows:

- Lower handling time and therefore probably lower handling cost. However, due to the fact that the skips are stored for multiple days, the efficiency of the handling could decrease
- Higher storage costs due to the fact that it is stored on a deck barge for multiple days
- Also, it might be possible that more vessel movements are needed due to the additional weight of the load carrier

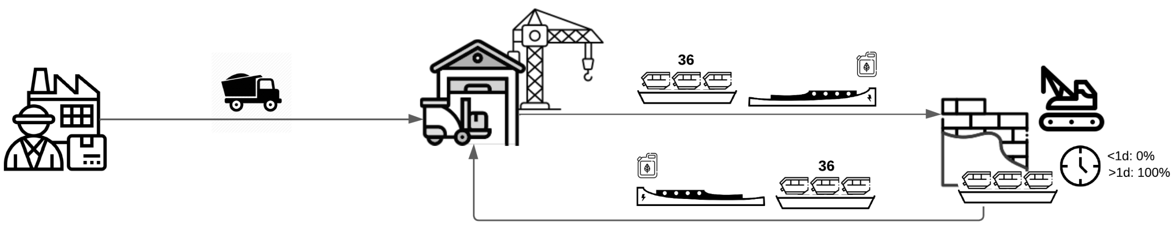



Figure 4.14: Physical design alternative 3

## 4.3. Subconclusion

In this section the first design objective has been met:

DO1 *To design a waterborne construction logistics system for quay wall renovation projects*

Based on the background analysis performed in chapter 3, the requirements, evaluation criteria and building blocks for the waterborne construction logistics design are defined. These are all used in this Section to design the waterborne construction logistics system. This is executed by stating the design requirements and perform a functional analysis to define the functions the system should have. For every separate function a variety of means are chosen. Together this is bundled in a design overview of a morphological chart. From this chart different design alternatives can be generated, which is done in subsection 4.2.3. Finally, physical design overviews are constructed based on the transport chain of the leading component: material type. From these physical design alternatives, the expected consequences of the system are summarised, which will form a starting point for the evaluation of the design alternatives in Section 6.

# 5

# Decision support tool to evaluate design alternatives

In Chapter 4 the design of the waterborne construction logistics system for quay wall renovations is presented. From this design several design alternatives are generated. In this chapter the design of a calculation tool to evaluate these alternatives of the waterborne construction logistics system are presented and discussed. In Section 5.1 up to and including Section 5.4 the decision support tool requirements and approach are discussed. Hereafter the decision support tool itself will be explained, including its parameters and calculations and a verification is performed and discussed in Subsection 5.8.

## 5.1. Decision support tool introduction

As earlier stated in this thesis, there is lack of insight in the characteristics of using a waterborne construction logistics system, and more specifically, in the consequences of using such a system. In order to evaluate the alternatives that come out of the waterborne construction logistics system, also a calculation tool is designed and developed. This decision support tool can be used by giving design alternative specific information as input and thereby simulate the consequences in the form of the KPIs shown in Section 3.3.3, such as logistics cost and amount of vessel kilometers. These outcomes can subsequently be compared to the outcome of the baseline case scenario described in Section 4.2.3. For this thesis the decision support tool will be applied to the design alternatives generated in Section 4.2.3 and the outcomes are discussed in Chapter 6. In this chapter the construction of the decision support tool will be explained in further detail and in Appendix C a guideline for using the decision support tool can be found.

## 5.2. Goal and scope of the decision support tool

The decision support tool is designed to provide a quantification of the consequences of the designed system in Section 4. The decision support tool will be used as a tool to evaluate the design alternatives that are generated from the waterborne construction logistics system. In order to do a proper evaluation, the goal of the decision support tool and its quantification can be divided into the following three main goals. The decision support tool should:

- provide insight into the consequences (KPIs) of the waterborne construction logistics system in comparison to the conventional way of construction logistics for quay wall renovations (road transport)
- provide insight into the consequences (KPIs) of different system alternatives of the waterborne construction logistics system compared
- provide insight into the sensitivity of several system variables to the consequences (KPIs) to support stakeholders in decision making concerning waterborne construction logistics

The decision support tool developed for this research is intended to provide insights into the potential benefits and challenges associated with using waterborne transport for quay wall renovations in Amsterdam. In order to achieve this purpose, a simplification of the waterborne construction logistics system is used as object of modelling.

In Figure 5.1 the functional flow block diagram of the waterborne construction logistics system is shown and the scope of the decision support tool is indicated with the green dotted rectangle. The objective of this decision support tool is to quantify the logistic parameters of these steps in the process, meaning only the transport from hub to site, the handling and storing activities at the construction site and the transport back to the end location is in scope of this decision support tool. The transshipment and handling activities at the construction site are in scope, but it is chosen to exclude transshipment on hubs, since for road transport it is not yet common to use these and the additional handling cost for waterborne transport is not competitive with road transport, unless it is known what the travelled distance was from supplier to the construction site. Also, it is difficult to predict the end location of the chain and the present handling equipment. Since this information could not be retrieved, this is not taken into account for this decision support tool.

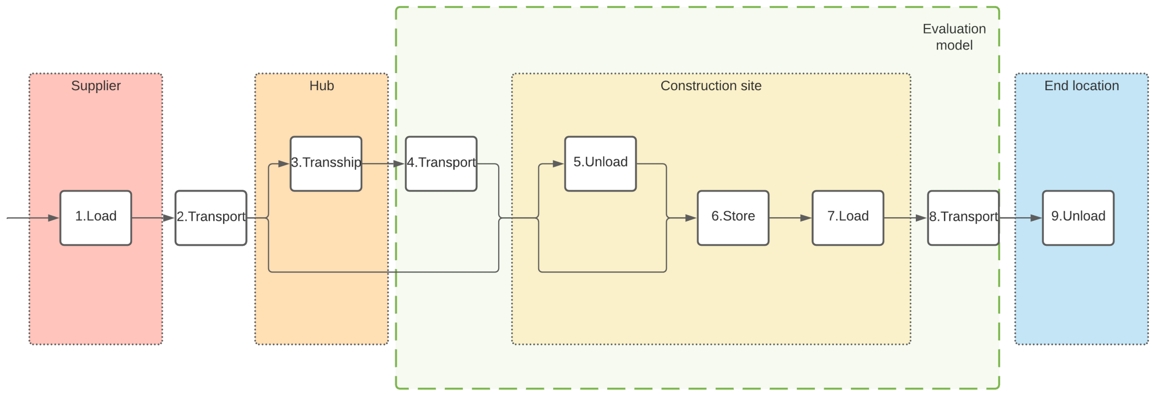



Figure 5.1: Scope of the decision support tool

## 5.3. Boundaries, requirements and assumptions

In order to reach the goal of the decision support tool, for the design and development of the decision support tool the following boundaries and requirements and assumptions are made.

### 5.3.1. Boundaries

As earlier explained in this chapter, the decision support tool only focuses on the system steps from leaving the hub to returning to the hub. In Figure 5.2 a visualisation is depicted in which the geographical boundaries are visible. These form a model constraint, since the tool will not calculate outcomes outside this circle. For road transport, often long distances must be travelled before arriving at the construction site. In order to make a proper comparison, comparable transport distances are taken into account for the decision support tool and is set on a range of 5 kilometres from the city center of Amsterdam. Nevertheless, it is still possible, and likely, that the actual driving or navigating distances are longer, and can be given as input to the decision support tool.

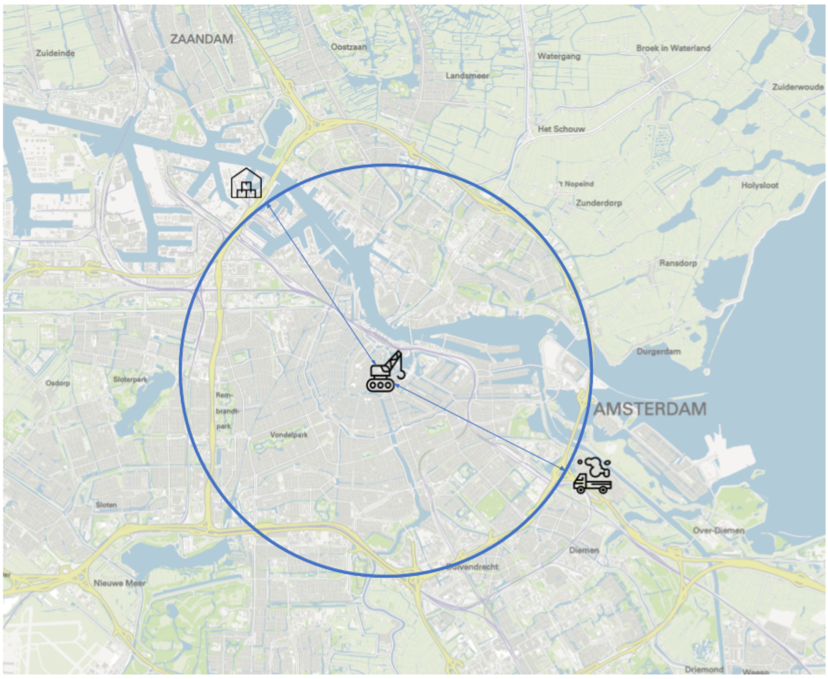



Figure 5.2: Geographical boundaries of the decision support tool

### 5.3.2. Decision support tool requirements

To support the earlier stated goals of the decision support tool, there are requirements that are considered during the development and are needed to secure a proper quantification and evaluation for the waterborne construction logistics design alternatives. Additionally, the tool input and output should be understandable for stakeholders of quay wall renovation projects in order to support decisions concerning waterborne construction logistics. The following requirements are taken into account. The decision support tool:

1. should give insight into the KPIs defined in Section 3.3.3
2. should be applicable to all possible design alternatives from the waterborne construction logistics system
3. should give the possibility to compare the waterborne construction logistics system design alternatives with conventional road transport
4. The tool should be easily usable for all relevant stakeholders

### 5.3.3. Decision support tool assumptions

For the development of the decision support tool several assumptions have been made, which will be briefly discussed.

- The calculations performed in this decision support tool consider the transport of material for a complete renovation project. Depending on the amount of meters quay to be renovated, the amount of tonnes will be defined
- In this decision support tool it is assumed that for a linear meter quay that needs to be renovated, an even amount of tonnes of material will be supplied as discharged. The material type does differ, but is not taken into account in the project broad calculation of this decision support tool
- This tool does not take into account fluctuations in driving and sailing speed at certain times of the day. For simplicity reasons possible traffic jams or rush hours are not considered, but a reasonable average value for the entire project has been assumed. Some delay has been included in the average vessel speed for the different modalities in the tool, since from interviews was retrieved trucks and vessels do have a longer transport time.
- An average transport speed for both modalities is chosen, which is not only the average speed for both the supply as the return flow, but also for the entire project in general

- The assumption is made that every vessel takes up some return flow, even if it only takes up 1% of the capacity.
- The distance from hub to site is assumed to be the same as the travel distance from site to hub or any other end location
- The handling and storage cost are only operational cost directly related to the construction logistics chain of the tool scope. The handling cost in this decision support tool are only the operational handling cost for transshipping material from hub to site and vice versa. Rental cost for mobile handling equipment or storage facilities on a project base are not taken into account, but the calculated cost in this decision support tool could be interesting for constructors to assign project cost to the right logistics activities

## 5.4. Modelling Approach

A tool has been developed in Microsoft Excel that meets the objective of this research to provide insights into the consequences of using waterborne construction logistics for quay wall renovation projects.

Because the choice of whether or not to use waterborne construction logistics depends on many project-specific factors, the output of this decision support tool is decision-supporting. This means the decision support tool will not make any decisions itself, the user shall have to draw conclusions and take actions accordingly based on the output of the decision support tool.

The consequences of the different system steps in scope of the tool will be quantified step-wise after which the principle of Activity Based Costing will be applied to the sub processes. With this method the different outputs per step will be summed up in order to give insight into the consequences on project level (Fang & Ng, 2011), but it is also possible to focus on a sub process itself.

## 5.5. Overview and explanation of tool parameters

In this section an overview of the decision support tool parameters is given in the form of Table 5.1. In addition to this table, a brief description of the input parameters and their significance in the decision support tool is provided in this section. This may help the users of the decision support tool in understanding the context of the parameter values and how they relate to the problem being solved. It is important to mention that the index $i$ in the abbreviations of the parameters stand for the different modalities, where i = water, road.

### 5.5.1. Input parameters

Table 5.1: Input parameters of the decision support tool

| Input parameters | Abbreviation | (Initial) value road | (Initial) value water | Unit |
|---|---|---|---|---|
| Quay wall length | $L_{quay}$ | 100 | 100 | metres |
| Distance hub - site | $Dist_{hs}$ | 7.5 | 7.5 | km |
| Speed transport mode | $V_i$ | 20 | 7 | km/h |
| Capacity of transport carrier | $Cap_i$ | 15 | 80 | tonnes |
| Loading rate of transport carrier | $Loadrate_i$ | 90 | 75 | % |
| Percentage transport with return flow | $\%_{ret}$ | 90 | 100 | % |
| Loading rate of returning transport carrier | $Loadrate_{ret}$ | 50 | 50 | % |
| Percentage store up to 1 day | $\%_{store1day}$ | 0 | 50 | % |
| Percentage store more than 1 day | $\%_{store3day}$ | 10 | 50 | % |

**Quay wall length**
*Description:* This is the to be renovated length of the quay in metres. With this input parameter the amount of material that needs to be transported to and from the construction site can be calculated. For the baseline case scenario we will set the initial value on 100 metres quay wall to be renovated.

*Significance:* The quay wall length is expected to be of low significance. It does influence the size of the construction project, but does not necessarily influence other factors than the amount of construction material to be transported. Whether the size of a project has significant impact other than what would be expected from a larger project, needs to be investigated in Section 6.

**Distance hub - site**
*Description:* Distance between construction site and storage/disposal site. This is the navigating or driving distance between the hub where the material is loaded onto the transport carrier, to the construction site and vice versa. Based on the location of the water transporter, supplier, or hub, the average transport distance can be chosen. Based on the average hub distances discussed in Section 3.4, a default value of 7.5 km is provided in the decision support tool, but users can adjust this parameter value. For road transport, as discussed in Section 5.3.1, the transport distance used is from a range of 5 km as the crow flies from the inner city of Amsterdam and for this decision support tool the actual driving distance will be used as input.
*Significance:* This parameter is expected to have a significant impact on the cost and efficiency of transport in the tool. Longer distances between the construction site and storage/disposal site may result in increased transportation costs, longer travel times, and higher emissions from vehicles and vessels. Therefore, it is important to accurately model and understand the relationship between distance and transport-related costs and emissions.

**Speed transport mode**
*Description:* The speed of the transport modes is defined as the distance the vehicle or vessel travels per unit of time. In this research kilometres per hour is used as the unit for speed. The speed restrictions as described in subsection 3.4 are taken into account for defining the average speed of the trucks and vessels, and are defined as 20 km/h and 7 km/h consecutively. These are project average speeds not specifically considering the calculated effect of different waterways, loads and other external factors to the parameter.
*Significance:* The speed of the transport mode has a direct impact on the travel time of the different transport modes and is therefore expected to be of great significance on the total logistics cost.

**Capacity of transport carrier**
*Description:* This parameter represents the maximum load capacity the transport carrier can transport from hub (or supplier) to construction site. This is the maximum tonnage the transport carrier can carry with a loading rate of 100%. In Section 3.4 the different transport carriers and their maximum loading capacity is discussed. In the decision support tool the default value for road will be 15 tonnes and for water transport 80 tonnes.
*Significance:* The loading capacity of the carriers have direct impact in the amount of movements necessary to transport a total amount of construction material. This has also impact on the amount of vessel and vehicle kilometres and the corresponding emissions and therefore expected to have a significant impact.

**Loading rate of transport carrier**
*Description:* This parameter indicates the average percentage filled of the total possible loading capacity with material during the transportation. Depending on the truck or vessel type and its dimensions, the loading capacity may differ. In this case, the initial values chosen are 90% for road transport and 75% for water transport. This means the average truck carries 13.5 tonnes per shipment and the average vessel 60 tonnes.
*Significance:* The loading rate of the transport carrier is expected to be a significant factor in determining the amount of movements and indirectly the amount of vehicle/vessel kilometres and emissions of the transport type.

**Percentage transport with return flow**
*Description:* This parameter can be explained as the amount of vessels dropping off construction materials that also loads discharge or waste flows aboard to transport back to the hub. A goal of the system is to make sure at least 90% of the vessels take up a return flow. From a project point of view it is best when a transport carrier always takes back some waste. Therefore it is chosen to set 100% as an initial value.
*Significance:* This percentage has impact in that sense, that it influences whether or not additional transport carriers need to be sent to the construction site to pick up waste. It is of low impact on the total amount of movements and vessel kilometres, but it could have impact on the transport cost for smaller projects.

**Loading rate of returning transport carrier**
*Description:* When a vessel takes up a return flow, what is the percentage filled of the total loading capacity of the vessel. This value can vary a lot and is dependent on the construction activities. A default value of 50% is chosen, but can be adjusted by the user of the tool.
*Significance:* This percentage has a comparable impact to the percentage transport with return flow and need to be as high as possible to ensure smooth and efficient operations.

**Percentage store up to 1 day**
*Description:* As mentioned above, it might in some cases be interesting to use the chosen transport type as a temporary storage location. This parameter is the percentage of movements that leave the transport carrier (not the tugboat or pushboat) at the construction site as temporary storage location up to one day. For road transport it is assumed that is does not occur often and this parameter is set on 0%, while for waterborne transport for the baseline case scenario the initial value is set on 50%.
*Significance:* This choice of this parameter is expected to have great impact on both the storage as handling cost, but since there is a strong correlation between these cost and the choice of this parameter, the impact on the total logistics cost is difficult to predict.

**Percentage store more than 1 day**
*Description:* This parameter is the percentage of movements that leave the transport carrier (not the tugboat or pushboat) at the construction site as temporary storage location more than one day. Also for the baseline case of waterborne transport this input value is set on 50%. Also for road transport, it may be convenient to store a waste container at the site for a couple of days before returning it. Therefore a value of 10% is chosen as input for road transport.
*Significance:* This parameter is expected to have great impact on both the storage as handling cost and due to the correlation between these two cost, the impact on total logistics cost is hard te predict.

## 5.5.2. System parameters

In this subsection the system parameters, that are set in the decision support tool with a default value, will be discussed briefly. In Table 5.2 an overview of the system parameters is shown. These system variables are background paramaters with a default value, which are used to generate output based on the input parameters. Under the table a brief explanation per parameter is given.

Table 5.2: System parameters of the decision support tool

| System parameters | Abbreviation | Default value road | Default value water | Unit |
|---|---|---|---|---|
| Tonnes per linear meter quay | $T_{p/m}$ | 31.2 | 31.2 | tonnes/m |
| Total material quantity | $Q_{tot}$ | $L_{quay}$ * $T_{p/m}$ | $L_{quay}$ * $T_{p/m}$ | tonnes |
| Calculation factor return movement | $f_{calc2way}$ | 2 | 2 | - |
| Calculation factor one way movement | $f_{calc1way}$ | 1.5 | 1.5 | - |
| Rental cost propelled transport type | $C_{truck}$ / $C_{vessel}$ | 90 | 130 | €/h |
| Rental cost transport carrier | $C_{barge}$ | - | 12.50 | €/h |
| Rental cost handling equipment | $C_{equip_i}$ | 30 | 30 | €/h |
| (Un)loading speed equipment | $S_{handling_i}$ | 75 | 75 | tonnes/h |
| (Un)loading personnel needed | $A_{pers_i}$ | 0 | 1 | - |
| Hourly salary cost personnel | $C_{pers_i}$ | 45 | 45 | €/h |
| Calculation factor loading | $f_{calcload}$ | 0.5 | 0.5 | - |
| Rental cost transport carrier per day | $C_{store_i}$ | 20 | 100 | €/day |
| Calculation factor no storage | $f_{no_{store}}$ | 0 | 0 | - |
| Calculation factor 1 day | $f_{store_1}$ | 1 | 1 | - |
| Calculation factor >1 day | $f_{store_{>1}}$ | 3 | 3 | - |
| Discount factor store more than 1 day | $f_{store_{disc}}$ | 10 | 10 | % |

**Tonnes per linear meter quay**
*Description:* This parameter stands for the amount of material needed in tonnes to renovate one linear meter quay wall of a project. The value chosen is based on the performed calculations of Section 3.2.3 in combination with the input variable Quay wall length. The default value chosen for a project is 31.2 tonnes per linear metre quay wall, which is only the supply of material, since it is mentioned in Section 5.3.3 that both supply as discharge quantities are comparable in the entirety of the project.
*Significance:* This parameter has direct impact on the amount of tonnes that need to be transported and therefore how many vessels or trucks need to be deployed. It is expected to be constant over the projects and therefore in this thesis not significant.

**Total material quantity**
*Description:* The total material quantity is the total amount of material [tonnes] need to be transported from hub to construction site and vice versa. It is the amount of metres quay that need to be renovated times the amount of tonnes needed per linear meter quay.
*Significance:* It is dependent on two other variables and therefore not expected to be significant to the outcomes of the decision support tool.

**Calculation factor return movement**
*Description:* This is a calculation factor used for determining the amount of vessel kilometres. When a truck or vessel picks up waste as a return flow, the calculation factor is 2, since the transport carrier covers the complete transport distance.
*Significance:* Expected to be medium significant. With the current value of 2 for a two-way movement, it should give a logical output. However, if a user does change this parameter value, it will have significant impact on the amount of vessel kilometres, because it is multiplied by all movements to the site and has indirectly impact on the total transport cost.

**Calculation factor one-way movement**
*Description:* This is a calculation factor used for determining the amount of vessel kilometres. When a percentage of vessels did not take up waste as a return flow immediately, the system needs to send an additional transport carrier to the construction site to pick up the remaining waste. Since it is also possible that the additional transport carrier does not need to travel the complete distance from hub to site, but was already stationed in the neighborhood or another project in the region, the default value for this calculation factor is 1.5.
*Significance:* Expected to not be significant, since it only influences a very small part of the total movements.

**Rental cost transport vehicle/vessel**
*Description:* The rental cost of the transport vehicle or vessel, is the rental cost of the part of the modality that propels the material from hub to site and vice versa. This is often the motorized part of the transport type and the personnel cost of the transporter is taken into account in these costs. The rental cost are modelled in €/h and are set as 90 €/h for road transport and 130€/h for water transport.
*Significance:* This parameter is expected to be of most significance on the total logistics cost due to the fact that water transport is already more expensive on an hourly basis. Every small change in this system parameter is expected to have major impact on the outcome of the tool.

**Rental cost transport carrier**
*Description:* These are the rental cost of the carrier of the transport type, the not propelling part of the transport type. It is assumed that trucks and trailers are used for road transport in this tool, not containers. Therefore the default value for road is set on zero. The water value however is set on €12.50 per hour rent of a barge.
*Significance:* Also this parameter is expected to be of significance for the outcome, but not comparable with the rental cost of the propelled part of the transport type.

**Rental cost handling equipment**
*Description:* This parameter is pretty straight forward, the rental cost in € per hour for using handling

equipment at the construction site for unloading and loading of the truck or vessel. it is estimated to be €30 per hour for a mobile crane on the construction site. This is of course a fraction of the total project cost, since the crane could be hired for weeks for construction activities as well.
*Significance:* This parameter is of significance for the impact on total cost for material handling. However, on project basis, the handling cost are expected to be significantly lower than the transport cost. Next to that, the personnel cost probably have more impact on the handling cost than the rental cost of the equipment.

**(Un)loading speed handling equipment**
*Description:* This is the average amount of material in tonnes the handling equipment can transship from transport type to the construction site and vice versa. For a mobile crane, which is used in general, the average handling speed is expected to be 75 tonnes per hour.
*Significance:* This has direct impact on the (un)loading time needed for handling all renovation material and waste and is therefore expected to be an interesting parameter to look into.

**Amount of (un)loading personnel needed**
*Description:* This is the amount of personnel needed during (un)loading of the material on the transport type as an addition to the personnel needed for transportation. For waterborne construction logistics it is usual to schedule additional personnel for good guidance of the large vessels through the narrow canals or for help during the unloading of certain materials or load carriers. For trucks it is assumed that no additional personnel is required for unloading.
*Significance:* Expected to be of significance to the handling cost, since personnel hours are usually more expensive than the hourly cost of handling equipment.

**Hourly salary cost personnel**
*Description:* These are the hourly cost in € per hour for the additional personnel required to help with unloading the vessel or other transport type.
*Significance:* Expected to be of the same significance to the handling cost as the amount of personnel needed. However, it is more likely to have changes over time in the amount of necessary personnel than the hourly salary cost.

**Calculation factor loading**
*Description:* This is a parameter that can be used as a way to influence the handling speed of the handling equipment. Apart from the speed it should actually operate at, other factors might influence this parameter. In this decision support tool, this calculation factor is used when it is chosen to not store at the construction site and directly use the unloaded material for construction activities of the quay wall. Therefore it is chosen to use a default value of 0.5 for that specific situation, which practically means the handling equipment will operate two times slower than it normally would.
*Significance:* Depending on the choice of storage from the design options, this parameter could have significant impact on the handling cost when it is chosen to not store on site.

**Rental cost transport carrier per day**
*Description:* This parameter stands for the rental cost of the transport carrier per day. This is the same rental cost as mentioned before, but in this case the user pays for the barge a complete day regardless of how many hours the barge is actually used. This could be interesting for using the barge as temporary storage site for one or multiple days. For road it is assumed the daily rental cost for a carrier like a container is €20 per day. For waterborne transport the default value for renting a barge for a day is €100 per day.
*Significance:* These cost might have significant impact on the storage cost when it is decided to use the barges as temporary storage location. The significance is dependent on the amount of storage days.

**Calculation factors storage choices**
*Description:* These are calculation factors used to make a difference in the calculation of the following three storage options:

- $f_{no_{store}}$ - Used when the transport type is not used as temporary storage facility and default value is set on 0.
- $f_{store_1}$ - Used when the transport type is used as storage facility for up to one day. Default value of the parameter is set on 1.

- $f_{store_{>1}}$ - Used when the transport type is used as storage facility for more than one day. Default parameter value is set on 3.

*Significance:* These parameter are dependent on the distribution chosen in the input parameters, but are expected to have a moderate impact on the outcome of the storage cost.

**Discount factor store more than 1 day**
*Description:* This parameter is a discount factor applied to the daily rental cost of a transport carrier when it is used as a temporary storage facility for more than one day.
*Significance:* This parameter is expected to not be of great significance to the storage cost, but it does lower the storage cost to a certain extent.

### 5.5.3. Output parameters

The output parameters of the decision support tool are based on the desired insight into the KPIs described in Section 3.3.3. In Table 5.3 an overview is shown where i = r, w. Where r and w stand for road and water transport. The calculations of the output parameters are described in the following section.

Table 5.3: Output parameters of the decision support tool

| **Output parameters** | **Abbreviation** | **Unit** |
|---|---|---|
| Total transport cost | $C_{transport_i}$ | € |
| Total handling cost | $C_{handling_i}$ | € |
| Total storage cost | $C_{storage_i}$ | € |
| Total logistics cost | $C_{total_i}$ | € |
| Amount of movements | $M_i$ | [-] |
| Amount of vehicle/vessel kilometres | $VKM_i$ | veh/vessel km |
| Amount of tonkm | $TKM_i$ | tonkm |

## 5.6. Decision support tool calculations

In this section the tool calculations used for determining the output parameters are discussed in more detail. For both road and water transport the same calculation is used, but the values of the input or system parameters might differ and generate different output values.

### 5.6.1. Amount of movements

The amount of vehicle or vessel movements is calculated by dividing the total amount of tonnage needed for supply of the quay wall renovation by the max capacity of the vessel multiplied by the average loading rate. For all the material that the supplying trucks or vessels could not take back, additional carriers need to be sent to the construction site. This is calculated after the '+' sign in equation 5.1. It is good to mention that the ceiling signs are used to make sure the complete amount of movements is calculated and not partial movements can be summed up or multiplied.

$$M_i = \left\lceil 2 \cdot \left\lceil \frac{Q_{tot}}{Cap_i \cdot Loadrate_i} \right\rceil \right\rceil + 2 \cdot \left\lceil \frac{max\left(Q_{tot} - \left\lceil \frac{Q_{tot}}{(Cap_i \cdot Loadrate_i} \right\rceil \cdot Loadrate_{ret\,i} \cdot Cap_i \; , \; 0\right)}{Cap_i} \right\rceil \tag{5.1}$$

where,
i = road scenario $r_1 ... r_n$ V water scenario $w_1 ... w_m$

### 5.6.2. Amount of vehicle/vessel km

The calculation for the amount of vehicle and vessel kilometres is comparable to the amount of movements calculation. As an addition, the distances that are covered during transport are multiplied by the amount of movements. For this formula (see equation 5.2) the calculation factors described in Section 5.5.2 are used to define the travelled distance for the return flow.

$$VKM_i = D_{hs} \cdot f_{calc2way} \cdot \left\lceil \frac{Q_{tot}}{Cap_i \cdot Loadrate_i} \right\rceil + D_{hs} \cdot f_{calc1way} \cdot \left\lceil \frac{max\left(Q_{tot} - \left\lceil \frac{Q_{tot}}{(Cap_i \cdot Loadrate_i} \right\rceil \cdot Loadrate_{ret_i} \cdot Cap_i, 0\right)}{Cap_i \cdot Loadrate_i} \right\rceil \tag{5.2}$$

where,
i = road scenario $r_1...r_n$ V water scenario $w_1...w_m$

### 5.6.3. Amount of tonkm

The amount of tonkm is the amount of tonnes transported over the transport distance. Since this decision support tool gives a project broad outcome, the calculation consists of multiplying the total transported load by the distance travelled per load.

$$TKM_i = Q_{tot} \cdot Dist_{hs} \cdot 2 \tag{5.3}$$

where,
i = road scenario $r_1...r_n$ V water scenario $w_1...w_m$

### 5.6.4. Total logistics cost

In this decision support tool the total logistics cost are divided into three different cost types and multiplied with Activity Based Costing as a principal.

- **Total transport cost** The total transport cost is calculated by the amount of hours needed for transporting all material (including waste) to and from the construction site multiplied by the rental cost of the total transport type per hour. The amount of hours needed for transport can be calculated by dividing the amount of vessel or vehicle kilometres by the average driving or sailing speed of the propelled part of the transport type as can be seen in equation 5.4.

  $$C_{transport_i} = \frac{VKM_i}{V_i} \cdot (C_{propel_i} \cdot C_{carrier_i}) \tag{5.4}$$

  where,

  i = road scenario $r_1...r_n$ V water scenario $w_1...w_m$

- **Total handling cost** The total handling cost consists of two cost parts. First the total amount of handling time is calculated by dividing the total material quantity by the handling speed of the equipment. Then the handling time is firstly multiplied by the handling equipment cost per hour and secondly with the transport type cost for waiting on the handling activities. In equation 5.5 this calculation is shown.

  $$\begin{aligned} C_{handling_i} = \\ 2 \cdot \Bigg( (1 - (\%_{store1day} + \%_{store3day})) \cdot \frac{Q_{tot}}{S_{handling_i}} \cdot (C_{equip_i} + (A_{pers_i} * C_{pers_i})) \\ + (\%_{store1day} \cdot \frac{Q_{tot}}{S_{handling_i} \cdot f_{store_1}} \cdot C_{equip_i}) \\ + (\%_{store3day} \cdot \frac{Q_{tot}}{S_{handling_i} \cdot f_{store_{>1}}} \cdot C_{equip_i}) \end{aligned} \tag{5.5}$$

  where,

  i = road scenario $r_1...r_n$ V water scenario $w_1...w_m$

- **Total storage cost** The total storage cost, shown in Table 5.6, is calculated in three parts. For the percentage of transport types that do not temporary store the material aboard, the storage cost are not included in the logistics cost. The other parts of the calculation are the percentages of storing up to one day on the transport carrier or more than one day times the storage cost of the transport carrier. For the storage cost, a discount factor for multiple days is taken into account.

$$C_{storage_i} = \left\lceil \left( \frac{Q_{tot}}{Cap_i \cdot Loadrate_i} - (\%_{store1day} + \%_{store3day}) \right) \cdot f_{no_{store}} \right\rceil + \left\lceil \frac{Q_{tot}}{Cap_i \cdot Loadrate_i} \cdot \%_{store1day} \right\rceil \cdot f_{store_1} \cdot \left( C_{store_i} \cdot (1 - f_{store_{disc}})^{f_{store_1} - 1} \right) + \left\lceil \frac{Q_{tot}}{Cap_i \cdot Loadrate_i} \cdot \%_{store>1day} \right\rceil \cdot f_{store_{>1}} \cdot \left( C_{store_i} \cdot (1 - f_{store_{disc}})^{f_{store_{>1}} - 1} \right) \quad (5.6)$$

where,

i = road scenario $r_1 ... r_n$ V water scenario $w_1 ... w_m$

When we sum the total transport, handling and storage cost, the formula for the **total logistics cost** is generated and is shown in equation 5.7.

$$C_{total_i} = C_{transport_i} + C_{handling_i} + C_{storage_i} \ where \ i = r, w \quad (5.7)$$

where,
i = road scenario $r_1 ... r_n$ V water scenario $w_1 ... w_m$

## 5.7. Tool limitations

The decision support tool does have some limitations, which will be mentioned below:

- The decision support tool only gives insights on project level, but does not zoom in on material level. So in order to draw conclusions on material level, the calculations need to be performed per material type separately.
- At this moment, some information of the waterborne construction logistics system as showed in the morphological chart of Figure 4.2, is not yet known. An example of this are the cost of autonomous vessels. This is why not all design alternatives can be quantified with help of the decision support tool. It is however possible to add this information to the system parameters when it is retrieved in the future.
- A large share of the system parameters are based on assumptions and have quite some uncertainty. This has impact on the outcomes of the decision support tool and will be discussed in further detail in Section 6.
- Since for the decision support tool a lot of input and system parameters need to be entered by the user of the system, it is very prone to human errors. When the decision support tool will be available for multiple users, this should be minimised as much as possible.
- The decision support tool does not take construction project phases into account. This means that the amount of material is assumed to be heterogeneous over time, while in practise this might not be the case.

## 5.8. Decision support tool verification

In this final section of the explanation of the decision support tool, a model verification is performed to see if the decision support tool performs as expected and generates feasible and logical results. For the verification a couple of parameters are increased with 10% and the expected output value is compared with the actual output value. When the result is as desired, in the most right column the verification will turn green.

Table 5.4: Decision support tool verification

| Method | Expectation | Initial value | Expected Value | Result | Verified |
|---|---|---|---|---|---|
| Increase $Dist_{hs}$ with 10% | Amount of tonkm + 10% | 46800 | 51480 | 51480 | TRUE |
| Increase $C_{vessel}$ with 10% | Transport cost increase | €18,856 | > €18,856 | €20,576 | TRUE |
| Increase $Loadrate_i$ with 10% | Decrease of $M_i$ | 130 | <130 | 126 | TRUE |

The results show that the decision support tool works as it is expected to work with all tests being positive. Therefore, the decision support tool can be positively verified.

## 5.9. Subconclusion

In this chapter the development of a decision support tool is discussed, which serves as a tool to quantify the consequences of the design alternatives generated in Chapter 4. The developed tool in Microsoft Excel uses an Activity Based Costing approach to define the logistics KPIs that are introduced in Section 3.3.3 and are therefore integrated in this decision support tool as output parameters. In scope of this decision support tool are the system steps from transportation from hub to construction site up to and including the system step of transportation from hub to the end location. In this chapter all parameters are discussed in full detail, as well as the decision support tool calculations. Finally, the limitations of the tool are mentioned in Section 5.7 and a verification is performed.

# 6
# Evaluation of the decision support tool and design alternatives

In this section the design and decision support tool will be evaluated. The physical design alternatives and their expected consequences will be tested by means of the output of the decision support tool. Next to that, the alternatives will be compared. Also, a sensitivity analysis will be performed in order to determine the sensitivity to different variables of the system and how stakeholders can be supported in their decisions considering the newly designed waterborne construction logistics system.

## 6.1. Application to the design alternatives

In order to evaluate the design alternatives and their consequences, a baseline case is designed as discussed in Section 4.2.3. For both the baseline case as the design alternatives, the input values will be shortly discussed. Subsequently, the output of the decision support tool and a brief overview of the remarks in comparison with the baseline case will be discussed. Firstly, a short description of a case study project the decision support tool will be applied to is introduced.

**Case study | Herengracht 1 - 103**
A short introduction into the specifications of a case study quay wall in Amsterdam that is used as a reference for applying the decision support tool to evaluate the design alternatives of the system. The renovation of Herengracht 1 - 103 is used as an generic example due to its central location in the city center of Amsterdam, and the convenient fairway profile of the canal. The following characteristics of the quay wall renovation are considered and used as input for the decision support tool:

- The quay that needs to be renovated has a length of 275 metres, but for this calculation we use 100 metres as a standard
- The distance from the hub location in the Coenhaven to the construction site is around 7.5 kilometers
- Since the vessel spends part of the driving time on the IJ, with an estimated navigating speed of 12 km/h and part of the time in the canals with difficult manoeuvring and an average navigating speed of 3 km/h, the estimated average speed of the vessels is set on 7 km/h
- The fairway profile corresponding to this part of the Herengracht is B, which means vessels with the average dimensions can reach the construction site. This means vessels may have a length of 20 metres and a width of 4.25 metres
- Based on the fairway profile only, it may be possible to ship around 80 tonnes per movement to and from the construction site. However, to give a more realistic image of the average vessel load, a loading rate of 75% is used as input, meaning on average a load of 60 tonnes is shipped to the site.
- It is assumed that on average 90% of the transport types take some waste back from the site to the hub. Waste is not always readily available in the same size as the supplied materials, which results in the assumption that the average loading rate of the returning transport carriers is 50% as opposed to 75% of the supplying transport carriers.

### 6.1.1. Baseline compared to Road transport

For the baseline case all parameters are set to their default values. In Table 6.1 the input parameter values that are used as a default are shown. The characteristics of the case study of Herengracht 1 - 103 are taken as a starting point for the input values. For the system parameters the default values as described in Section 5.5.2 are used and will not be further explained.

Table 6.1: Input parameters for the baseline case

| Input parameter | Abbreviation | Value | Unit |
|---|---|---|---|
| Quay wall length | $L_{quay}$ | 100 | metres |
| Distance hub - site | $Dist_{hs}$ | 7.5 | km |
| Speed transport mode | $V_w$ | 7 | km/h |
| Capacity of transport carrier | $Cap_w$ | 80 | tonnes |
| Loading rate of transport carrier | $Loadrate_w$ | 75 | % |
| Loading rate of returning transport carrier | $Loadrate_{ret}$ | 50 | % |
| Percentage store up to 1 day | $\%_{store1day}$ | 50 | % |
| Percentage store more than 1 day | $\%_{store3day}$ | 50 | % |

For the road scenario to which the baseline case scenario can be compared, all default values shown in Table 5.1, 5.2 and 5.3 of Chapter 5 are used.

**Output values for baseline case scenario**
The output values of the decision support tool are shown in table 6.2. The results will be briefly discussed below.

Table 6.2: Output baseline case scenario

| Output parameters | Output value water | Output value road | Unit |
|---|---|---|---|
| Total transport cost | 18,856 | 20,318 | € |
| Total handling cost | 3,744 | 8,986 | € |
| Total storage cost | 8,918 | 1,166 | € |
| Total logistics cost | 31,518 | 30,470 | € |
| Amount of movements | 130 | 672 | [-] |
| Amount of vessel kilometres | 927 | 4515 | vessel km |
| Amount of tonkm | 46800 | 46800 | tonkm |

When we look at the output parameters of running the baseline case scenario in the decision support tool, a few results need to be discussed about the cost parameters. Firstly, the total transport cost are lower for waterborne transport than for road transport, which is lower than expected and will be discussed in more detail in Section 6.2.1. The total handling cost for water transport are significantly lower than for road transport, which can be explained by the fact that the handling activities happen while the barge is used as a storage site for one or multiple days. The handling activities must still be executed (at a slower pace), but no expensive tugboat or other vessel has waiting cost during unloading and loading of the vessel. For road transport it is plausible that a truck does wait for handling activities at the site, but the rental cost are lower than for the waterborne transport types. The storage cost of the waterborne scenario are much higher than the storage cost for road, which is a logical result when keeping in mind that 100% of the load transported via water will be stored at the site with a minimum of one day. For the road scenario this is only 10% of the transported total. All in all, when we look at the total logistics cost for both scenarios, it can be concluded that based on transport cost only transportation via water is the most interesting option. However, the handling and storage cost are significantly higher than for road transport, resulting in a higher total logistics cost. In Section 6.2.1 the trade-off between water and road for the costs is explained in more detail.

For the other logistical parameters it can be concluded that concerning amount of movements through the city and the corresponding amount of vehicle or vessel kilometres, waterborne transport is always the preferred modality. For waterborne transport, a structural decrease of 80.32% in amount of movements and 79.20% in vessel movements as opposed to road transport can be seen, which is a nice result.

Since the travel distance from hub to site is assumed to be comparable, the results for the amount of tonkm stay the same for both modalities. However, for road transport it might be interesting to include a congestion factor in the future, since trucks often tend to take a longer route in kilometers, but shorter in time. This has its impact on the amount of emissions and other environmental criteria.

### 6.1.2. Alternative analysis

Next, we will compare the outcomes of the design alternatives compared to the baseline case for waterborne construction logistics. In Table 6.3 the values that are given as input to the decision support tool are shown.

Table 6.3: Input parameters of the decision support tool

| Input parameters | Abbreviation | Alternative 1 | Alternative 2 | Alternative 3 | Unit |
|---|---|---|---|---|---|
| Quay wall length | $L_{quay}$ | 100 | 100 | 100 | metres |
| Distance hub - site | $Dist_{hs}$ | 7.5 | 7.5 | 7.5 | km |
| Speed transport mode | $V_i$ | 8 | 7 | 7 | km/h |
| Capacity of transport carrier | $Cap_i$ | 80 | 80 | 80 | tonnes |
| Loading rate of transport carrier | $Loadrate_i$ | 50 | 33,3 | 45 | % |
| Percentage transport with return flow | $\%_{ret}$ | 100 | 100 | 100 | % |
| Loading rate of returning transport carrier | $Loadrate_{ret}$ | 50 | 50 | 45 | % |
| Percentage store up to 1 day | $\%_{store1day}$ | 0 | 0 | 0 | % |
| Percentage store more than 1 day | $\%_{store3day}$ | 0 | 0 | 100 | % |

There are a few remarks for the given input values. For alternative 1 a small increase in the vessel speed is taken into account due to the fact that this transport type does not have an additional tugboat and therefore has a higher mobility and speed through the canals. The capacity of the transport carrier and loading rate of the carriers are modified in that sense that it corresponds with the average load per shipment for the design alternative situations, which is 40 tonnes (maximum for the City Supplier) for alternative 1 and 36 tonnes (3 x 12 tonnes) for alternative 3. For alternative 2 an assumption is made that loading a third of the total capacity might be interesting for JIT deliveries. The final assumption that needs some further explanation, is the fact that for alternative 3 the percentage transport with return flow is 100. This is caused by the fact that the vessel will always be stored for more than one day. Waste can accumulate in the skips during the days, which is why 100% is a logical percentage to assume. However, the loading rate remains the same as on the supply part of the chain, not more than 36 tonnes can be transported back each time.

Table 6.4: Output values for the design alternatives

| Output value | Transport | Handling | Storage | Total logistics cost | Movements | Vesselkm | Tonkm |
|---|---|---|---|---|---|---|---|
| Alternative 1 | €24,131 | €17,472 | €0 | €41,603 | 156 | 1170 | 46.800 |
| Alternative 2 | €36,032 | €18,096 | €0 | €54,128 | 236 | 1770 | 46.800 |
| Alternative 3 | €26,566 | €1,248 | €21,141 | €48,955 | 174 | 1305 | 46.800 |
| ***Compared to*** | | | | | | | |
| Baseline | €18,856 | €3,744 | €8,918 | €31,518 | 130 | 926 | 46.800 |
| Road transport | €20,318 | €8,986 | €1,166 | €30,470 | 672 | 4515 | 46.800 |

**Outcome design alternative 1**

For this design alternative it was expected that the amount of vessel movements would increase in comparison with the baseline scenario, since the vessel load is a third lower. The amount of movements did indeed increase with 20%. It was not clear from the expected consequences whether the handling cost would increase or decrease due to the handling equipment on board being more cost effective, but the transport cost being higher while waiting for the handling activities. From the outcomes of the decision support tool can be seen that the handling cost do increase significantly, from which can be concluded that it needs further research on the trade-off between handling equipment on board versus using equipment on site. The total transport cost also increase, which is an expected consequence of the increase amount of vessel movements and the higher rental price per hour.

**Outcome design alternative 2**
As expected in Section 4.2.3 the amount of movements and vessel km did increase for this design alternative caused by the lower vessel load per shipment. In this design alternative, the consequences of doing JIT deliveries with smaller loads versus inefficient operations at the site with larger loads will be investigated. From the outcomes can be concluded that except for storage cost, this scenario is not cost effective, but does also under perform on the other logistics parameters such as amount of movements and vessel km. It is therefore not a desirable alternative unless it significantly increases the on site efficiency, which needs further investigation.

**Outcome design alternative 3**
For design alternative 3 lower handling time and therefore lower handling cost were expected, which is indeed the case. However, the increase of storage cost does outweigh the decrease in handling cost, since these are more than twice times higher than the baseline case scenario. Another expected consequence was a possible increase in amount of movements caused by a lower load. This is also an outcome of the decision support tool.

Overall, the outcomes of the decision support tool highlight the importance of considering multiple scenarios and parameters when designing and evaluating construction logistics systems. By examining the changes in key variables under different conditions, we can gain a deeper understanding of the potential benefits and drawbacks of different approaches, and make more informed decisions about how to optimize performance and minimize environmental impact.

## 6.2. Tactical trade-offs for waterborne construction logistics

In Section 3 some important trade-offs are defined for performing construction logistics of quay wall renovations over water. In this section the most important trade-offs are analysed based on the outcomes of the decision support tool. The trade-offs are introduced as subsections and later in this section categorised by importance for different stakeholder groups.

### 6.2.1. Trade-off water versus road transport

What we can conclude from the calculation tool is that water transport is always a preferred alternative when we look at the output parameters **amount of movements** through the city and corresponding **kilometres**. This is in line with the expected impact mentioned in Section 3. The metric that does need some further investigation is the **total logistics cost**. The total logistics cost vary based on several input variables and assumptions in system parameters. In this subsection the most interesting variables and parameters are used to discuss the trade-off between water and road transport.

In Figure 6.1 the total logistics cost are plotted against the average load in tonnes that the vessel carries every transport to the construction site. For this calculation a project with a to be renovated quay wall of 100 metres is used as a reference. Also in this figure the base case scenario of performing the same project of 100 metres with road transport is shown. In this base case we assume that a truck can carry a maximum load of 15 tonnes each trip. As you can see in this graph the total logistics cost decrease in a polynomial way as the average tonnage increases per shipment. It can be concluded that when a vessel structurally carries a minimum of 81.9 tonnes per shipment the total logistics cost are lower than the cost for road transport. Since most vessels in the current waterborne construction logistics available fleet have a load capacity of around 80 - 90 tonnes, this is a nice result. Good to point out that this 81.9 tonnes per shipment is calculated with a loading rate of 75%. When moving towards a 100% loading rate, the minimum amount of tonnes that is required per shipment moves towards the 70.7. That is of interest because smaller vessels can be considered to use. For smaller fairway profiles, it is not possible to reach 81.9 tonnes per average shipment, since the maximum passage load is sometimes as small as 25 tonnes. So in not every situation the total logistics cost of water can be lower than the road costs. In addition, the intersection point of the two total logistics costs are under the assumption that 50% of all vessels are stored up to 1 day and 50% are stored more than 1 day. More information about the values of these input parameters can be found in Section 6.3.

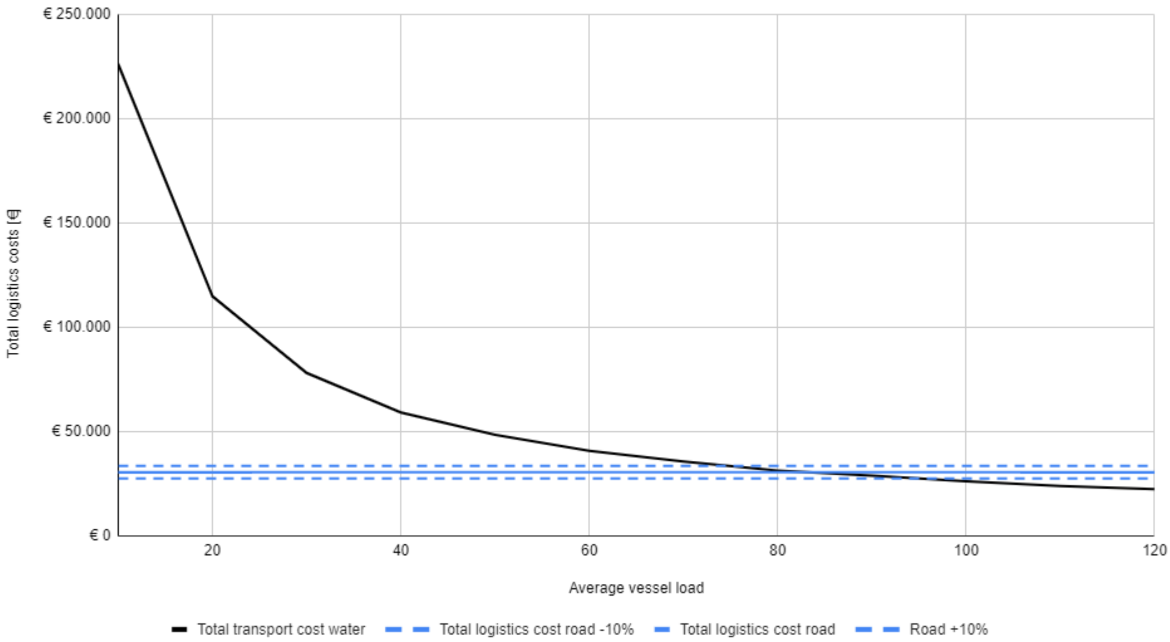



Figure 6.1: Total logistics cost per vessel load

**Relation speed, carrier cost and tonnage**

For the comparison of using water transport versus road transport for the quay wall renovations, there are three variables with direct impact on each other and on this trade-off:

- Average speed for both water and road transport carriers
- Rental cost per hour for both water and road transport carriers
- Average amount of tonnage that is transported per movement by road and water transport carriers

The ratio between the first two variables, the average speed and the carrier cost per modality, has direct impact on the ratio between the load that each shipment should carry. For example when the ratio between the first two variables is 1/3, the vessel should take three times the load of the truck each shipment to make sure the transportation cost are comparable.
In Figure 6.2 the impact of alternating the average vessel speed between 1 and 12 km/h is shown.

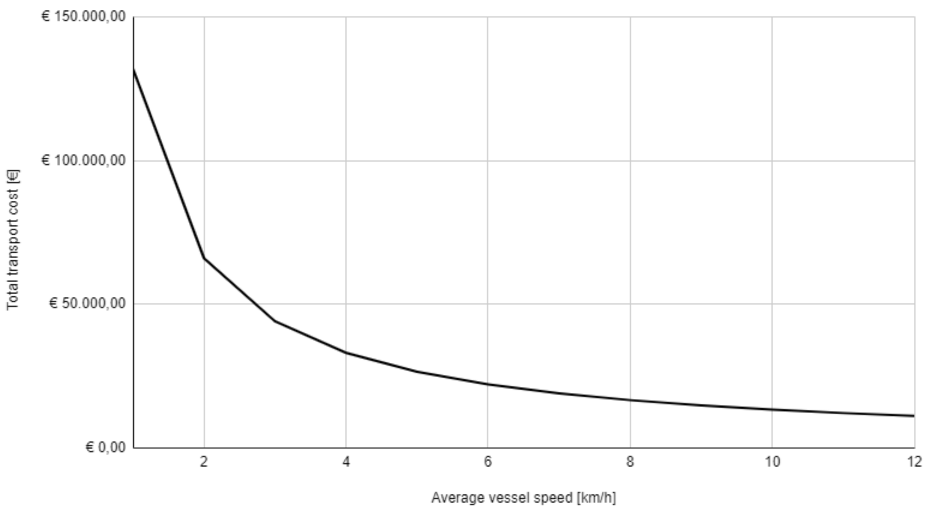



Figure 6.2: Relation vessel speed on total logistics cost

From this graph can be concluded that the total logistics cost do decrease when the average vessel speed increases, but the cost are most impacted on speed changes in the lower range between 3 - 8 km/h.

### 6.2.2. Trade-offs in waterborne construction logistics scenarios

In this section a brief overview of potential trade-offs for waterborne construction logistics alternatives are listed that can be used by stakeholders to make tactical decisions.

- Shipment size - the shipment size has significant impact on the total logistics cost and it might be investigated for which waterborne alternative the cost are most cost effective.
- Navigating speed regulations - The navigating speed is proven to have large impact on the outcomes of the decision support tool. It is interesting to look further into the navigating speed regulations on the water and how, while maintaining a safe environment, the vessel speed can be optimized.

### 6.2.3. Advice for the Municipality of Amsterdam

Based on the outcomes of the decision support tool, some relevant policies or further investigations are recommended.

- Investigate the optimal trade-off value between the average vessel load and vessel speed. In this thesis project the impact of vessel load on transport speed is not taken into account. Nevertheless, both these parameters show significance on the total logistics cost and are therefore of interest to further optimize. This can be performed in the form of a pilot during one of the executed quay wall renovation projects.
- From the results can be concluded that an increase in vessel load does score well on all KPIs. It is therefore recommended to investigate the possibilities of making optimal use of the maximum vessel capacity by for example stimulating cooperation between logistics parties and look into smarter ways to store material in vessels to transport more per movement.
- Invest in coordination for the return waste flows. The loading rate of the waste return flows shows a significant impact on the results of the total logistics cost. At this moment, little coordination of waste flows is present in the system, but optimizing the amount of material transported back from the site might impact the KPIs positively. This might be combined with other waste initiatives over water.
- Investigate the impact of vessel length on the vessel speed. It might on larger scale be more interesting to invest in propelled vessels when higher vessel speeds can be generated. It could for example be investigated if a stronger motor can be used while navigating on the IJ.

## 6.3. Sensitivity analysis

This chapter presents a sensitivity analysis of the waterborne construction logistics system for quay wall renovations in Amsterdam, as described in Chapter 4 and Chapter 5. The aim of this analysis is to identify the key variables that affect the system's performance and to evaluate the impact of changes in these variables on the system's efficiency and feasibility. By varying the input parameters of the decision support tool, we can assess the sensitivity of the waterborne construction logistics system to different factors and identify potential opportunities and matters that require further attention.

The sensitivity analysis considers a range of factors that are likely to impact the performance of the waterborne logistics system, including the distance between the construction site and the storage location, the use of the capacity of vessels, the average vessel speed and the rental carrier cost. By varying these factors, we can assess their impact on key performance indicators such as logistics cost, vessel kilometres and amount of movements.

The outcomes of the sensitivity analysis will inform the design of the logistics system and provide guidance for decision-makers in the construction project. This analysis can help identify trade-offs between different factors and potentially give guidance in defining the most effective configuration of the logistics system for the quay wall renovation project in Amsterdam.

### 6.3.1. 10% sensitivity

In order to determine the sensitivity of the outcome of the decision support tool, a sensitivity analysis has been performed. For this analysis a 10% decrease and increase compared to the base case scenario for the parameters is taken as input. With this, the influence of each separate parameter on the output parameters can be compared. The parameters that have been changed are:

- Distance between hub and construction site over water in kilometres [km]
- Vessel speed [km/h]
- Rental cost of the towing vessel [€]
- Average loading rate of waste flow on the return transport of a vessel [% of tonnage]
- Average loading rate of the capacity of the vessel [% of tonnage]

The numbers used in the sensitivity analysis are listed in Table 6.5. The table shows the used input for system parameters and variables to determine the sensitivity of the system.

Table 6.5: 10% sensitivity analysis

| | **Distance hub to site [km]** | **Vessel speed [km/h])** | **Rental cost towing vessel [€])** | **Loading rate vessel [%]** | **Loading rate waste flow [%]** |
|---|---|---|---|---|---|
| - 10% | 6.75 | 6.3 | 117 | 67.5 | 45 |
| Baseline | 7.5 | 7.0 | 130 | 75 | 50 |
| + 10% | 8.25 | 7.7 | 143 | 82.5 | 55 |

#### Sensitivity on total logistics cost

In Figure 6.3 an overview of the sensitivity of changing the above mentioned variables and parameters with +/- 10% on the total logistics cost is shown. The percentage change of the total logistics cost is shown as a deviation from the baseline scenario described in Section 4.2.3.

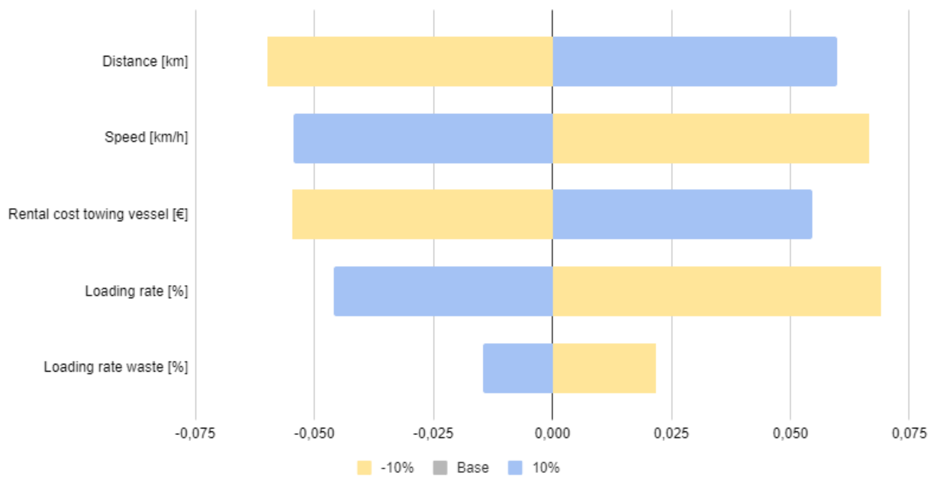



Figure 6.3: Sensitivity of change in parameters/variables on total logistics cost

What can be seen in this figure is that the logistics cost are most sensitive to changes in the transport distance, vessel speed, rental cost and loading rate. For both the distance as the rental cost a linear change of the parameters can be seen, while for the speed and loading rate an decrease of changing the parameter has a more sensitive reaction. This can also be seen in the relation of total logistics cost over speed and over vessel load as discussed in Section 6.2. Also for the loading rate of the waste flow a more significant change is visible for a decrease of the parameter.

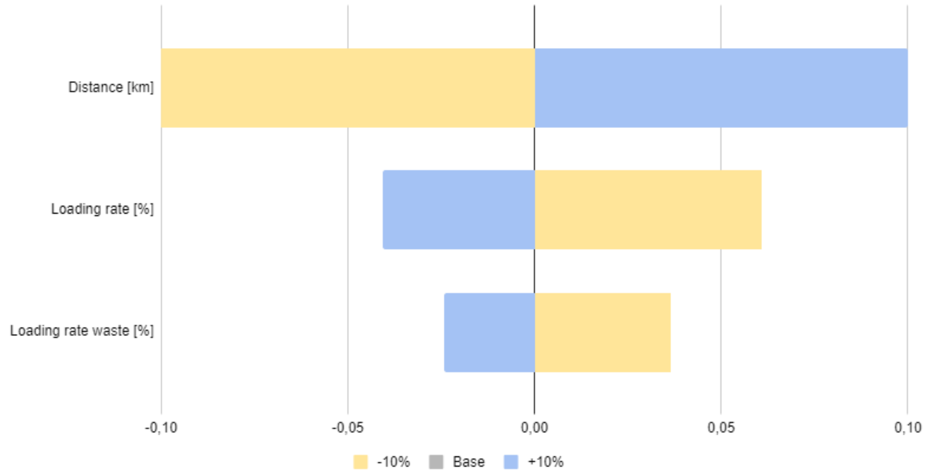



Figure 6.4: Sensitivity of change in parameters/variables on amount of vessel km

For the sensitivity of the parameters on the amount of vesselkm, the same outcome follows for the loading rate and loading rate waste as in Figure 6.3. Namely, both rates are more sensitive for negative changes than positive changes. However, the magnitude of the sensitivity is less for the amound of vesselkm compared to the total logistics cost.

### 6.3.2. MIN/MAX analysis

In this section a MIN/MAX analysis is performed and discussed in which for every input variable the most pessimistic (MIN) and optimistic (MAX) value is chosen while considering it still being realistic scenarios. In Table 6.6, the values for the MIN values are given and Table 6.7 contains the MAX values for this analysis. In addition, both tables contain a column indicating what the difference is compared to the baseline including the direction it drives the costs.

Table 6.6: MIN values with reasoning

| Input parameter | MIN value | Deviation baseline | Reasoning |
|---|---|---|---|
| Distance hub - site | 9 [km] | +20% | Longest measured navigating distance between Coenhaven (hub area) and the furthest canal inside the S100 (Retrieved from https://maps.marineplan.com/) (see Figure D.1 in Appendix D) |
| Speed transport mode | 6 [km/h] | -14.3% | Educated guess based on distance on 't IJ times 8 km/h with speed restriction of 18 km/h and 5 km on the canals with a speed restriction of 6 km/h. |
| Capacity of transport carrier | 38.6 [ton] | -51.5% | Transport carrier with the lowest loading capacity in terms of weight (Retrieved from https://pkwaterbouw.nl/pontons-ruim-en-dekschepen/) (See Figure D.3 in Appendix D) |
| Loading rate of transport carrier | 31 [%] | -59%p | According to van Rijn (2020), the smallest project in Amsterdam had a capacity limit of 25 ton. Given the baseline value for *Capacity of transport carrier* of 80 [ton], the smallest loading rate possible then becomes 31 [%]. |
| Loading rate of returning transport carrier | 30 [%] | -40%p | Educated guess, based on the assumption of inefficient communication and coordination between the different water transport parties who have not been collaborating in earlier projects. |
| Percentage store up to 1 day | 20 [%] | -60%p | Educated guess, based on the assumption that construction site is a busy location. Hence, most transport carriers are unable to be stored at site for over a 1 day period. |
| Percentage store more than 1 day | 80 [%] | +60%p | Educated guess, based on the assumption that construction site is a busy location. Hence, most transport carriers are unable to be stored at site for over a 1 day period. |
| Percentage no storage | 10 [%] | +10%p | Educated guess, based on the assumption that the construction site is for safety reasons too narrow for storing large transport carriers. Hence, these cannot be stored at all. |

A few remarks are important to mention in addition to the reasoning in Table 6.6. The MIN values presented are the values that can be chosen in the most pessimistic scenario independently from each other. The values are chosen under the assumption that all other input variable values are equal to the baseline values. However, when combining all these most pessimistic values in a single MIN analysis the outcome will become unrealistic or infeasible.

First, when combining the MIN values of the *transport carrier capacity* and *loading rate of transport carrier* the total amount of ton the vessel can transport at once is 11.97 ton. But, the study of van Rijn (2020) shows that the smallest amount of ton a vessel could transport in Amsterdam was 25 ton. That is why in the MIN analysis the two input parameters are combined in such a way that together they have a maximum of 25 ton to transport by every movement. The chosen values are 40.0 ton and 63.0% for capacity of transport carrier and loading rate of transport carrier respectively, leading to a realistic MIN analysis.

Second, the MIN values of the three storage parameter options lead to a total of 110% when using them as given in Table 6.6, leading to an infeasible analysis. Because all three input variables focus on storage and analysing the MIN scenario, the realistic combination where storage costs are the highest is 20% - 80% 0% for percentage storage up to 1 day, percentage storage more than 1 day and percentage no storage respectively making the MIN analysis feasible.

Table 6.7: MAX values with reasoning

| Input parameter | MAX value | Deviation baseline | Reasoning |
|---|---|---|---|
| Distance hub - site | 4.5 [km] | -40% | Shortest measured navigating distance between Coenhaven (hub area) and the closest canal inside the S100 (Retrieved from https://maps.marineplan.com/) (see Figure D.2 in Appendix D)) |
| Speed transport mode | 12 [km/h] | +71.4% | Calculated by multiplying half of the distance on 't IJ times 18 km/h and half of the distance on the canals with a 6 km/h speed, which are both the maximum speeds. |
| Capacity of transport carrier | 91.5 [ton] | +14.4% | Transport carrier with the largest loading capacity in terms of weight (Retrieved from https://pkwaterbouw.nl/pontons-ruim-en-dekschepen/) (See Figure D.4 in Appendix D) |
| Loading rate of transport carrier | 95 [%] | +27%p | Given that weight is normative over volume (Section 3.2.3), it is especially for dry bulk possible to fully fill the vessel capacity. A margin of 5% less is used to make the value more realistic. |
| Loading rate of returning transport carrier | 70 [%] | +40%p | Educated guess, based on the assumption of efficient communication and coordination between the different water transport parties who have been collaborating in earlier projects. |
| Percentage store up to 1 day | 80 [%] | +60%p | Educated guess, based on the assumption that construction site is an idle location. Hence, most transport carriers are able to be stored at site for over a 1 day period. |
| Percentage store more than 1 day | 20 [%] | -60%p | Educated guess, based on the assumption that construction site is an idle location. Hence, most transport carriers are able to be stored at site for over a 1 day period. |
| Percentage no storage | 0 [%] | +0%p | The base case scenario already assumes 0% hence a lower percentage for this parameter is infeasible. |

The remarks about some of the input parameters for Table 6.6 do not hold true for MAX values in Table 6.7. Combining all of these together gives a realistic and feasible MAX analysis. The outcome of the MIN/MAX analysis is given in Table 6.8, together with the output values in the baseline scenario as a reference.

Table 6.8: Outcome MIN/MAX analysis

| Output parameter | Outcome MIN scenario | Outcome Baseline scenario | Outcome MAX scenario |
|---|---|---|---|
| Total transport cost | €66,583 | €18,856 | €4,569 |
| Total handling cost | €2,995 | €3,744 | €4,493 |
| Total storage cost | €26,800 | €8,918 | €4,844 |
| Total logistics cost | €96,378 | €31,518 | €13,906 |
| Amount of movements | 332 | 130 | 90 |
| Amount of vesselkm | 2804 | 926 | 385 |
| Amount of tonkm | 56160 | 46800 | 28080 |

**Outcome MIN/MAX analysis**

From Table 6.8 can be seen that the total logistics costs of the most optimistic scenario are almost a factor 7 smaller compared to the most pessimistic scenario. Especially the transport costs differ significantly between the two extreme scenarios.

Furthermore, the total handling cost in the MIN scenario are lower than those costs in the MAX scenario. As shown in equation 5.5 the duration of unloading a vessel is longer when in the meantime people are working on the construction site. That is why the handling costs are higher when less vessels are stored for 1 day or more. But when looking overall, storage costs have a bigger impact on the total logistics costs than handling costs. Hence, minimizing storage costs is of a bigger interest than minimizing the total handling costs. That is why preventing vessels at the construction site for storage is preferred over an increase in handling time.

Next, the number of movements in the MIN scenario are approximately 2.6 more compared to the baseline scenario. An undesired burden on the canals and city of Amsterdam. However, the total number of movements is even in this most pessimistic scenario less than half of the number of required movements with road transport (see Table 6.4).

Besides comparing the number of movements, comparing the total logistics costs between the road and MIN scenario as well as the road and MAX scenario is of interest. This first comparison can be seen in Figure 6.5 and the latter in Figure 6.6.

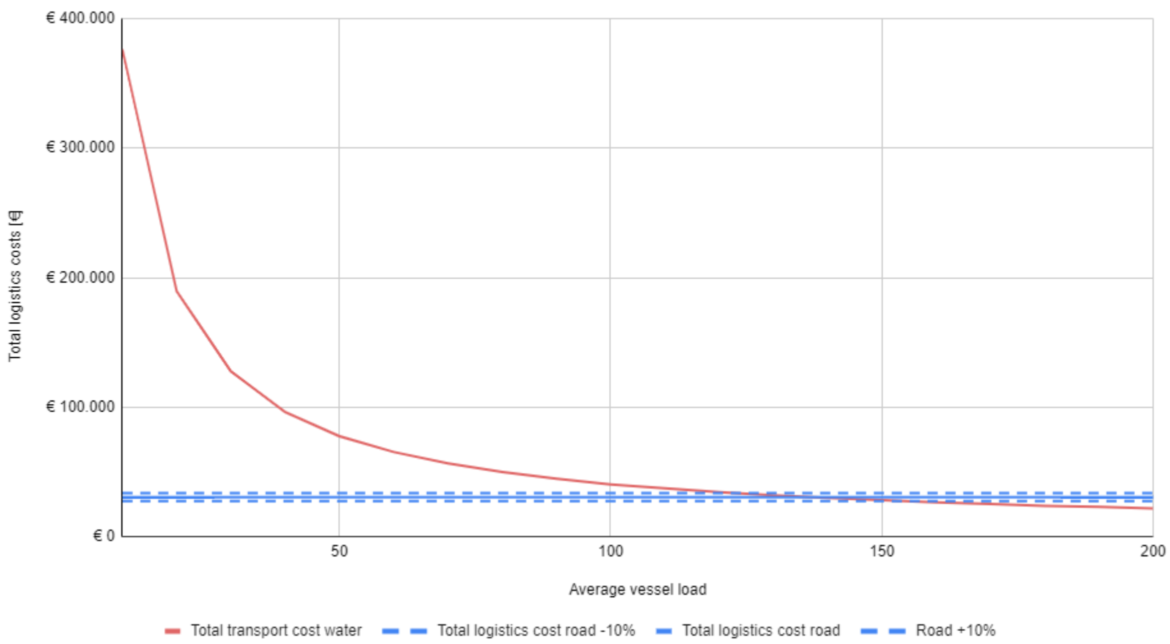



Figure 6.5: Total logistics cost per vessel load in the MIN scenario for water

While the number of total movements between the road and the MIN scenario over water are in favor of the MIN scenario, this cannot be concluded about the total logistics costs. The intersection between the logistics costs of the road and the water is at an average vessel load of 136.9 ton. In the MIN scenario with a loading capacity of 40 ton and a loading rate of 63% of the transportation carrier, this intersection value cannot be met.

On the contrary, Figure 6.6 shows an intersection in total logistics costs between the road and most optimistic water scenario at 31.3 ton. With a capacity of 91.5 ton and a loading rate of 95% of the transportation carrier in this MAX scenario, the total logistics costs for water transport are significantly lower than the road logistics costs.

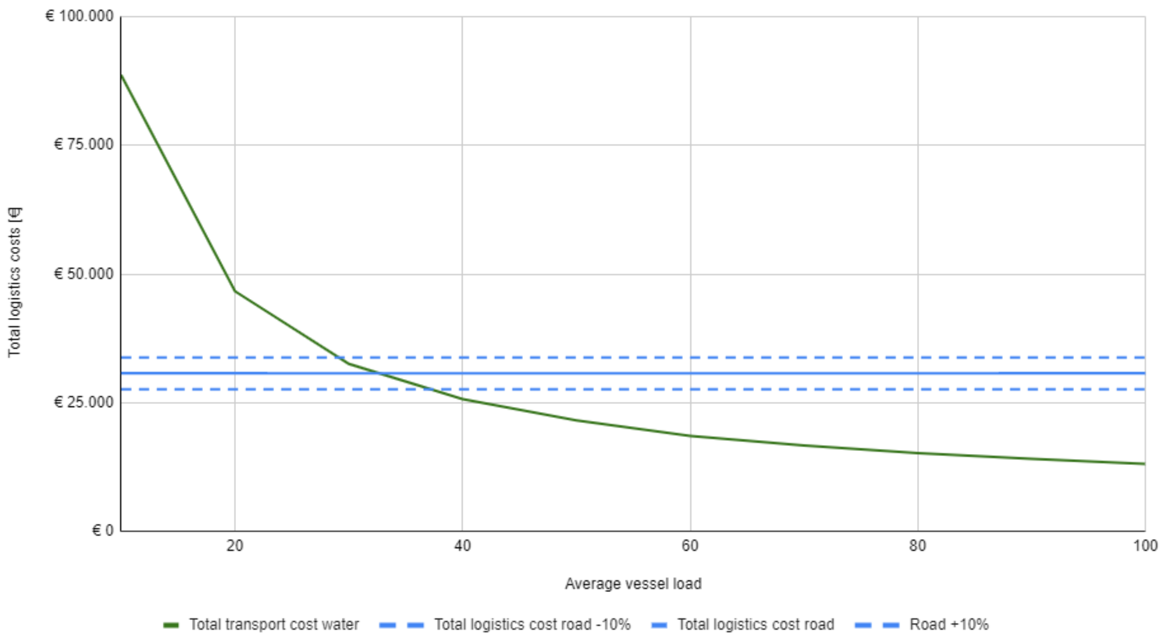



Figure 6.6: Total logistics cost per vessel load in the MAX scenario for water

## 6.4. Subconclusion

In this chapter the calculated consequences calculated by the decision support tool discussed in Chapter 5 are compared to the expected consequences of the design alternatives generated in section 4.2.3. When waterborne alternatives are compared to road transport, the amount of movements for water (-80%) and vessel kilometres (-79%) is always more advantageous. When looking at total logistics cost, it only becomes interesting when vessels can take up more than 81.9 tonnes on average per shipment. Furthermore, the lower amounts carried to the site for Just In Time deliveries do not outweigh the additional on site storage cost. The waterborne construction logistics system is most sensitive to the vessel speed, especially the total logistics cost increase significantly for lower speeds, and for the load capacity or average loading rate of the vessels.

Regarding the MIN/MAX analysis, it follows that the total logistics costs can vary between the €13,906 and €96,378 which is a range of €82,472. Most of these costs come from the total transportation cost. In the MIN scenario, 69.1% of the total logistics cost come from the transport cost while this percentage is 32.9% in the MIN scenario. Hence, these costs are the most important to control.

On the contrary, the handling costs in the most pessimistic scenario are lower compared to the most optimistic scenario. The reason for this is due to a higher number of vessels which are stored for more than 1 day in the former scenario. The handling task is executed faster with no workers on the construction site which is more often the case when the vessel is stored at the site also during moments when nobody else is working. In the MAX scenario, preventing storage of vessels is required over faster handling, which is reflected in the total costs of both output parameters.

Finally, interesting to mention is the number of road movements compared to the number of vessel movements in the MIN scenario. Almost twice as many movements are required with road transportation than in the most pessimistic water scenario. An interesting finding for the Municipality of Amsterdam for having the least burden for her citizens.

# 7

# Conclusion and recommendations

In this chapter the conclusion of this thesis project is presented in Section 7.1 based on the answers to the research questions stated in Chapter 1. Additionally recommendations for further research and for practical use are discussed in Section 7.2.

## 7.1. Conclusion

This section contains the conclusions of this thesis project to answer the research questions that contributed to reaching the main thesis project objective:

*"To design a waterborne construction logistics system for quay wall renovation projects in the city center of Amsterdam and to provide insight into the consequences of this system."*

In order to be able to reach the thesis project objective stated above, multiple research questions are investigated contributing indirectly or directly to the objective. In the following section these research question are answered.

- *"What characteristics of a quay wall renovation project need to be taken into account for designing a waterborne construction logistics system?"*

From the analysis conducted in Chapter 3 three important characteristics are considered in the design of the waterborne construction logistics system.

Firstly, the most important characteristic of a quay wall renovation compared to regular construction projects is the construction material composition per shipment. Seven sorts of material types have been identified, from which dry bulk takes up the largest share of the total material supply. Quay wall renovation projects are particularly characterised by the material specific flow (monoflows) of material. A new project phase can only commence when the previous project phase is finished and due to the large amounts of tonnes per material type during a project phase, it does not occur often that material types are bundled. The material type is therefore taken as leading building block in designing the waterborne construction logistics system.

Based on the background analysis, it is concluded that the weight of construction material is normative over the volume, which practically means that transport types are not always fully loaded in case of transporting heavy materials. This is taken as an important consideration in this thesis project.

Lastly, the Municipality of Amsterdam is actively focusing on stimulating transport over water for all purposes to relieve roads, quays and bridges. It would therefore be contradictory when the supply and discharge of quay wall renovation material and equipment would be performed via road transport. Nevertheless, this is not the only reason the Municipality is enforcing transport over water for quay wall renovations as much as possible. The accessibility of most quay walls is sufficient over water, which might even be an improvement compared to late road deliveries caused by congestion, or limited storage space. Since the quays are located near the water front, there are some opportunities such as performing construction activities on the water.

- *"What are the performance indicators of interest for designing a waterborne construction logistics system and how do they influence the stakeholders of this system?"*

For the introduction of a waterborne construction logistics system nine stakeholder groups are identified. First, the interests and role of the stakeholder group are discussed. Hereafter the drivers and barriers of the to be designed system are listed. It can be concluded from this analysis that most stakeholders have a positive attitude towards waterborne construction logistics, since it is expected to be beneficial on environmental factors like nuisance, emissions, safety and movements. However, since stakeholders have little insight into the necessities for performing transport over water and the corresponding consequences on for example logistics cost or required equipment needed (or any other practical implication), there is some hesitation in actually executing the projects via waterways.

For this thesis project four Key performance indicators (KPIs) are defined based on desk research and interviews, that are used to evaluate the design alternatives of the waterborne construction logistics system, which are the amount of movements through the city, the amount of vessel kilometres, the amount of tonnes kilometres and the total logistics cost, consisting of three components: total transport cost, total handling cost and total storage cost.

- *"What are the waterborne construction logistics building blocks that need to be considered in the design problem?"*

In Section 3.4 two main elements are defined as pillars for categorizing the building blocks of a waterborne construction logistics system for quay wall renovations, namely transport elements and handling and storage elements. For transport elements, the most important building blocks are the transport type and the fariway profiles of the canals. For handling and storage elements, it is important to be aware of the dependency of load carriers and handling equipment on the material type. Also, for waterborne construction logistics, other than for conventional construction logistics, it is interesting to look into the consequences of storing material at the construction site. These building blocks are not only explained in this section, also the specifications per building block are elaborated.

- *"To design a waterborne construction logistics system for quay wall renovation projects."*

By making use of background analysis and functional analysis, the knowledge can be transferred to constructing a morphological chart. From this, the functions of the to be designed system become clear and with creative thinking the means of the functional components can be generated, leading to the design of the waterborne construction logistics system. An important conclusion is the fact that material choice is leading in the generation of alternatives, since it impacts almost all consecutive choices due to their interdependencies.

From the morphological chart a baseline scenario and three design alternatives are generated, from which the expected consequences are stated that form a base for the evaluation. For these design alternatives, also a physical design overview is presented in which the transport chain including made choices are depicted.

- *"To develop a calculation tool that can quantify the consequences of transport over water on relevant performance indicators."*

For this thesis project objective a decision support tool is developed that can be used to evaluate the design alternatives generated from the waterborne construction logistics system designed in Chapter 4. With an Activity based costing approach the decision support tool calculations are constructed, with which it is possible to calculate the consequences of the design alternatives. The decision support tool scope however, only captures the logistics activities from leaving the hub to the construction site and vice versa.

- *"How can the tool support decision makers in the shift to the waterborne construction logistics system?"*

By looking into the decision support tool dynamics and sensitivity of parameters, stakeholders can play with different waterborne construction logistics alternatives and make an estimation on the impact of making tactical decisions like hub locations, vessel sizes, storage options and handling equipment. The most important outcomes of this section, is that the waterborne construction logistics system is always the preferred alternative when looking at the KPIs total amount of movements and amount of vessel/vehicle kilometers. For the logistics cost it is a bit more complex due to a large variety of system parameters. However, it can be concluded that for an average vessel load of more than 70.7 tonnes per shipment, waterborne transport does become the more cost effective alternative compared to road transport.

## 7.2. Recommendations

### 7.2.1. Recommendations for further research

First of all, the design of the waterborne construction logistics system is only applied to the conventional way of renovating a quay wall. The innovative construction methods devised by the IPKs are not taken into account. It would be interesting and recommended to conduct further research on these methods and integrate these solutions in the waterborne construction logistics system designed in this thesis project. In that way it would also be possible to compare the consequences of using different construction methods.

Furthermore, for the designed waterborne construction logistics system the complete transport chain from supplier to end location has been worked out. However, for the decision support tool it is chosen to scope the object of modelling to a smaller part of the supply chain. This is the reason the total inventory cost on project level could not be compared to the transport cost to determine the optimal shipment size or best storage choices keeping in mind the inventory throughout the whole supply chain. It is recommended to expand the decision support tool to the full scope of the design in order to draw system broad conclusions. In addition to this, in the decision support tool of this thesis project only operational cost are considered and no fixed cost. It would be recommended to investigate these fixed cost as well to make high level decisions like purchasing your own fleet or investing in innovative storage solutions.

This thesis project had its focus on the design of a waterborne construction logistics system for an individual quay wall renovation project. In order to make optimal use of the resources in the system, it is recommended to further investigate the possibilities of combining multiple quay wall renovation projects or perhaps even other construction projects in the same system. This could be in the form of bundling material flows, but it could also be possible to share a fleet with multiple projects in the neighbourhood.

There are some assumptions made in the decision support tool, which are recommended to further research in the future to determine the impact on the KPIs:

- It is assumed that the construction material demand at the construction site is heterogeneous over the project duration, but it might be interesting to keep the project phases and critical timeline into account in the calculations to see to what extent the output parameters fluctuate.
- In the decision support tool the assumption is made that the vessel speed is constant over the transport distance in both directions. It is recommended to further research how the vessel speed behaves over different types of waterways and under specific weather conditions. This not only influences the travel time and thus the total logistics cost, but also the corresponding emissions.
- The distance from hub to site is assumed to be the same as the travel distance from site to hub or any other end location, not taking into account one-way waterways or the usage of different hubs. Since there are multiple hubs available in the network, it is recommended to perform a network optimization to ensure the most efficient routes are generated.

### 7.2.2. Recommendations for the Municipality of Amsterdam

Firstly, as concluded from this thesis project, the amount of tonnes necessary for renovating one linear meter quay has significant impact on all defined KPIs. For the Municipality it would be recommended to keep challenging the parties executing the quay wall renovations to find innovative ways to use less material for renovating a quay wall. Also, since the weight is normative over the volume of material, making use of lighter construction materials might also be a solution for positively influencing the KPIs.

Additionally, it is recommended for the Municipality and other stakeholders to keep monitoring the design elements and their status. Some means of the morphological chart might become a feasible solution in a couple of years, such as autonomous vessels, or new load carriers might enter the system and should be added to the waterborne construction logistics system.

Furthermore, the Municipality of Amsterdam is recommended to ensure good collaboration and coordination between all the involved stakeholders. As mentioned in the evaluation of the alternatives, an example of inadequate communication can be about the loading rate of the return transport carrier. When this returning carrier is unaware to transport material from the construction site back to the hub, an increase in movements and therefore costs is the unnecessary consequence.

Another recommendation for the Municipality is to increase the usability of the current calculation tool. At this moment the decision support tool is prone to human errors, since all parameters are easy to adjust, which is why an automation and security step for the decision support tool is desired. Also, it is recommended to make both the waterborne construction logistics system as the decision support tool publicly accessible, so that every stakeholder that requires more knowledge and insights on the consequences of using the waterborne construction logistics system could use the tool.

For this thesis project, it is chosen to leave the integration of logistics for transportation of personnel to and from the construction site out of scope, even though this is officially part of construction logistics. It might be interesting for the Municipality to investigate incentives for construction workers to use transport over water to construction sites of quay wall renovations.

Before this decision support tool is put into use, a few additions or changes might be considered:

- The decision support tool only gives insights on project level, but does not zoom in on material level. So in order to draw conclusions on material level, the calculations need to be performed per material type separately and can be bundled on a project level.
- As earlier mentioned, the emission or nuisance measures can all be calculated by multiplying the amount of vessel kilometres or tonnes kilometres to an emission or nuisance calculation factor. However, this is currently not integrated in the decision support tool outcomes and is expected to be of interest for the stakeholders and users of the waterborne construction logistics system
- In the decision support tool potential emissions of handling equipment are not taken into account and could be added to give a full overview of the nuisance of the system

Besides the Municipality, other stakeholders are also involved in projects like this. Recommendations for various of these stakeholders are:

- The coordination and communication between the *waterborne freight transporter* and *contractors* about all construction sites and the availability of vessels. The hourly rate of a towing vessel is high. Therefore, when multiple (nearby each other) construction sites require a towing vessel which is available, the usage of this vessel can shared over all construction sites. Leading to an reduction in rental costs of the towing vessel per construction site. Moreover, these two stakeholder could involve a *logistics service provider* to support in this coordination.
- The *suppliers* are recommended to anticipate on the system. When a supplier is located at the canal, they can replace a *hub operator* for required transshipment and with that transshipment costs.
- The Municipality is also recommended to investigate together with the *hub operator* about the location of these hubs. Smaller hubs such as a pop-up hub located closer by the construction site would prevent vessels to move in and out of the canals every day. The involvement of the *waterborne freight transporter* is recommended here as well, since they need to provide in the vessels.

## 7.3. Reflection

- At the start of this thesis project, the idea of this research would be to solve an optimization problem of using the current waterborne infrastructure for renovating all quay wall renovation projects in scope of the Program Bridges Quays. Therefore, at the first couple of months a lot of research has been conducted in network optimization problem methodologies. When comparing these methodologies to the practical availability of the infrastructure, the attitude of the stakeholders and other limitations, such as a lack of coordination, it became clear that this problem was not an optimization problem. First, the elements of the waterborne construction logistics system in general and its potential consequences needed to be defined, which is why this has become the subject of this thesis project. The lesson learned is that, in this specific case, it is best to first investigate and analyse the complex system you are working with before diving into possible solution methods.

- The transportation, handling and storage cost are only operational cost directly related to the construction logistics chain of the decision support tool scope. The handling cost in this decision support tool are only the operational handling cost for transshipping material from hub to site and vice versa. Fixed rental cost for mobile handling equipment or storage facilities on a project base are not taken into account, but the calculated cost in this decision support tool could be interesting for constructors to assign project cost to the right logistics activities

- The same holds for the holding cost of material in the supply chain. It would have been interesting to include the construction material inventory into the decision support tool. However, as earlier mentioned in Chapter 3 the flows of both materials are uncoordinated within construction logistics and mostly performed on an ad hoc basis. Construction material suppliers and waste management operators have their own vehicles and schedules and therefore it is at this moment difficult to include this in the decision support tool.

- Also the Municipality is providing in discounts for using waterborne transport for the transport of materials for quay wall renovations. This is not taken into account in the calculations, but might lead to an adjustment based on the expected logistics cost on project base. With the right strategical decisions, the total logistics cost could become lower than for road transport.

- In the upcoming years many quay wall renovations will be executed with their own observations and discoveries. It could be possible that the relevance of the waterborne construction logistics system of this thesis project decreases with the introduction of new innovations with consequences that cannot be captured in this system.

# References


Balm, S., Berden, M., Morel, M., & Ploos van Amstel, W. (2018). Smart construction logistics. Retrieved 11/01/2022, from https://research.hva.nl/en/publications/smart-construction-logistics

Beitz, W., Pahl, G., & Grote, K. (1996). Engineering design: a systematic approach. *Mrs Bulletin*, *71*.

Börekçi, N. A. (2018). Design divergence using the morphological chart. *Design and Technology Education*, *23*(3), 62–87.

Breederveld, C. (2017). Influence of stakeholders on urban quay walls. Retrieved 20/11/2020, from https://repository.tudelft.nl/islandora/object/uuid%3Aca58aadb-b82c-49c8-abdb-7f6ccba3e4a5?collection=education

Browne, M., Allen, J., Nemoto, T., Patier, D., & Visser, J. (2012). Reducing social and environmental impacts of urban freight transport: A review of some major cities. *Procedia-Social and Behavioral Sciences*, *39*, 19–33.

Cheung, S. O., Suen, H. C., & Cheung, K. K. (2004). Ppms: a web-based construction project performance monitoring system. *Automation in construction*, *13*(3), 361–376.

de Bes, J., Eckartz, S., van Kempen, E., van Merrienboer, S., Ploos van Amstel, W., van Rijn, J., & Vrijhoef, R. (2018). Duurzame bouwlogistiek voor binnenstedelijke woning-en utiliteitsbouw. Retrieved 19/12/2022, from http://resolver.tudelft.nl/uuid:c5d6ae27-6252-4b86-ac69-a7bdaf62c4b7

Dym, C. L. (2013). *Engineering design: A project-based introduction.* John Wiley & Sons.

Dym, C. L., & Little, P. (1999). *Engineering design: A project-based introduction.* John Wiley and sons.

Fang, Y., & Ng, S. T. (2011). Applying activity-based costing approach for construction logistics cost analysis. *Construction Innovation*, *11*(3), 259–281.

Gemeente Amsterdam. (2019). *Actieplan schone lucht.* Gemeente Amsterdam. Retrieved 03/05/2023, from https://assets.amsterdam.nl/publish/pages/863561/actieplan_schone_lucht.pdf

Gemeente Amsterdam. (2020a). *Analyserapport - uitvoeringsplan transport over water.* Gemeente Amsterdam. Retrieved 02/05/2023, from https://openresearch.amsterdam/nl/page/65640/analyserapport---uitvoeringsplan-transport-over-water

Gemeente Amsterdam. (2020b). *Nota varen deel 2.* Gemeente Amsterdam. Retrieved 10/05/2023, from https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/water-varen/

Gemeente Amsterdam. (2020c). *Programmaplan bruggen en kademuren. herstellen en verbinden.* Gemeente Amsterdam. Retrieved 03/05/2023, from https://amsterdam.raadsinformatie.nl/document/8679848/1/Bijlage_1_-_Programmaplan_Bruggen_en_Kademuren_-_Herstellen_en_verbinden_-_vastgesteld_op_14_april_2020

Gemeente Amsterdam. (2020d). *Uitvoeringsplan transport over water.* Gemeente Amsterdam. Retrieved 02/05/2023, from https://openresearch.amsterdam/nl/page/65638/uitvoeringsplan-transport-over-water

Gemeente Amsterdam. (2023a). *Dashboard programma bruggen en kademuren.* Author. Retrieved from https://experience.arcgis.com/experience/5f24774720454550ae8e2b93e909f564/page/page_7/ (Accessed: 2023-05-05)

Gemeente Amsterdam. (2023b). *Regels op het water.* Gemeente Amsterdam. Retrieved 02/05/2023, from https://www.amsterdam.nl/verkeer-vervoer/varen-amsterdam/regels-varen/

Guerlain, C., Renault, S., & Ferrero, F. (2019). Understanding construction logistics in urban areas and lowering its environmental impact: A focus on construction consolidation centres. *Sustainability*, *11*(21), 6118.

Harvey-Jordan, S., & Long, S. (2001). The process and the pitfalls of semi-structured interviews. *Community Practitioner*, *74*(6), 219.

Janjevic, M., & Ndiaye, A. B. (2014). Inland waterways transport for city logistics: A review of experiences and the role of local public authorities. In *Wit transactions on the built environment* (Vol. 138, pp. 279–292). WITPress. doi: 10.2495/UT140241

Janné, M. (2018). *Construction logistics solutions in urban areas* (Vol. 1806). Linköping University Electronic Press.

Lundesjo, G. (2011). Using construction consolidation centres to reduce construction waste and carbon emissions. *Waste & Resources Action Programme (WRAP)*, 1–19.

Lundesjö, G. (2015). *Supply chain management and logistics in construction: delivering tomorrow's built environment.* Kogan Page Publishers.

Maes, J., Sys, C., & Vanelslander, T. (2015). City logistics by water: Good practices and scope for expansion. *Operations Research/ Computer Science Interfaces Series*, *58*, 413–437. doi: 10.1007/978-3-319-16133-4_21

PK Waterbouw. (2022). *Equipment.* Author. Retrieved from https://pkwaterbouw.nl/pontons-ruim-en-dekschepen/ (Accessed: 2022-01)

Port of Amsterdam. (2020). *Amsterdam beter bereikbaar door bouwlogistiek over water.* Port of Amsterdam. Retrieved 07/05/2023, from https://www.portofamsterdam.com/sites/default/files/2020-12/whitepaper_AV_final.pdf

Quak, H. (2008). *Sustainability of urban freight transport: Retail distribution and local regulations in cities* (No. EPS-2008-124-LIS).

Quak, H., Klerks, S., Aa, S., de Ree, D., Ploos van Amstel, W., & Merriënboer, S. (2011). *Bouwlogistieke oplossingen voor binnenstedelijk bouwen* (Tech. Rep.). TNO.

Roosmale Nepveu, M. J. (2020). *Implementing urban waterway transport as a sustainable freight transport solution: A case study for the city of amsterdam* (Unpublished master's thesis). Delft University of Technology.

Roozenburg, N. F. M., & Eekels, J. (2002). *Product design: fundamentals and methods.* UMI Books on Demand.

Shakantu, W., Muya, M., Tookey, J., & Bowen, P. (2008). Flow modelling of construction site materials and waste logistics: A case study from Cape Town, South Africa. *Engineering, Construction and Architectural Management*, *15*(5), 423–439. doi: 10.1108/09699980810902721

Smith, G. P. (2007). *Morphological charts: a systematic exploration of qualitative design space* (Unpublished doctoral dissertation). Clemson University.

Suh, N. P., & Suh, N. P. (2001). *Axiomatic design: advances and applications* (Vol. 4). Oxford university press New York.

Sullivan, G., Barthorpe, S., & Robbins, S. (2011). *Managing construction logistics.* John Wiley & Sons.

van Amstel, W. P., van Merriënboer, S., & Balm, S. (2015). A framework for tendering based on emat approach to support sustainable urban construction logistics.

van der Does de Willebois, J. (2019). *Assessing the impact of quay-wall renovations on the nautical traffic in amsterdam: A simulation study* (Unpublished master's thesis). Delft University of Technology.

Van Merrienboer, S. (2013). Best practices in bouwlogistiek. *TNO, Delft, Netherlands.*

van Rijn, H. J. R. A. E. S., J. (2020). *Amsterdam vaart! 2019 resultaten duurzame bouwlogistiek over water.* TNO. Retrieved 03/05/2023, from http://resolver.tudelft.nl/uuid:95b8186f-f17e-413b-a56b-06f9680c3072

Vidalakis, C., Tookey, J. E., & Sommerville, J. (2011). The logistics of construction supply chains: the builders' merchant perspective. *Engineering, Construction and Architectural Management*.

Ward, S., Curtis, B., & Chapman, C. (1991). Objectives and performance in construction projects. *Construction Management and Economics*, *9*(4), 343–353.

Ying, F., & Tookey, J. (2017). Key performance indicator for managing construction logistics performance. In *25th annual conference of the international group for lean construction (iglc). july* (pp. 9–12).

Ying, F., Tookey, J., & Roberti, J. (2014). Addressing effective construction logistics through the lens of vehicle movements. *Engineering, construction and architectural management*.

ZOEV city. (2022). *Hoe het werkt.* Author. Retrieved from https://www.zoevcity.nl/hoe-het-werkt/ (Accessed: 2022-01)

# A

# Scientific paper

# Design of a waterborne construction logistics system for quay wall renovations in Amsterdam

C.P.G. van der Storm
MSc. Transport, Infrastructure and Logistics
Delft University of Technology

***Abstract*—In the upcoming years the Municipality of Amsterdam has to cope with renovation works to approximately 200 kilometers of quay walls and 800 bridges. These projects need to be executed in the least burdensome manner, which is why executing parties are obliged to perform their construction logistics via waterways instead of the road. Stakeholders want to have more insight into the consequences of using waterborne construction logistics and what the possible choices and decisions are within the system. In this research a waterborne construction logistics system is presented from which waterborne scenarios can both be compared with each other and with the conventional road modality. A decision support tool is developed and used to quantify these consequences and it can be concluded that water is always the preferred alternative when looking at movements and vessel/vehicle kilometers through the city, which is for both indicators a decrease of approximately 80%. From this analysis can be concluded that in the most optimistic scenario it is possible for waterborne logistics to become less expensive than road transport, but under the conditions that the average transported load and vessel speed are rather high. It is therefore recommended to further investigate the optimum between vessel capacity, loading rate and vessel speed and for the Municipality of Amsterdam to involve executing stakeholders to contribute to reaching this optimum.**

***Keywords*— Construction logistics, urban waterway transport, waterborne construction logistics, quay wall renovations, key performance indicators, decision support tool, total logistics cost.**

## I. Introduction

The Municipality of Amsterdam faces a major challenge in the upcoming years as around 200 kilometres of quays are in need of replacement [1] [2]. In addition to this, cities are subject to a large increase in construction related movements due to urbanisation and the corresponding demand for construction projects worldwide [3]. These movements pose a threat to the already vulnerable quays and bridges in the historical city center of Amsterdam. Also, during these projects large quantities of construction material and equipment need to be transported, causing safety issues, accidents, congestion, emissions and other nuisance to the city environment [4]. Construction logistics, for which the definition is "all supply and disposal shipments of building materials, construction equipment and construction personnel to and from the construction site [3]", in urban areas is often performed by large trucks entering the supply roads to the city center.

From 2017 onward the Municipality of Amsterdam has started with monitoring and the execution of reinforcement and renovation works to the quays and bridges [5]. Since the Municipality is amongst other roles also the principal of these construction projects, it is possible to enforce project executors like contractors and logistics providers to perform their construction logistics via waterways instead of roads. Expectations are that the amount of movements will decrease significantly as will the corresponding effects on the city such as emissions, noise hindrance and accidents, which are part of a big social cost benefit analysis for the Municipality. An expected drawback of waterborne construction logistics is an increase in logistics cost due to higher operational and storage cost.

This paper focuses on providing insight into the consequences of waterborne construction logistics on a project level, but it should be clear that the potential additional cost for transporting over water need to be balanced against the social benefits such as saved cost for traffic deaths, increased health of residents and accessibility of the city.

The purpose of this paper is to provide stakeholders of quay wall renovation projects, and in specific the Municipality of Amsterdam, insight into the different elements the waterborne construction logistics system for these kind of projects and the strategic choices one can make. Therefore this research also provides quantitative insight into the consequences of using waterborne construction logistics both compared to the conventional way of transport, via road, as to compare several waterborne scenarios with one another.

In scope of this research are all movements of transporting construction material and equipment to and from the construction site on project level, but personnel is not taken into account. Additionally, based on the planned quay wall projects for the coming years, only quay wall renovation projects within the historical center of Amsterdam are considered, which is inside the ring road S100.

In Section II the background of quay wall renovation projects is discussed, how waterborne construction logistics might facilitate the Municipality in social benefits and the potential drawbacks of using this system, and finally the characteristics of waterborne construction logistics system are described. The design of the waterborne construction logistics system is discussed in Section III. The application of the decision support tool to a use case is described in Section IV and the results are discussed in Section IV-C. Finally in Section V, the conclusion of this paper and recommendations for further research and applications are stated.

## II. Background

In this section more background of quay wall renovation projects and the potential drivers and barriers for performing the corresponding construction logistics via water are discussed. Furthermore, key performance indicators are generated which can be used to evaluate the design.

### *Characteristics quay wall renovation projects*

There are a couple of characteristics of quay wall renovation projects that require some further attention regarding this paper. Firstly, the most important characteristic of a quay wall renovation compared to regular construction projects is the construction material composition per shipment. Seven sorts of material types can be identified, which are (1) dry bulk (2) palletised (3) liquid bulk (4) prefab (5) material and equipment (6) long material and (7) miscellaneous material. From these material types dry bulk takes up the largest share as around 50% of this type is supplied to the construction site and the returning material flows are almost all in dry bulk form (approximately 98%). Due to the large material demand of quay wall renovation projects, the material flows can be identified as monoflows.

Based on the background analysis, it is concluded that the weight of construction material is normative over the volume, which practically means that transport types are not always fully loaded in terms of volume when transporting heavy materials. This is taken as an important consideration in this paper. The Municipality of Amsterdam is actively stimulating contractors to perform construction logistics via water instead of the road. Quay wall renovation projects as opposed to other construction projects in Amsterdam have an advantage as they are already located on the water front, which means no last mile delivery of materials is necessary on land, since vessels and barges can reach the site directly via the waterways.

### *Drivers and barriers of waterborne construction logistics in Amsterdam*

Based on interviews with experts from the field and desk research the expected drivers and barriers of using waterborne construction logistics are defined. The most important drivers are better accessibility of and improved operational conditions on the construction site and less movements through the city which corresponds with a positive impact on safety, nuisance, accessibility and emissions.

The main barriers that should be kept in mind are fairway profiles restricting certain vessels or vessel loads to enter canals, more crowded waterways, limited fleet availability and an expected increase in logistics cost.

### *Key performance indicators*

When the drivers and barriers of interest are translated into project based logistics indicators, seven key performance indicators (KPIs) are chosen which will be used to provide insight into the consequences of several design alternatives. The key performance indicators are stated below:

- Total transport cost
- Total handling cost
- Total storage cost
- Total logistics cost: a combination all cost
- Amount of vessel movements
- Amount of vessel kilometres
- Amount of tonkm

The output on these indicators can be used by the Municipality of Amsterdam or other stakeholders to evaluate the performance of design scenarios and can support in the decision making of tactical choices within the system.

## III. Design of the waterborne construction logistics system

For designing the waterborne construction logistics system an adapted version of the engineering design cylce of Roozenburg and Eekels is used as this methodology is considered the most fundamental model for designing [6]. Even though this design methodology is normally applied to product design, this basic design cycle is often used as a framework for the designing in general [6]. One of the starting points was determining the functions of the to be designed system, which are presented in Figure 1. These functions are also leading for the functional requirements of the waterborne construction logistics system, since the system must be able to perform all functions of the functional flow block diagram. The non-functional requirements of the system are giving the system direction in terms of local laws and regulations and safety hazards.

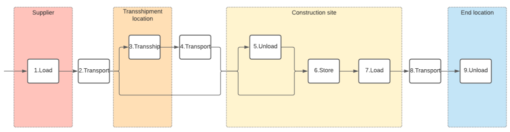



Fig. 1. Functional flow block diagram of waterborne construction logistics

One of the creativity techniques for coming up with conceptual designs is making use of a morphological chart [6]. A morphological chart, in essence, is a table of functions and solutions for each function. Normal convention is to list the functions in a column in the left hand side of the table, and list the solutions to each function to the right of the function. Various terms exist for these solutions. Dym and Little use the term "means" [7], Suh [8] uses "design parameters" for software design and [9] use a term which can be translated to "working principles". For each function of the system, several means are generated, which are derived from brainstorming with information retrieved from interviews, desk research and observations. In the next section the most important components and means of the waterborne construction logistics system are discussed.

*Components and means of the waterborne construction logistics system*

For every component, which is based on one of the functions of the waterborne construction logistics system, several means are presented below. These means present different system choices with which endless design alternatives can be generated.

1) *Material type:* These are the seven material types mentioned in Section II.
2) *Transport type supplier to hub:* For transportation from supplier to construction site, a hub or construction consolidation center can be used to transship material to waterborne transport types.
3) *Transshipment to vessel:* Based on the chosen transport type to the hub, several handling equipment choices can be made at the hub for transshipment. This is based on the material type, load carrier and transport type. Options are i.e. (gantry) cranes, dumping load or chutes.
4) *Load carrier to site:* The load carrier chosen to transport material to the site are dependent on the chosen material type. Examples of load carriers are pallets, skips, concrete mixers or no load carrier at all in case of loose material.
5) *Transport type to and from site:* Examples of transport types that are considered for this system are tugboats with push barges or deck barges, self-propelled barges and pontoons.
6) *Vessel load:* The vessel load chosen may vary between 25 and 100 tons since this is the current vessel fleet availability and the canals can not cope with bigger loads.
7) *Fuel type:* These fuel types correspond to the transport type to and from the site and range from Diesel to electric vessels.
8) *Unloading equipment:* For the unloading equipment to transship material from the transport type to the construction site and vice versa several choices can be made such as crane, hydraulic excavator, forklift truck. These all have their own characteristics like handling speed, operational cost and suitability for certain material types.
9) *Storage type:* There are four available choices as storage type, which are no storage by direct unloading or using or storing up to one day or more than one day on the chosen transport type.
10) *Material type return flow:* Based on an analysis performed, it can be concluded that most return flows consist of dry bulk material. Nevertheless, material like machinery and equipment or other large materials need to be returned as well.
11) *Load carrier return flow:* Mostly dry bulk material will be returned, but there are several load carriers possible for return, which are equal to the previous mentioned load carriers.

It is important to mention that there is interdependency between means of components. It is for example not possible to choose pallets as a load carrier when as a material type dry bulk is chosen. Components material type and load carrier are leading in consecutive choices and therefore important elements of the waterborne construction logistics system.

The physical design can be presented as indicated in Figure 2, where the complete system is shown with indicated in orange which choices have to be made to generate design alternatives.

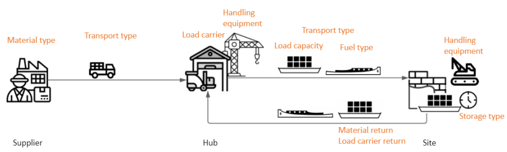



Fig. 2. Physical design of the waterborne construction logistics system

## IV. Use case

The alternatives that can be generated from the waterborne construction are evaluated by a decision support tool by applying a baseline use case. In this chapter, a use case is introduced of a quay wall renovation project located at Herengracht 1 - 103 in Amsterdam. This use case will be used as a baseline for calculating the consequences of using waterborne construction logistics. Firstly, the use case will be introduced in a brief way. Hereafter the decision support tool will be explained with which the consequences of waterborne transport can be calculated and different waterborne scenarios can be compared.

### *A. Use case description: Herengracht 1-103*

The renovation of Herengracht 1 - 103 is used as an generic example due to its central location in the city center of Amsterdam, and the convenient fairway profile of the canal. The following characteristics of the quay wall renovation are considered and used as input for the decision support tool:

noitemsep

- The quay that needs to be renovated has a length of 275 metres, but for the calculation 100 metres is used as a comparison baseline
- The distance from the hub location in the Coenhaven to the construction site is around 7.5 kilometers
- Since the vessel spends half of the driving time on the IJ, with an estimated average navigating speed of 12 km/h and half of the time in the canals with difficult manoeuvring and an average navigating speed of 6 km/h, the average speed of the vessels is set on 7 km/h

- The fairway profile corresponding to this part of the Herengracht is B, which means vessels with the average dimensions can reach the construction site. This means vessels may have a length of 20 metres and a width of 4.25 metres
- Based on the fairway profile only, it may be possible to ship around 80 tonnes per movement to and from the construction site. However, to give a more realistic image of the average vessel load, a loading rate of 75% is used as input, meaning on average a load of 60 tonnes is shipped to the site.
- It is assumed that on average 100% of the transport types take some waste back from the site to the hub. Waste is not always readily available in the same size as the supplied materials, which results in the assumption that the average loading rate of the returning transport carriers is 50% as opposed to 75% of the supplying transport carriers.

TABLE I
Summary of input parameters for the baseline scenario

| Input parameter | Value | Unit |
|---|---|---|
| Quay wall length | 100 | metres |
| Distance hub - site | 7.5 | km |
| Speed transport mode | 7 | km/h |
| Capacity of transport carrier | 80 | tonnes |
| Loading rate of transport carrier | 75 | % |
| Loading rate of returning transport carrier | 50 | % |
| Percentage store up to 1 day | 50 | % |
| Percentage store more than 1 day | 50 | % |

### B. *Decision support tool*

In order to provide insight into the consequences of using the waterborne construction logistics system, a decision support tool is developed in Microsoft Excel that can be used by the Municipality of Amsterdam. It is chosen to use Microsoft Excel as a modelling program, since it is readily available and accessible for the Municipality of Amsterdam and easy to use for other stakeholders with interest in the consequences of waterborne construction logistics. For the calculations in the decision support tool the Activity based costing approach is used [10] to define the quantitative outcomes for the earlier defined KPIs in Section II. In this decision support tool different choices can be made that are elements of the waterborne construction logistics system as described in Section III, such as vessel capacity, storage type and type of handling equipment. The impact of choices made on the KPIs will be discussed in the next section.

Some assumptions are made and simplifications are used in the decision support tool are as follows. The scope of the decision support tool is from leaving the hub to transportation to the construction site and back to the hub. Furthermore, the assumption is made that every vessel takes up some load as a return flow, the average loading rate of the return flow however, might vary.

### C. *Results*

To begin with, the earlier described use case that functions as a baseline scenario in this research, is compared to a conventional way of transportation, via road.

TABLE II
Output baseline case scenario

| **Output parameters** | **Value water** | **Value road** |
|---|---|---|
| Total transport cost | €18,856 | €20,318 |
| Total handling cost | €3,744 | €8,986 |
| Total storage cost | €8,918 | €1,166 |
| Total logistics cost | €31,518 | €30,470 |
| Amount of movements | 130 | 672 |
| Amount of vehicle/vessel kilometres | 927 | 4515 |
| Amount of tonkm | 46800 | 46800 |

From running a few other waterborne scenarios like Just-in-time deliveries and using self-propelled barges instead of push barges with tugboats, the following outcomes are interesting for this research.

When we look at the total logistics cost for both scenarios, it can be concluded that based on transport cost only transportation via water is the most interesting option. However, the handling and storage cost are significantly higher than for road transport, resulting in a higher total logistics cost. For the other logistical parameters it can be concluded that concerning amount of movements through the city and the corresponding amount of vehicle or vessel kilometres, waterborne transport is always the preferred modality. For waterborne transport, a structural decrease of 80.32% in amount of movements and 79.20% in vessel movements as opposed to road transport can be seen, which is a nice result.

Since the travel distance from hub to site is assumed to be comparable, the results for the amount of tonkm stay the same for both modalities. However, for road transport it might be interesting to include a congestion factor in the future, since trucks often tend to take a longer route in kilometers, but shorter in time. This has its impact on the amount of emissions and other environmental criteria.

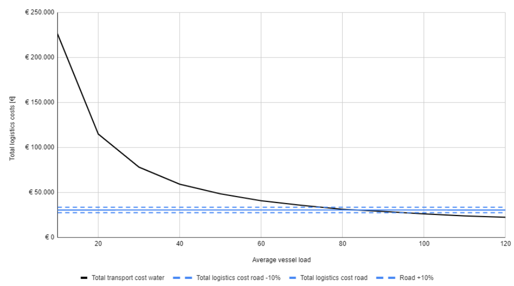



Fig. 3. Total logistics cost per vessel load

In Figure 3 the total logistics cost are plotted against the average load in tonnes that the vessel carries every transport to the construction site. For this calculation a project with a to be renovated quay wall of 100 metres is used as a reference. Also in this figure the base case scenario of performing the same project of 100 metres with road transport is shown. In this base case we assume that a truck can carry a maximum load of 15 tonnes each trip. As you can see in this graph the total logistics cost decrease in a polynomial way as the average tonnage increases per shipment. It can be concluded that when a vessel structurally carries a minimum of 81.9 tonnes per shipment the total logistics cost are lower that the cost for road transport. Since most vessels in the current waterborne construction logistics available fleet have a load capacity of around 80 - 90 tonnes, this is a nice result. This is extra promising since in this baseline scenario a loading rate of 75% is taken as a value.

*D. Sensitivity*

In this section the sensitivity of the following input parameters are considered with a -10% and +10% parameter value, compared to the baseline value

a) Distance hub - site
b) Speed transport mode
c) Rental cost of towing vessel
d) Loading rate of the transport carrier
e) Loading rate of the returning transport carrier

The outcome of this analysis indicates that changes in transport distance, vessel speed, rental cost and loading rate of the transport carrier have the biggest impact on the total logistics cost. Regarding the loading rate of the returning transport carrier, the interesting finding is that the total logistics cost are more sensitive for a decrease in this parameter than for an increase.

In addition to the 10% sensitivity analysis, a MIN/MAX analysis is performed, where the minimum and maximum realistic values for all input variables are generated creating a pessimistic and optimistic scenario respectively. The outcome of this second analysis on the total logistics cost illustrate that these cost can vary between €13,906 and €96,378. Furthermore, the total number of movements in the MAX scenario are 90 while the movements in the MIN scenario increase to a total of 332. When comparing with the number of movements on the road (see Table II, about half of the movements are necessary in the most pessimistic scenario. The values of all output parameters for the MIN/MAX analysis can be found in Table III.

TABLE III
OUTCOME MIN/MAX ANALYSIS

| Output parameter | Outcome MIN scenario | Outcome Baseline scenario | Outcome MAX scenario |
|---|---|---|---|
| Total transport cost | €66,583 | €18,856 | €4,569 |
| Total handling cost | €2,995 | €3,744 | €4,493 |
| Total storage cost | €26,800 | €8,918 | €4,844 |
| Total logistics cost | €96,378 | €31,518 | €13,906 |
| Amount of movements | 332 | 130 | 90 |
| Amount of vesselkm | 2804 | 926 | 385 |
| Amount of tonkm | 56160 | 46800 | 28080 |

## V. Conclusion and Recommendations

*Conclusion*

The objective of this research is to provide the Municipality of Amsterdam and other stakeholders that are engaged with logistics concerning quay wall renovation projects with insights into the consequences of performing construction logistics via water. Therefore in this paper a background of quay wall renovation projects and potential drivers and barriers of waterborne construction logistics are presented and turned into Key performance indicators. Based on this information the waterborne construction logistics system is designed with the engineering design cycle of Roozenburg and Eekels as a basis. From this design several design alternatives can be generated with which the consequences of performing a waterborne construction logistics scenario can be quantified in a decision support tool. What we can conclude from the decision support tool is that water transport is always a preferred alternative when we look at the output parameters amount of movements through the city and corresponding kilometres. This is in line with the expected impact mentioned in Section II. The metric that did need some further investigation is the Total logistics cost. When we look at this indicator, it can be concluded that when a vessel structurally transports 81.9 tonnes per shipment on average, the total logistics cost are lower for waterborne construction logistics than for road transport.

*Recommendations*

A first recommendation for further research is to expand the decision support tool to the full scope of the design in order to draw system broad conclusions. In addition to this, in the decision support tool of this thesis project only operational cost are considered and no fixed cost. It would be recommended to investigate these fixed cost as well to make high level decisions like purchasing your own fleet or investing in innovative storage solutions. Furthermore, since this research focuses on individual construction projects, it might be interesting to investigate the possibilities of combining multiple quay wall renovation projects or perhaps even other construction projects in the same system. This could be in the form of bundling material flows, but it could also be possible to share a fleet with multiple projects in the neighbourhood.

For the Municipality of Amsterdam there are a few important recommendations. First, the amount of tonnes necessary for renovating one linear meter quay has significant impact on all defined KPIs, it would be recommended to keep challenging the parties executing the quay wall renovations to find innovative ways to use less and lighter material for renovating a quay wall. Second, the optimal trade-off value between the average vessel load and vessel speed requires more research as both these parameters show significance on the total logistics cost. The last recommendation is to invest in coordination of return waste flows, since the loading rate of the waste return flows shows a significant impact on the results of the total logistics cost

## References


[1] Gemeente Amsterdam, "Gefundeerd herstellen actieplan bruggen en kademuren 2023-2026," 2022. [Online]. Available: https://assets.amsterdam.nl/publish/pages/973509/actieplan-programma-bruggen-en-kademuren-2023-2026.pdf

[2] "Actieplan bruggen en kademuren," Gemeente Amsterdam, Tech. Rep., 2019.

[3] W. P. van Amstel, S. van Merriënboer, and S. Balm, "A framework for tendering based on emat approach to support sustainable urban construction logistics," 2015.

[4] W. Shakantu, M. Muya, J. Tookey, and P. Bowen, "Flow modelling of construction site materials and waste logistics: A case study from Cape Town, South Africa," *Engineering, Construction and Architectural Management*, vol. 15, no. 5, pp. 423–439, 2008.

[5] Gemeente Amsterdam, "Programmaplan bruggen en kademuren. herstellen en verbinden." 2020. [Online]. Available: https://amsterdam.raadsinformatie.nl/document/8679848/1/

[6] N. F. M. Roozenburg and J. Eekels, *Product design: fundamentals and methods*. UMI Books on Demand, 2002.

[7] C. L. Dym, *Engineering design: A project-based introduction*. John Wiley & Sons, 2013.

[8] N. P. Suh and N. P. Suh, *Axiomatic design: advances and applications*. Oxford university press New York, 2001, vol. 4.

[9] W. Beitz, G. Pahl, and K. Grote, "Engineering design: a systematic approach," *Mrs Bulletin*, vol. 71, 1996.

[10] Y. Fang and S. T. Ng, "Applying activity-based costing approach for construction logistics cost analysis," *Construction Innovation*, vol. 11, no. 3, pp. 259–281, 2011.

# B

# IPK Amsterdam

### B.0.1. G-Kracht

Amsterdam is the first city where G-Kracht will start developing the so-called GRB system, type Amsterdam (Giken Reaction Based System). The equipment to be deployed moves over the own work area, so that both the road and the water remain available for normal use. In total, two hundred kilometers of quay in Amsterdam must be replaced.

G-Kracht has given itself the task from the start to develop an innovative method for quay replacement, in which the impact on a city is greatly minimized.

The advantages of the GRB system are countless. For example, there is less nuisance for the neighbourhood, there are lower costs for the client and a faster delivery is possible. But there is also little space requirement on the quay, because the work takes place on and over the water.

It is also very important that trees and houseboats hardly need to be moved during construction. GRB is a scalable system and is possible in many quay variants and with different load classes.

### B.0.2. Kade 2.020

Working from the water:

- Material supply via water and not by road
- No big equipment in front of the door
- The quay will remain accessible to all traffic (the road will remain open)

New technology:

- EZ-flow is low-vibration: the piles in the new construction are screwed (instead of driven)
- Our modular prefab system can be used in at least 80% of the quays
- The solution is applicable and scalable in different contexts: EZ-flow also fits in curves, narrower and shallower waterways or quays and near trees

Short turnaround time:

- Renew 5 meters of quay per week
- Houseboats are only moved temporarily, within the range (between 2 bridges)
- Fast work possible by using prefab material
- Work area is up to 20 meters long

### B.0.3. Koningsgracht

For the municipality of Amsterdam, we looked for an innovative way to renew the quay walls. Which we carry out safely on a (much) smaller scale than the current method to minimize the impact on the environment. With SAVE we work on a building site that is as small as possible and that is easily scalable. It is also applicable to all possible failure mechanisms. We work with as small equipment and material as possible. And we reuse as much material as possible.

The essence of SAVE is to renew the quay wall step by step in small segments. We move our work area along the quay wall like a ’train’. In front of us the houseboats temporarily shift to another place and behind us we leave a new ready-to-use quay.

We work in four phases:

Ground level preparation;
Placing temporary retaining construction;
Realization floor of the construction;
Remove existing quay wall and install new quay wall and finish ground level.

These four construction phases take place simultaneously because we work from three pontoons. Each with his own task. This makes the work area as small as possible. We make the floor of the new quay wall construction in parts in the trench box. The trench box principle is an existing method for replacing cables and pipes in segments. We use the slotted box as a reusable mold to make the floor of the construction. Everything fits together like a puzzle.
The advantages of SAVE:
With SAVE we innovate both the process and the product. The main innovations are:

Product innovations:

- Using a trench box as a mold for pouring concrete and securing soil stability;
- The use of fibre-reinforced concrete as a ground retaining structure.As a result, no steel reinforcement is required in the underwater concrete;
- A T-head coupling for creating a flexible (in dimensions) moment-resistant connection for the retaining wall elements.

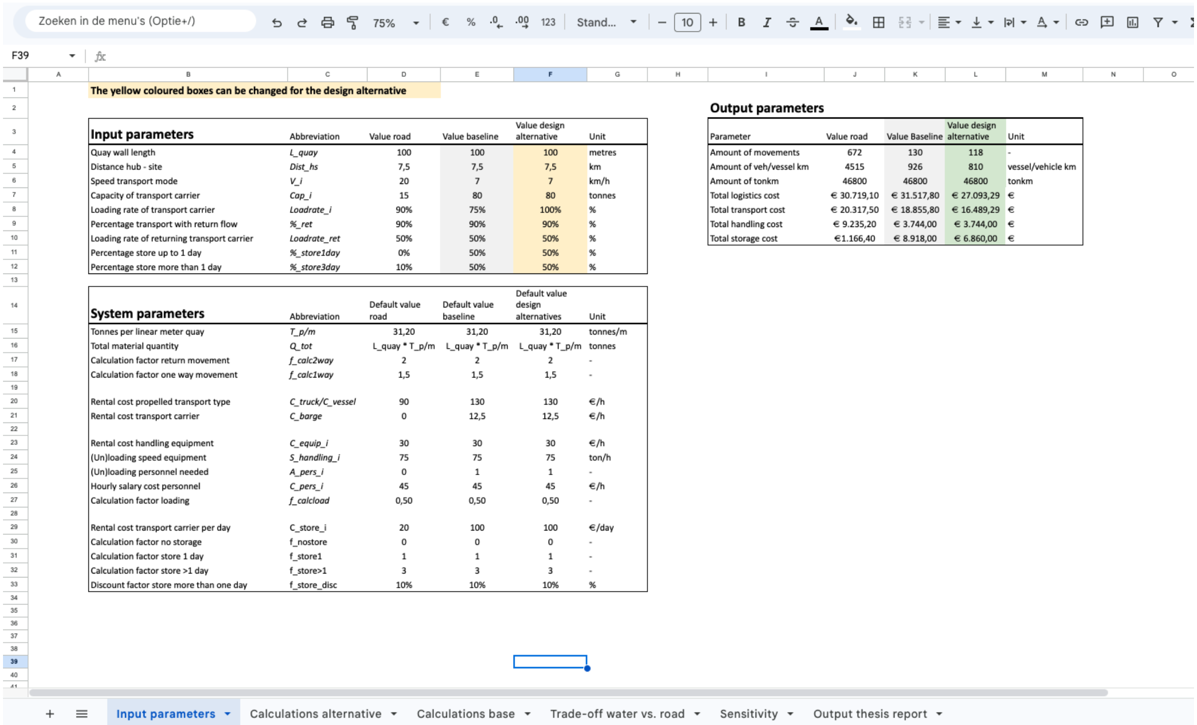
Process innovations:

- A small work area because we work with three specialized pontoons in succession that we move along the quay walls like a ’train’. For example, we only renew the quay wall locally;
- Working in small segments. This causes local nuisance instead of nuisance on the entire quay. This is radically different from tackling the entire quay in one go with work platforms and dry cofferdams that extend over the entire canal. Long-term drainage is therefore no longer necessary;
- The use of the existing quay wall and existing floor as temporary retaining walls during construction. We are taking measures to be able to use our SAVE concept in all possible failure mechanisms of the original quay wall.

# C

# Guideline decision support tool

In this section, a short underpinning of the decision support tool, introduced in Chapter 5, is given to better understand the usage of the tool. Firstly, an overview of the most important tab in Excel is shown in Figure C.1. On this page all tool parameters are visible and can be adjusted as desired.



The yellow coloured boxes can be changed for the design alternative

| Input parameters | Abbreviation | Value road | Value baseline | Value design alternative | Unit |
|---|---|---|---|---|---|
| Quay wall length | *L_quay* | 100 | 100 | 100 | metres |
| Distance hub - site | *Dist_hs* | 7,5 | 7,5 | 7,5 | km |
| Speed transport mode | *V_i* | 20 | 7 | 7 | km/h |
| Capacity of transport carrier | *Cap_i* | 15 | 80 | 80 | tonnes |
| Loading rate of transport carrier | *Loadrate_i* | 90% | 75% | 100% | % |
| Percentage transport with return flow | *%_ret* | 90% | 90% | 90% | % |
| Loading rate of returning transport carrier | *Loadrate_ret* | 50% | 50% | 50% | % |
| Percentage store up to 1 day | *%_store1day* | 0% | 50% | 50% | % |
| Percentage store more than 1 day | *%_store3day* | 10% | 50% | 50% | % |

| System parameters | Abbreviation | Default value road | Default value baseline | Default value design alternatives | Unit |
|---|---|---|---|---|---|
| Tonnes per linear meter quay | *T_p/m* | 31,20 | 31,20 | 31,20 | tonnes/m |
| Total material quantity | *Q_tot* | L_quay * T_p/m | L_quay * T_p/m | L_quay * T_p/m | tonnes |
| Calculation factor return movement | *f_calc2way* | 2 | 2 | 2 | - |
| Calculation factor one way movement | *f_calc1way* | 1,5 | 1,5 | 1,5 | - |
| Rental cost propelled transport type | *C_truck/C_vessel* | 90 | 130 | 130 | €/h |
| Rental cost transport carrier | *C_barge* | 0 | 12,5 | 12,5 | €/h |
| Rental cost handling equipment | *C_equip_i* | 30 | 30 | 30 | €/h |
| (Un)loading speed equipment | *S_handling_i* | 75 | 75 | 75 | ton/h |
| (Un)loading personnel needed | *A_pers_i* | 0 | 1 | 1 | - |
| Hourly salary cost personnel | *C_pers_i* | 45 | 45 | 45 | €/h |
| Calculation factor loading | *f_calcload* | 0,50 | 0,50 | 0,50 | - |
| Rental cost transport carrier per day | C_store_i | 20 | 100 | 100 | €/day |
| Calculation factor no storage | f_nostore | 0 | 0 | 0 | - |
| Calculation factor store 1 day | f_store1 | 1 | 1 | 1 | - |
| Calculation factor store >1 day | f_store>1 | 3 | 3 | 3 | - |
| Discount factor store more than one day | f_store_disc | 10% | 10% | 10% | % |

**Output parameters**

| Parameter | Value road | Value Baseline | Value design alternative | Unit |
|---|---|---|---|---|
| Amount of movements | 672 | 130 | 118 | - |
| Amount of veh/vessel km | 4515 | 926 | 810 | vessel/vehicle km |
| Amount of tonkm | 46800 | 46800 | 46800 | tonkm |
| Total logistics cost | € 30.719,10 | € 31.517,80 | € 27.093,29 | € |
| Total transport cost | € 20.317,50 | € 18.855,80 | € 16.489,29 | € |
| Total handling cost | € 9.235,20 | € 3.744,00 | € 3.744,00 | € |
| Total storage cost | €1.166,40 | € 8.918,00 | € 6.860,00 | € |



Figure C.1: Overview of the decision support tool

### C.0.1. Choosing input parameters

As can be seen in Figure C.2 with yellow is indicated which values need to be adjusted when the user wants to compare a design alternative to the baseline and road alternative. All other values can be adjusted as well, but is not always necessary when using the tool.

**The yellow coloured boxes can be changed for the design alternative**

| **Input parameters** | Abbreviation | Value road | Value baseline | Value design alternative | Unit |
|---|---|---|---|---|---|
| Quay wall length | *L_quay* | 100 | 100 | 100 | metres |
| Distance hub - site | *Dist_hs* | 7,5 | 7,5 | 7,5 | km |
| Speed transport mode | *V_i* | 20 | 7 | 7 | km/h |
| Capacity of transport carrier | *Cap_i* | 15 | 80 | 80 | tonnes |
| Loading rate of transport carrier | *Loadrate_i* | 90% | 75% | 100% | % |
| Percentage transport with return flow | *%_ret* | 90% | 90% | 90% | % |
| Loading rate of returning transport carrier | *Loadrate_ret* | 50% | 50% | 50% | % |
| Percentage store up to 1 day | *%_store1day* | 0% | 50% | 50% | % |
| Percentage store more than 1 day | *%_store3day* | 10% | 50% | 50% | % |

Figure C.2: Choosing input parameters for the decision support tool

## C.0.2. Check system parameters

For both the baseline as the design alternatives certain system parameters have a default value which is added to the list of system parameters on the main tab of the decision support tool. These system parameters and their default values are described in section 5.5.2. It is however important to always do a check before you use the decision support tool.

| **System parameters** | Abbreviation | Default value road | Default value baseline | Default value design alternatives | Unit |
|---|---|---|---|---|---|
| Tonnes per linear meter quay | *T_p/m* | 31,20 | 31,20 | 31,20 | tonnes/m |
| Total material quantity | *Q_tot* | L_quay * T_p/m | L_quay * T_p/m | L_quay * T_p/m | tonnes |
| Calculation factor return movement | *f_calc2way* | 2 | 2 | 2 | - |
| Calculation factor one way movement | *f_calc1way* | 1,5 | 1,5 | 1,5 | - |
| | | | | | |
| Rental cost propelled transport type | *C_truck/C_vessel* | 90 | 130 | 130 | €/h |
| Rental cost transport carrier | *C_barge* | 0 | 12,5 | 12,5 | €/h |
| | | | | | |
| Rental cost handling equipment | *C_equip_i* | 30 | 30 | 30 | €/h |
| (Un)loading speed equipment | *S_handling_i* | 75 | 75 | 75 | ton/h |
| (Un)loading personnel needed | *A_pers_i* | 0 | 1 | 1 | - |
| Hourly salary cost personnel | *C_pers_i* | 45 | 45 | 45 | €/h |
| Calculation factor loading | *f_calcload* | 0,50 | 0,50 | 0,50 | - |
| | | | | | |
| Rental cost transport carrier per day | C_store_i | 20 | 100 | 100 | €/day |
| Calculation factor no storage | f_nostore | 0 | 0 | 0 | - |
| Calculation factor store 1 day | f_store1 | 1 | 1 | 1 | - |
| Calculation factor store >1 day | f_store>1 | 3 | 3 | 3 | - |
| Discount factor store more than one day | f_store_disc | 10% | 10% | 10% | % |

Figure C.3: System parameters

## C.0.3. Calculation

To the input variables that can be chosen and the default values for the system parameters, certain values are redirected to the calculation tab of the tool. In this tab the actual calculations are performed. These calculations are executed for every amount of tonnes freight to be transported for a project. In the lower left corner of Figure C.4, the chosen quay wall length and tonnes per linear meter quay are multiplied. The amount of tonnes freight that come from this calculation, serves as the value for which the values are selected as output parameters corresponding to the tonnes freight for a project.

| A | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Water | | | | | | | |
| Name variable/paramter | Water alternativ | | Tonnes freight for project | Transport water | Handling water | Storage | Total logistic cost water | Logistic cost per ton freight | Total movements | Total tonkm | Total vessel km |
| #KM's to CCC | 7,5 | | 0 | € 0,00 | € 0,00 | € 0,00 | € 0,00 | #DEEL/0! | 0 | 0 | 0 |
| #km/hour avg. speed | 7 | | 30 | € 305,36 | € 36,00 | € 343,00 | € 684,36 | € 22,81 | 2 | 450 | 15 |
| € rent per hour transport vehicle | € 130,00 | | 60 | € 534,38 | € 72,00 | € 343,00 | € 949,38 | € 15,82 | 4 | 900 | 26 |
| € rent per hour transport carrier | € 12,50 | | 90 | € 839,73 | € 108,00 | € 343,00 | € 1.290,73 | € 14,34 | 6 | 1350 | 41 |
| #tonnes per freight | 80 | | 120 | € 839,73 | € 144,00 | € 343,00 | € 1.326,73 | € 11,06 | 6 | 1800 | 41 |
| Loading rate | 100% | | 150 | € 839,73 | € 180,00 | € 343,00 | € 1.362,73 | € 9,08 | 6 | 2250 | 41 |
| %waste from inflow | 90% | | 180 | € 1.145,09 | € 216,00 | € 686,00 | € 2.047,09 | € 11,37 | 8 | 2700 | 56 |
| Loading rate waste | 50% | | 210 | € 1.374,11 | € 252,00 | € 686,00 | € 2.312,11 | € 11,01 | 10 | 3150 | 68 |
| Calculation factor return movement | 2 | | 240 | € 1.374,11 | € 288,00 | € 686,00 | € 2.348,11 | € 9,78 | 10 | 3600 | 68 |
| Calculation factor one-way movement | 1,5 | | 270 | € 1.679,46 | € 324,00 | € 686,00 | € 2.689,46 | € 9,96 | 12 | 4050 | 83 |
| | | | 300 | € 1.679,46 | € 360,00 | € 686,00 | € 2.725,46 | € 9,08 | 12 | 4500 | 83 |
| | | | 330 | € 1.984,82 | € 396,00 | € 1.029,00 | € 3.409,82 | € 10,33 | 14 | 4950 | 98 |
| **Storage costs** | | | 360 | € 1.984,82 | € 432,00 | € 1.029,00 | € 3.445,82 | € 9,57 | 14 | 5400 | 98 |
| %laten liggen/staan <= 1 dag | 50,00% | | 390 | € 2.213,84 | € 468,00 | € 1.029,00 | € 3.710,84 | € 9,51 | 16 | 5850 | 109 |
| % laten liggen/staan > 1 dag | 50,00% | | 420 | € 2.519,20 | € 504,00 | € 1.029,00 | € 4.052,20 | € 9,65 | 18 | 6300 | 124 |
| Calc. factor <= 1 dag | 1 | | 450 | € 2.519,20 | € 540,00 | € 1.029,00 | € 4.088,20 | € 9,08 | 18 | 6750 | 124 |
| Calc factor > 1 dag | 3 | | 480 | € 2.519,20 | € 576,00 | € 1.029,00 | € 4.124,20 | € 8,59 | 18 | 7200 | 124 |
| Calc factor no storage, only unloading | 0 | | 510 | € 2.824,55 | € 612,00 | € 1.372,00 | € 4.808,55 | € 9,43 | 20 | 7650 | 139 |
| € rent per day transport carrier | € 100,00 | | 540 | € 3.053,57 | € 648,00 | € 1.372,00 | € 5.073,57 | € 9,40 | 22 | 8100 | 150 |
| Discount factor multiple days | 10% | | 570 | € 3.358,93 | € 684,00 | € 1.372,00 | € 5.414,93 | € 9,50 | 24 | 8550 | 165 |
| | | | 600 | € 3.358,93 | € 720,00 | € 1.372,00 | € 5.450,93 | € 9,08 | 24 | 9000 | 165 |
| **Handling costs** | | | 630 | € 3.358,93 | € 756,00 | € 1.372,00 | € 5.486,93 | € 8,71 | 24 | 9450 | 165 |
| € per hour (un)loading machine | 30 | | 660 | € 3.664,29 | € 792,00 | € 1.715,00 | € 6.171,29 | € 9,35 | 26 | 9900 | 180 |
| #tonnes per hour loading rate | 75 | | 690 | € 3.893,30 | € 828,00 | € 1.715,00 | € 6.436,30 | € 9,33 | 28 | 10350 | 191 |
| Calculation factor loading during construction activities | 0,50 | | 720 | € 3.893,30 | € 864,00 | € 1.715,00 | € 6.472,30 | € 8,99 | 28 | 10800 | 191 |
| Amount of extra people needed when no direct unloading | 0 | | 750 | € 4.198,66 | € 900,00 | € 1.715,00 | € 6.813,66 | € 9,08 | 30 | 11250 | 206 |
| Amount of extra people needed to (un)load besides shipper(s)/driver | 1 | | 780 | € 4.198,66 | € 936,00 | € 1.715,00 | € 6.849,66 | € 8,78 | 30 | 11700 | 206 |
| € hourly salary cost (un)loading crew | 45 | | 810 | € 4.504,02 | € 972,00 | € 2.058,00 | € 7.534,02 | € 9,30 | 32 | 12150 | 221 |
| Time to (un)load full load in hrs | 1,07 | | 840 | € 4.504,02 | € 1.008,00 | € 2.058,00 | € 7.570,02 | € 9,01 | 32 | 12600 | 221 |
| Equipment costs (un)loading full load | € 32,00 | | 870 | € 4.733,04 | € 1.044,00 | € 2.058,00 | € 7.835,04 | € 9,01 | 34 | 13050 | 233 |
| Extra personnel costs (un)loading full load | € 48,00 | | 900 | € 5.038,39 | € 1.080,00 | € 2.058,00 | € 8.176,39 | € 9,08 | 36 | 13500 | 248 |
| Waiting costs for transport unit | € 152,00 | | 930 | € 5.038,39 | € 1.116,00 | € 2.058,00 | € 8.212,39 | € 8,83 | 36 | 13950 | 248 |
| | | | 960 | € 5.038,39 | € 1.152,00 | € 2.058,00 | € 8.248,39 | € 8,59 | 36 | 14400 | 248 |
| **Tonnes freight calculation** | | | 990 | € 5.343,75 | € 1.188,00 | € 2.401,00 | € 8.932,75 | € 9,02 | 38 | 14850 | 263 |
| Quay wall length | 100 | | 1020 | € 5.572,77 | € 1.224,00 | € 2.401,00 | € 9.197,77 | € 9,02 | 40 | 15300 | 274 |
| Tonnes per linear meter quay | 31,20 | | 1050 | € 5.878,13 | € 1.260,00 | € 2.401,00 | € 9.539,13 | € 9,08 | 42 | 15750 | 289 |
| Tonnes freight | 3120 | | 1080 | € 5.878,13 | € 1.296,00 | € 2.401,00 | € 9.575,13 | € 8,87 | 42 | 16200 | 289 |
| | | | 1110 | € 5.878,13 | € 1.332,00 | € 2.401,00 | € 9.611,13 | € 8,66 | 42 | 16650 | 289 |
| | | | 1140 | € 6.183,48 | € 1.368,00 | € 2.744,00 | € 10.295,48 | € 9,03 | 44 | 17100 | 304 |
| | | | 1170 | € 6.412,50 | € 1.404,00 | € 2.744,00 | € 10.560,50 | € 9,03 | 46 | 17550 | 315 |
| | | | 1200 | € 6.412,50 | € 1.440,00 | € 2.744,00 | € 10.596,50 | € 8,83 | 46 | 18000 | 315 |
| | | | 1230 | € 6.717,86 | € 1.476,00 | € 2.744,00 | € 10.937,86 | € 8,89 | 48 | 18450 | 330 |

Figure C.4: Calculation tab of decision support tool

## C.0.4. Output of the decision support tool

The output of the decision support tool, as can be seen in Figure C.5, is shown as a comparison of the output parameters of the design alternative to the baseline and road scenario. With these insights, the impact of changing input or system parameters can be tested. With this, stakeholders are supported in decisions that need to be made concerning waterborne construction logistics alternatives.

**Output parameters**

| Parameter | Value road | Value Baseline | Value design alternative | Unit |
|---|---|---|---|---|
| Amount of movements | 672 | 130 | 118 | - |
| Amount of veh/vessel km | 4515 | 926 | 810 | vessel/vehicle km |
| Amount of tonkm | 46800 | 46800 | 46800 | tonkm |
| Total logistics cost | € 30.719,10 | € 31.517,80 | € 27.093,29 | € |
| Total transport cost | € 20.317,50 | € 18.855,80 | € 16.489,29 | € |
| Total handling cost | € 9.235,20 | € 3.744,00 | € 3.744,00 | € |
| Total storage cost | €1.166,40 | € 8.918,00 | € 6.860,00 | € |

Figure C.5: Output parameters in the decision support tool

# D
# MIN/MAX values

### Distance hub - site MIN value

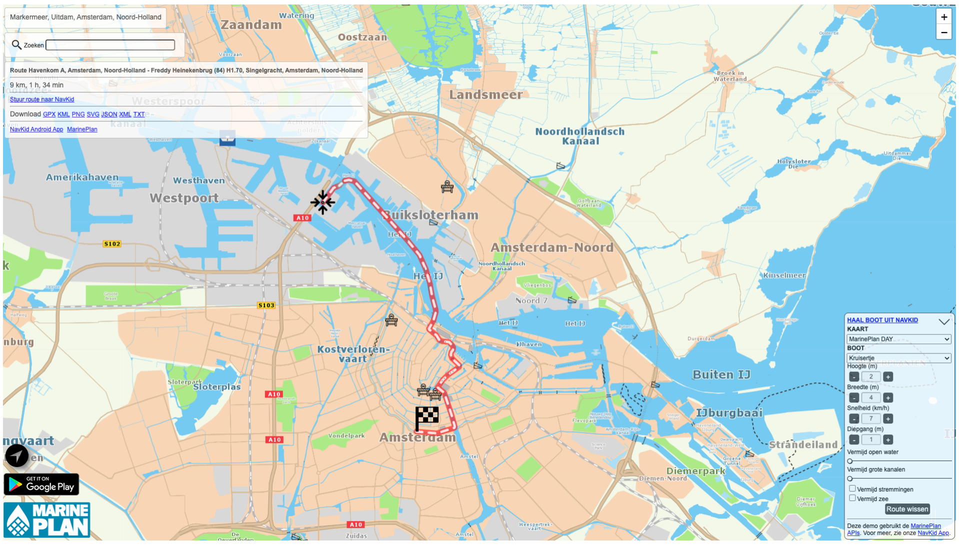



Figure D.1: Longest distance from the hub to a construction site on the S100 in Amsterdam

### Distance hub - site MAX value

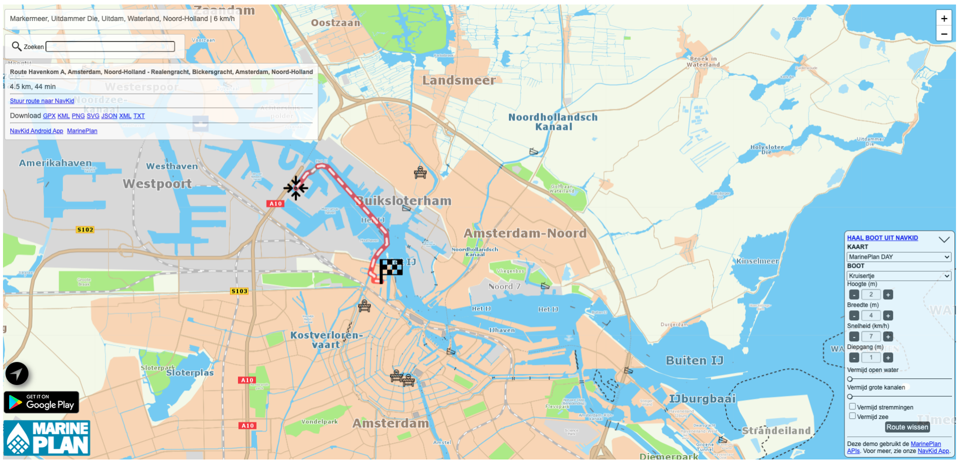



Figure D.2: Shortest distance from the hub to a construction site on the S100 in Amsterdam

### Capacity of transport carrier MIN value


Figure D.3: Transport carrier with the lowest capacity used in Amsterdam

### Capacity of transport carrier MAX value

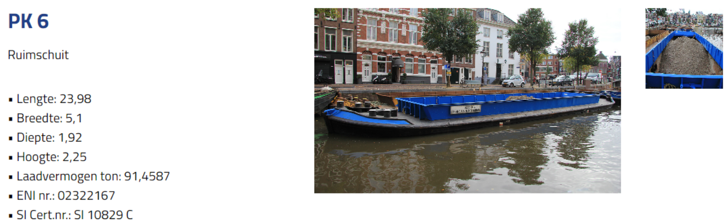



Figure D.4: Transport carrier with the largest capacity used in Amsterdam